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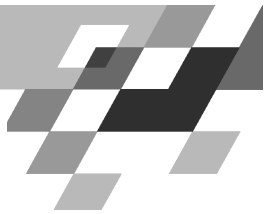

Analysis of Web Caching in the Gigabit Research Network G-WiN

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Abschlußbericht zum Projekt

Analyse der Wirksamkeit von Web Caching im G-WiN

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Project Summary

The tremendous growth expected in World Wide Web traffic in the next years requires huge efforts to insure scalability and user acceptance. Web caching is a common tool for reducing network traffic and guaranteeing reasonable response times. To provide optimal Web caching solutions, network operators need in-depth understanding of how the performance of a proxy cache is influenced by workloads characteristics and network technology. This requires detailed analysis and evaluation of different organizations of a standalone web proxy caches as well as evaluation of different forms of cooperation between caching proxies distributed across a wide area network.

In the first part of this report, we present a comprehensive performance study of different organizations of a standalone web proxy cache under current and future workload characteristics. As a novel feature of our study, we characterize request streams seen at a Web proxy cache to HTML, images, and multi media documents seen at a proxy cache. Based on this workload characterization, we derive workload forecasts for institutional Web proxy caches and proxies residing in a backbone network. The goal of our study constitutes the understanding how these replacement schemes deal with different Web document classes. This understanding is important for the effective design of Web cache replacement schemes under changing workload characteristics.

While bandwidth for previous IP backbone networks deployed by Internet Service Providers typically has been limited to 34 Mbps, current and future IP networks provide bandwidth ranging from 155 Mbps to 2.4 Gbps. Thus, it is important to investigate the impact of emerging network technologies on the performance of cooperative Web caching protocols. In the second part of this project, we present a comprehensive performance study of four cooperative Web caching protocols. The goal of this performance study lies in understanding the behavior and limiting factors of the considered protocols for cooperative Web caching under measured traffic conditions. Based on this understanding, we give recommendations for Internet Service Providers, Web clients, and Application Service Providers.

Key words:

Performance-oriented design and evaluation studies of Web caches, Web cache replacement schemes, protocol support for cooperative Web caching, workload characterization and forecasting, trace-driven simulation.

Contents

1 Introduction

Applications of the World Wide Web reach form browsing of information and online catalogs over e-business solutions, teleteaching and –learning up to video conferences. The continued exponential growth of the traffic volume and growing demand for access to web resources anytime form anywhere sets new challenges to network operators, e.g Internet Service Providers and academic institutions. Web caching is a common tool for reducing network traffic and guaranteeing reasonable response times. Standalone Web proxy caches reduce the traffic between local and wide area network. Internet Service Providers widely use hierarchical clusters of web proxy caches. Several protocols for cooperation were developed, e.g. the Internet Cache Protocol, ICP. These protocols make it easy to build up heterogeneous caching solutions, employing cache appliances developed by different hardware vendors. Transparent techniques enable users to benefit form the advantages of Web Caching without even knowing of its existence.

Providing optimal caching solutions requires in-depth understanding of caching technologies, workload characteristics as well as sensitivity to changes in technology and user behavior. Therefore, detailed studies must be employed to explain and optimize the performance of standalone web proxy caches. Furthermore, the behavior of cooperating web caches has to be investigated with respect to the changing characteristics of the underling network infrastructure, e.g. increasing bandwidth availability in the backbone network of a national Internet Service Provider. Both studies must be accomplished by detailed analysis of workload characteristics seen by caching proxies at different locations, i.e. institutional or backbone proxies. Sensitivity studies help to understand behavior of protocols and algorithms and supports design of long-term scalable caching solutions.

This report consists of two parts. Part 1 focuses on the organization of standalone web proxy caches. It gives an overview over replacement schemes and protocols supported by commercial caching solutions. A comprehensive performance study of widely used as well as recently proposed replacement scheme is provided. The presented results are derived using trace driven simulation. As simulation input, we use traces recorded by proxy caches located at Universities and commercial institutions as well as in the backbone of the German research network G-WiN. As a novel feature of our study, we characterize request streams seen at a Web proxy cache to HTML, images, and multi media documents seen at a proxy cache. Based on this workload characterization, we derive workload forecasts for institutional Web proxy caches and proxies residing in a backbone network. The goal of our study constitutes the understanding how these replacement schemes deal with different Web document classes. This understanding is important for the effective design of Web cache replacement schemes under changing workload characteristics.

Part 2 focuses on the cooperation of Web proxy caches located in the backbone of a national internet service provider, e.g. the G-WiN. While bandwidth for previous IP backbone networks deployed by Internet Service Providers typically has been limited to 34 Mbps, current and future IP networks provide bandwidth ranging from 155 Mbps to 2.4 Gbps. Thus, it is important to investigate the impact of emerging network technologies on the performance of cooperative Web caching protocols. In this report, we present a comprehensive performance study of four cooperative Web caching protocols. We consider the Internet cache protocol ICP, Cache Digests, the cache array routing protocol, CARP, and the Web cache coordination protocol, WCCP. The performance of these protocols is evaluated using trace-driven simulation with measured Web traffic from DFN and NLANR. The goal of this performance study lies in understanding the behavior and limiting factors of the considered protocols for cooperative Web caching under measured traffic conditions. Based on this understanding, we give recommendations for Internet Service Providers, Web clients, and Application Service Providers.

Part 1: Evaluating Hardware and Software Web Proxy Caching Solutions

2 Overview

The continued growth of the World Wide Web and the emergence of new multi media applications necessitates the use of proxy caches to reduce end-user latency and network traffic. Commercial Web caching solutions include CacheFlow's Server Accelerator, Cisco CacheEngine, InforLibria's DynaCache, Network Appliance NetCache, Inktomie's Traffic Server, Novell's Internet Cache System. These products differ in cache size, disk storage, and throughput. However, all commercial products currently on the market solely rely on the replacement scheme Least-Recently-Used. Only Squid as open-source software freely available to academic institutions can be configured to employ other cache replacement schemes which have been proposed recently.

The optimization of cache replacement schemes is important because the growth rate of Web content (i.e., multi media documents) is much higher that anticipated growth of memory sizes for future Web caches [JB00]. Furthermore, recent studies (see e.g. [BCF+99]) have shown hit rate and byte hit rate grow in a log-like fashion as a function of size of the Web cache. Cao and Irani introduced the Web cache replacement scheme Greedy Dual Size [CI97] which takes into account document sizes and a user defined cost function. They showed that Greedy Dual size is on-line optimal with respect to this cost function. Jin and Bestavros introduced Web cache replacement scheme Greedy Dual * as an improvement to Greedy Dual Size [JB00]. They compared the performance of this newly proposed replacement scheme with traditional schemes, are Least Recently Used (LRU), Least Frequently Used with Dynamic Aging (LFU-DA), and with the size-aware scheme Greedy Dual Size [JB00]. Eager, Ferris, and Vernon developed analytical models for determining optimal proxy cache content for supporting continuous-media streaming [EFV00]. Arlitt, Friedrich, and Jin provided a comparative performance study of six Web cache replacement schemes among which are LRU, LFU-DA, and Greedy Dual Size [AFJ00]. They also observed an extreme nonuniformity in popularity of Web requests seen at proxy caches. All these previous performance studies consider a single request stream for analyzing the performance of replacement schemes.

The first part of this project focuses on the evaluation of the replacement schemes of hardware and software solutions of Web proxy caching solutions [CMT01]. The second part focuses on the evaluation of the cooperative Web caching protocols (i.e., the Internet Cache Protocol, ICP, the Cache Array Routing Protocol, CARP, and Cache Digests). In this part of the report, we present comprehensive performance studies for LRU as traditional replacement schemes as well as newly proposed schemes LFU-DA, Greedy-Dual-Size and Greedy-Dual *

under current and future workload characteristics. The goal of our study constitutes the understanding how these replacement schemes deal with different Web document classes. This understanding is important for the effective design of Web cache replacement schemes under changing workload characteristics.

A comprehensive characterization of previous Web workloads was given by Arlitt and Williamson [AW97]. A recent survey article on performance characteristics of the Web provided by Crovella [Cro00] explains why many of the characteristics of Web workloads (e.g., document sizes and document popularity) possess high variability. The temporal locality in Web workloads have been subject to two recent papers. Jin and Bestavros investigated temporal locality in Web cache request streams [JB99]. Mahanti and Williamson provided a detailed workload characterization for Web proxy caches [MW99]. They observed that in several workload measured in 1998 HTML and image documents account for over 95% of all requests. Eager, Mahanti and Williamson investigated the impact of temporal locality on proxy cache performance [MEW00].

The workload characterization presented in Section 5 indicates that in future workloads percentage of request for multi media documents will be substantially larger than in current Web request streams seen at a proxy cache. Furthermore, we observed that the popularity of some multi media documents rapidly increases. Moreover, the time between two successive references to the same Web document denoted as temporal correlation decreases. These trends are derived from five traces measured in 1996, 1998, and 2000. Based on these trends, using linear regression we derive workload forecasts both for institutional Web proxy caches and for proxy caches located in backbone networks. We present curves plotting the hit rate and byte hit rate broken down for the HTML, image, and multi media documents. This breakdown of hit rates and byte hit rates per document class shows that the overall hit rate is mainly influenced by the hit rate on images. The overall byte hit rate is mainly influenced by the byte hit rate on multi media documents. The presented curves indicate that in an overall evaluation considering both hit rates and byte hit rates the software Web caching solution Squid with the replacement scheme GD*(1) should be the choice for current workloads whereas Squid with the replacement scheme GDS(1) should be the choice for future workloads. The performance results are derived by trace-driven simulation. The simulator for the Web cache replacement strategies has been implemented using the simulation library CSIM [Sch95].

This part of the report is organized as follows. Section 3 introduces commercial Web caching products currently on the market. The replacement schemes employed in these Web caching solutions are described in Section 4. Section 5 provides a comprehensive characterization of the workloads derived from the considered traces. Moreover, we present two workload forecasts taking into account the rapidly increasing popularity of multi media applications. In Sections 6, we present performance curves for the considered Web cache replacement schemes derived from trace data and workload forecasts.

3 Web Caching Products

3.1 Hardware Solutions

CacheFlow

Cache Flow [CF01] offers two Web caching product lines called *Client Accelerators* and *Server Accelerators*. Server Accelerators are surrogates also known as *reverse proxy caches*. They are placed in front of a Web server in order to service request for documents located on the Web server. Their functionality adds availability to popular Web sides by taking load form the origin server. Server Accelerators are outside the scope of this report. Client Accelerators (CA) are Web caches, which can be placed in existing networks. They reduce response times and bandwidth requirements by moving Web and streaming content closer to the user and accelerate client requests. Thus, they achieve scalability of existing networks.

All CacheFlow accelerators are run by the patent-pending CacheOS operating system. CacheOS is a specially designed operating system for offering scalability and reliability to Web caching applications. All CacheFlow accelerators can be upgraded by software-addons to enable firewall functionality and content filtering. CacheFlow accelerators support the Hypertext Transfer Protocol (HTTP) v1.0 and v1.1, the File Transfer Protocol (FTP), the Network News Transfer Protocol (NNTP) and domain name system (DNS) caching. The CA 600 family additionally supports the Internet Cache Protocol (ICP) as well as the Web Cache Coordination Protocol (WCCP) v1.0 and v2.0 for cooperative Web caching. The WCCP protocol is shipped with Cisco routers and offers transparent Web caching. Network management support is provided through compatibility with the Simple Network Management Protocol (SNMP). The CacheFlow products currently available do not offer protocol support for streaming applications like digital audio and video transmission over the Internet.

CacheFlow product line of accelerators differs in cache size, throughput, and price. The CA 600 family is designed for small Internet Service Providers (ISPs) and enterprises, while CA 3000 and 5000 families are designed for large ISPs who aim at saving substantial bandwidth in the wide area network. The CA-600 series of client accelerators are used by enterprises, ISPs, and other organizations worldwide to manage and control Web traffic growth, while accelerating the delivery of content to users. The CacheFlow client accelerator is deployed between users and the Internet or at remote sites, and intelligently manages requests for content. The *CacheFlow 3000* is a high performance Internet caching appliance. Supporting incoming traffic loads from 10 to 45 Mbps, the 3000 Series is a mid-range Web caching solution for ISPs and enterprises. According to its vendor, CacheFlow 3000 products scale network capacity with minimal infrastructure investments. The *CacheFlow 5000* is the high-end product of CacheFlow supporting incoming traffic loads up to 135 Mbps containing

126 GB disk storage. The technical data of CacheFlow client accelerators is summarized in Table 1.

Cisco

Cisco's Web caching solution comprises of the Cache Engine 500 series [CS01]. The Cisco Cache Engine 500 series products accelerate content delivery, optimize network bandwidth utilization, and control access to content. Opposed to the operating-system-based caching solution provided by CacheFlow, Cisco cache engines are integrated into the network infrastructure. Cisco caching solutions can be cost-effectively deploy on a wide-scale basis and gain the benefits of caching throughout your entire network. Traditional proxy-based or standalone caches are not inherently designed to be network integrated, resulting in relatively higher costs of ownership and making them less desirable for wide-scale deployment.

All Cisco products support HTTP v1.0 and v1.1, FTP, NNTP, and DNS caching. Supporting ICP provides compatibility to existing environments for cooperative Web caching. In 1997, Cisco pioneered the industry's first content routing technology, the Web Cache Coordination Protocol (WCCP) version 1.0. WCCP is a router-cache protocol that localizes network traffic and provides network-intelligent load distribution across multiple network caches for maximized download performance and content availability. Since spring 2000, the protocol WCCP v2.0 is available and widely employed. According to Cisco, they will continue to lead the innovations and enhancements to this protocol and other content routing technologies. As for CacheFlow products, Cisco provides network management support through compatibility with SNMP and Cisco products currently available do not offer protocol support for streaming applications.

Cisco Cache Engine Series products differ in storage capacity and throughput. Cisco Cache Engine 505 is a entry-level cache engine for small enterprise branch offices with incoming traffic up to 1.5 Mbps. Cisco's Cache Engine 550 is a midrange a Web caching solution for regional offices with uplink network bandwidth up to 11 Mbps. Cisco's Cache Engine 570 is a Web caching solution for small service provider POPs and medium-sized enterprises with incoming traffic up to 22 Mbps. Storage expansion is available via the Cisco Storage Array. Cache Engine 590 is a high-end caching solution designed for service providers and large enterprises with incoming traffic up to 44.7 Mbps. The technical data of Cisco Cache Engine series products is summarized in Table 1.

InfoLibria

The Web caching solution offered by InfoLibria's comprises of the DynaCache [Inf01] products. According to InfoLibria, DynaCache offers carrier-grade caching and intelligent content management. By automatically storing commonly requested Web objects at the edge of the local network, DynaCache enables high-speed access to the freshest Internet content

while minimizing bandwidth demand to popular Web sites. The result is increased network reliability, faster performance and shorter end-user latency. DynaCache products comes in configurations to meet the diverse networking and business needs. DynaCache technology is applied at ISPs and Application Service Providers (ASPs), wireless ISPs, and Satellite Service Providers.

As CacheFlow accelerators InfoLibria's DynaCache products are run by a special-purpose operating system specially designed for offering scalability and reliability to Web caching applications. DynaCache contains software for firewall functionality and content filtering. DynaCache supports the protocols HTTP v1.0 and v1.1, FTP, NNTP, and DNS caching. For cooperative Web caching, DynaCache supports ICP and WCCP v2.0. Network management support is provided through compatibility with SNMP. As for CacheFlow and Cisco products, InfoLibria's products currently available do not offer protocol support for streaming applications like digital audio and video transmission over the Internet.

InfoLibria's DynaCache series offer products with different storage capacity and throughput. The entry solution constitutes the *DynaCache 10* with a hard disk storage capacity of 36 GB and a maximal throughput of 12 Mbps. The most powerful Web caching device of InfoLibria's product line is the *DynaCache 40*. Its hard disks offer up do 144 GB of cache storage. Its maximum throughput is 34 Mbps. The technical data of InfoLibria's DynaCache products is summarized in Table 1.

Network Appliance

The hardware Web caching solution offered by Network Appliance [NA01] comprises of the NetCache product lines. NetCache products solve content delivery problems faced by enterprises, content distribution networks, ISPs, and ASPs. These appliances can be used in the entire network, from central headquarters to remote points of presence and local offices. Opposed to the products introduced above, the NetCache product line does support streaming applications. Thus, NetCache can also deliver digital audio and video enabling next-generation network applications such as large-scale video-on-demand services.

As CacheFlow accelerators and InfoLibria's DynaCache, the NetCache products are run by a special-purpose operating system specially designed for offering scalability and reliability to Web caching and media streaming applications. NetCache supports the protocols HTTP v1.0 and v1.1, FTP, NNTP, and DNS caching. For cooperative Web caching, DynaCache supports ICP and WCCP v2.0. Network management support is provided through compatibility with SNMP. NetCache also include support for major streaming media technologies through compatibility with the Real Time Streaming Protocol (RTSP) and the internet Content Adaptation Protocol (iCAP).

The NetCache family includes three distinct product lines: *NetCache C1100*, *NetCache C700*, and *NetCache C6100*. *NetCache C1100 Series* are the entry-level NetCache products

designed for enterprise remote or branch offices as well as small and medium enterprises. The C1100 series supports multiple connections for HTTP environments with 1.5 Mbps bandwidth and connections with 155 Mbps for streaming applications. The mid-range *NetCache C700 Series* products supporting a wide range of capacity, performance, and reliability features. Reliability and availability of mission-critical data is ensured with features like RAID, redundant hardware, and hot-swap drives. The expansion choices make the NetCache C700 series ideal solutions for environments experiencing rapid growth. The high-end *NetCache C6100 Series* products deliver highest performance and reliability for the data center and other high-bandwidth locations. The C6100 solutions support 155 Mbps and more for HTTP environments and 622 Mbps and more for streaming applications. Large content libraries with up to 2 TB of storage can be reliably stored and accessed.

Table 1 summarizes the technical data of the hardware solutions for Web caching. Note that the commercial products differ in size of disk storage and RAM while all products employ Least Recently Used (LRU) as replacement scheme for Web documents.

3.2 Software Solutions

Inktomi

Inktomi [Inc01] offers a software Web caching solution called *Traffic Server*. Inktomi's Traffic Server is a robust network cache platform that improves quality of service, optimizes bandwidth usage and provides a foundation for the delivery of new services at the edge of the network. Traffic Server is available in three versions: *Traffic Server C-Class* for carriers and

Vendor	Product	Disk in GB	RAM in MB	Throughput in Mbps	Replacement Scheme
CacheFlow	CacheFlow 600	36	768	10	LRU
	CacheFlow 3000	63	1,024	45	LRU
	CacheFlow 5000	126	N/A	135	LRU
Cisco Systems	Cache Engine 505	18	128	1.5	LRU
	Cache Engine 550	18	256	11	LRU
	Cache Engine 570	144	384	22	LRU
	Cache Engine 590	144	384	44.7	LRU
InfoLibria	DynaCache DC 10	36	512	12	LRU
	DynaCache DC 20	40	512	21	LRU
	DynaCache DC 30	72	512	27	LRU
	DynaCache DC 40	144	1,024	34	LRU
Network Appliance	NetCache C1100	9	256	1.5	LRU
	NetCache C1105	72	512	1.5	LRU
	NetCache C720	1,024	512	N/A	LRU
	NetCache C6100	2,048	3,096	155	LRU

Table 1. Technical summary of hardware caching solutions

service providers, *Traffic Server E-Class* for enterprise networks, *Traffic Server Engine cache appliance* solutions. The first two products are true software solutions; the latter one constitutes an integrated hardware and software package through Inktomi's partners called original equipment manufacturers (OEM). These OEMs associated with Inktomie include Sun, HP, and SGI. As a software solution, Traffic Server easily allows the integration of services like on-demand streaming media, filtering and transformation at the edge of the network. According to Inktomie, Traffic Server is the only network cache that also functions as a platform for delivering services at the edge of the network. Traffic Server allows the integration of applications directly into the network to perform valuable functions like filtering out inappropriate or offensive Web content or transforming Internet content so that it can be viewed on cell phones or hand-held PCs.

As all hardware cache solutions introduced in the previous section, Inktomi's Traffic Server supports the protocols HTTP v1.0 and v1.1, FTP, NNTP, and DNS caching. For cooperative Web caching, the Traffic Server products support the protocols ICP and WCCP v2.0. ICP is used for cache coordination and provides compatibility with existing network caches. Transparent caching using the WCCP protocol enables interoperability between Inktomi's Traffic Server and Cisco-based routers. Network management support is provided through compatibility with SNMP. As the NetCache products of Network Appliance, Inktomi's Traffic Server include support for major streaming media technologies through compatibility with the Real Time Streaming Protocol (RTSP) and the internet Content Adaptation Protocol (iCAP).

Inktomie's Traffic Server can be run on the operating system platforms Sun Solaris 2.6 and Solaris 7 under a Sun Ultra SPARC with at least 256 MB RAM, True64 UNIX on a Digital Alpha/OSF server with at least 256 MB RAM, SGI IRIX 6.5 on SGI MIPS systems with at least 256 MB RAM, as well as FreeBSD 3.1 and Windows NT 4.0 on any Pentium-based system or equivalent. On these systems, the Traffic Server software platforms support six to eight disks for Web caching. Employing the largest SCSI disks currently available, the high-end Traffic Server product can manage cache size of 400 GB. Throughput values achieved by Inktomie's Traffic Server products cannot be specified since it depends on the underlying hardware and operation system.

Novell

The software Web caching solution offered by Novell [Nov01] comprises of the *Internet Caching System* (*ICS*) product line. ICS enables small and medium enterprises as well as ISPs to increase the efficiency of their network infrastructures while reducing their associated costs by acting as forward proxy to accelerate organizations' access to the Internet. According to Novell, ICS appliances typically serve 40% to 70% of requests directly from the cache, thus, reducing request latency and tremendously improving the network efficiency. ICS appliances

can be configured in clusters for load balancing and fault tolerance. Furthermore, ICS also supports activity logging and transparent proxy. ICS provides high-speed delivery of any static multimedia object through HTTP encapsulation. For December 2000, Novell has announced to add native support for common media formats, providing control of live and on-demand media streams. Novell's partners include major PC manufacturers such as Compaq, Dell, and IBM. These original equipment manufacturers (OEM) have licensed ICS and integrate this software caching solution into their own internet appliances.

As Inktomi's Traffic Server, Novell's ICS supports the protocols HTTP v1.0 and v1.1, FTP, and NNTP. However, opposed to the Traffic Server product line, ICP does not support DNS caching. Again as Inktomi's Traffic Server, ICS products support the protocols ICP and WCCP v2.0 for cooperative Web caching and network management support is provided through compatibility with SNMP. As the hardware solutions of CacheFlow, Cisco, and Novell's products currently available do not offer protocol support for streaming applications like digital audio and video transmission over the Internet.

Novell's ICS products run on Intel Pentium based PCs with at least 256 MB RAM. As operating system, the ICS products run under the special purpose operating system Proxy-OS provided by Novell. Depending on the hardware platform, ICS product can manage cache size between 9 and 27 GB. As for Inktomie's Traffic Server, throughput values achieved by Novell's ICS products cannot be specified since it depends on the underlying hardware platform.

Squid

Opposed to the commercial hardware and software caching solutions introduced above, Squid [Squ01] is a non-commercial, full-featured software Web proxy cache. Squid is designed to run on Unix systems. Squid is open-source software freely available to academic institutions. The Squid software was originally developed at the National Laboratory for Applied Network Research (NLANR) in a project funded by the National Science Foundation. The Squid project was lead by Duane Wessels. The current version of Squid, Squid v2.3, is the result of efforts by numerous individuals from the Internet community. Due to its open source philosophy, Squid constitutes an ideal platform for implementation of academic prototypes of Web caching schemes and protocols.

Squid supports the protocols HTTP v1.0 and v1.1, FTP, NNTP, and DNS caching. For cooperative Web caching, Squid supports the protocols ICP and WCCP v2.0. Moreover, opposed to all other caching solution introduced above Squid also supports cooperative caching using the Cache Array Routing Protocol (CARP) and Cache Digests. As Novell's software solution, Squid does not offer protocol support for streaming applications like digital audio and video transmission over the Internet.

Squid is a high-performance proxy caching server for Web clients. Unlike traditional caching software, Squid handles all requests in a single, non-blocking, I/O-driven process. Squid keeps meta data and especially hot objects cached in RAM, caches DNS lookups, supports non-blocking DNS lookups, and implements negative caching of failed requests. Squid supports the Secure Sockets Layer (SSL), extensive access controls, and full request logging. By using the lightweight ICP, Squid caches can be arranged in a hierarchy or mesh for additional bandwidth savings. Squid consists of a main server program called *squid*, a DNS lookup program called *dnsserver*, some optional programs for rewriting requests and performing authentication, and some management and client tools. When *squid* starts up, it spawns a configurable number of *dnsserver* processes, each of which can perform a single blocking DNS lookup.

Squid runs on any modern Unix platform. In particular, Squid runs on Linux, FreeBSD, NetBSD, OSF and Digital Unix, IRIX, SunOS/Solaris, AIX, HP-UX, and OS/2. The minimum hardware requirements comprise of a single-processor PC or workstation with 128 MB RAM. Depending on the hardware platform, Squid can manage cache size up to 512 GB. As in case of the other software solutions, throughput values achieved by Squid cannot be specified.

Table 2 summarizes the product data of the software solutions for Web caching. Note that again all commercial products employ LRU as replacement scheme for Web documents. Note that Squid not only can be configured to use the cache replacement schemes LRU but also Least Frequently Used with Dynamic Aging (LFU-DA), Segmented LRU, and Greedy Dual Size (GDS).

Table 3 provides a summary of the protocols for data transport, cooperative Web caching, streaming and content adaption supported by the considered hardware and software solutions for Web caching.

Vendor	Product	Replacement	Original Equipement Manufacturer
Inktomi	Traffic Server E-Class Traffic Server C-Class Traffic Server Engine	LRU	Intel NetStructure 3Com
Novell	Internet Caching System	LRU	Compaq TaskSmart Dell PowerAppliance IBM Netfinity
NLANR	Squid	LRU, SLRU, LFU-DA, GDS	Unix Workstations

Table 2. Technical summary of software caching solutions

Vendor	Transport Protocol				Cooperative Web Caching				Streaming and Content Adaption	
	HTTP 1.0/1.1	FTP	NNTP	DNS	ICP	CARP	Cache Digests	WCCP	RTSP	iCAP
Cache Flow	x	x	x	x	-	-	-	x	-	-
Cisco	x	x	-	-	x	-	-	x	-	-
InfoLibria	x	x	-	x	x	-	-	x	-	x
Network Appliance	x	x	x	-	x	-	-	x	x	x
Inktomi	x	x	x	-	x	-	-	x	x	-
Novell	x	x	x	-	x	-	-	x	-	-
Squid	x	x	-	x	x	x	x	x	-	-

Table 3. Protocol support provided by hardware and software caching solutions

4 Web Cache Replacement Schemes

In traditional memory systems object sizes (i.e., a cache line or a memory page) and miss penalties (delay for bringing an object into the cache) are constant. The salient feature of Web caching lies in the high variability of both the cost for bringing in new Web documents and the size of such documents. In this report, we present the results for Least Recently Used, Segmented Least Recently Used, a frequency based algorithm Least Frequently Used with Dynamic Aging, and two size-aware replacement schemes Greedy Dual Size and Greedy Dual * which have been recently proposed.

In [JB00], two cost models for Web cache replacement schemes have been introduced. In the *constant cost model*, the cost of document retrieval is fixed. The *packet cost model* assumes that the number of packets transmitted determines the cost of document retrieval. The constant cost model is the model of choice for institutional proxy caches, which mainly aim at reducing end user latency by optimizing the hit rate. The packet cost model is appropriate for backbone proxy caches aiming at reducing network traffic by optimizing the byte hit rate.

Least Recently Used (LRU [AW97]) is a recency-based policy. It is based on the assumption that a recently referenced document will be referenced again in near future. Therefore, on replacement LRU removes the document from cache, which has not been referenced for the longest period of time. The functionality of LRU is illustrated in Figure 1. LRU uses a LRU-Stack. On a cache miss, the requested document is put on the most recently used (MRU) end

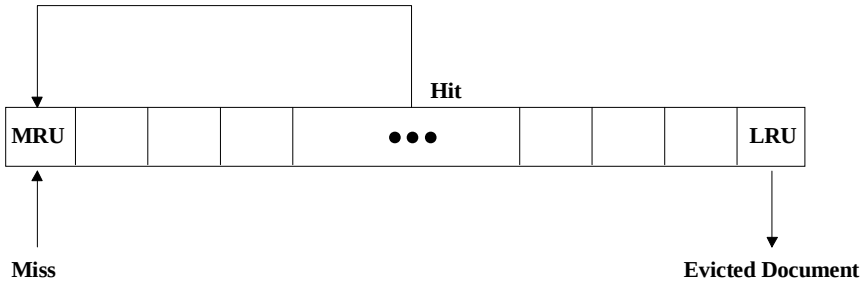


Figure 1. Illustration of the Least Recently Used replacement scheme

of the stack. All other documents are pushed one step towards the least recently used (LRU) end of the stack. On a cache hit, the requested document is located in the stack and moved again to the MRU end. On document eviction, the document at the LRU end of the stack is evicted. LRU can be implemented using a reference stack as illustrated in Figure 1.

LRU is the most widely used cache replacement scheme. Because LRU considers a fixed cost and size of documents, LRU aims at optimizing the hit rate. The good performance of LRU is due to the exploitation of locality of reference in the document request stream. The disadvantage of LRU lies in neglecting the variability in cost and size of Web documents. Furthermore, LRU does not take into account frequency information in the request stream.

Segmented Least Recently Used (SLRU [AW97]) was originally designed for disk-caches with a fixed size of cached objects. It can be easily adapted to environments with variable sizes of cached objects. The problem of LRU is that after the first reference a document is put to the MRU end of the stack. From there it is pushed down step by step towards the LRU end, even if it is never referenced again. LRU uses a large fraction of the cache for this kind of

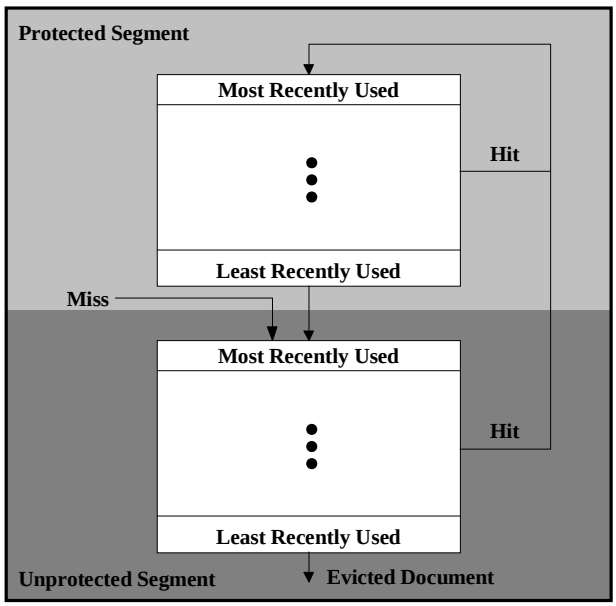


Figure 2. Illustration of the Segmented Least Recently Used replacement scheme

one timers. Segmented LRU solves the problem of one timers by dividing the stack in two segments, a *protected segment* and an *unprotected segment*. Both segments are implemented by LRU stacks. After a cache miss, the requested document is fetched and put at the MRU end of the unprotected segment. From there it is pushed down towards the LRU end. If the document is never referenced again, it is evicted form cache when reaching the LRU end. On a cache hit, the requested document is located in the stacks and placed at the MRU end of the protected segment from which is pushed down step by step towards the LRU end of the segment. If an object reaches the LRU end, it is placed at the MRU end of the unprotected segment and treated as after a cache miss. The functionality of SLRU is illustrated in Figure 2.

SLRU is a parameterized replacement scheme. It requires a parameter specifying the fraction f_p of cache memory used for the protected segment. Previous studies have shown that a f_p = 0.6 yields best results [AFJ00]. Therefore, in performance studies we set size of the protected segment to 60% of cache size.

Least Frequently Used with Dynamic Aging (LFU-DA [AFJ00]) is a frequency-based policy that also takes into account the recency information under a fixed cost and fixed size assumption. In LFU, a decision to evict a document from cache is made by the number of references made to that document. The reference count for all documents in cache is kept and the document with smallest reference count is evicted. LFU-DA extends LFU by an dynamic aging algorithm in order to avoid cache pollution. LFU-DA keeps a cache age which is set to the reference count of the last evicted document. When putting a new document into cache or referencing an old one, the cache age is added to the documents reference count. It has been shown that LFU-DA achieves high byte hit rates. A basic implementation of LRU-DA shown in Figure 3. A value A_p is associated with each cached document. The cache age is denoted by

```
Initialize
Set L ← 0
for each request to a document p do
   if p resides in cache
      A_p ← L + V(p)
   else
      fetch p
      while there is not enough free space in the cache
         Set L ← min{ A_q | q is a document in the cache }
         evict the document q with smallest A_q value
      end while
    Set A_p ← L + V(p)
   end if
end for
```

Figure 3. Pseudo code implementation for LFU-DA, GDS and GD*

L, whereas the value of a document $V(p)$ is set to its reference count. On every request, the value A_p of the requested document is updated. On every eviction, L is set to the value A_p of the evicted document.

Greedy Dual Size (GDS [CI97]) proposed by Cao and Irani considers variability in cost and size of Web documents by choosing the victim based on the ratio between the cost and size of documents. As LFU-DA, GDS associates a value H_p with each Web document p in the cache. When document p is brought initially into the cache or is referenced while already in cache, $H(p)$ is set to $c(p)/s(p)$. Here $s(p)$ is the document size and $c(p)$ is a cost function describing the cost of bringing p into the cache. When a document has to be replaced, the victim $\hat{p}$ with $\hat{H}_{\min} := \min_p\{H(p)\}$ is chosen among all documents resident in the cache. Subsequently, the H values are reduced by $H_{\min}$ [CI97]. However, as LRU, the disadvantage of GDS lies in not taking into account frequency information in the request stream. An efficient implementation of the GDS functionality is provided in Figure 3. Here, the Value $V(p)$ of a document p is set to $H(p)$.

Greedy Dual * (GD* [JB99], [JB00]) proposed by Jin and Bestavros captures both popularity and temporal correlation in a Web document reference stream. The frequency in the formula for the base value L captures long-term popularity. Temporal correlation is taken into account by the rate of aging controlled by the parameter β. GD* sets the values of H for a document p to $H'(p) = (f(p) \cdot c(p)/s(p))^{-\beta}$ where $f(p)$ is the document's reference count. The parameter β is characterizing the temporal correlation between successive references to a certain document observed in the workload as described in Section 5. The novel feature of GD* is that $f(p)$ and β can be calculated in an on-line fashion which makes the algorithm adaptive to these workload characteristics. GD* can be implemented by setting $V(p) = H'(p)$ in the pseudo code implementation shown in Figure 3.

GDS and GD* describe families of algorithms. The optimized performance measure (i.e. hit rate or byte hit rate) of a specific implementation depends on definition of the cost function $c(p)$. In this report, we examine two variants of GDS and GD*. The first applies the constant cost model by setting cost function to $c(p) = 1$. We refer to the resulting algorithms as GDS(1) and GD*(1), respectively. The second variant applies the packet cost model by setting the cost function to the number of TCP packets needed to transmit document p, i.e., $c(p) = 2 + s(p)/536$. These replacement schemes are denoted GDS(packets) and GD*(packets), respectively.

A discrete-event simulator has been implemented for the replacement schemes LRU, SLRU, LFA-DA, GDS(1), GD*(1), GDS(packets), and GD*(packets) using the simulation library CSIM [JB00]. This simulator consists of 15,000 lines of C++ code. The simulation runs presented in Section 5 are performed on a dual processor Sun Enterprise 450 workstation. For details of the simulation environment see Appendix A and B.

5 Workload Characterization of Traces and Workload Forecast

5.1 Characterization of Current Web Proxy Workloads

To characterize the workload of Web proxy caches, we consider five different traces. The oldest trace was collected in 1996 by DEC [Mog96] and already used in previous performance studies of replacement schemes [BCF+99], [CF01], [JB00]. The most recent trace was recorded in July 2000 in the German research network by DFN [GPV01]. For workload forecasting, we additionally consider traces collected at the Canadian CA* net II [MW99], at the University of Saskatchewan [MW99] both of 1998, and at the University of Dortmund of July 2000. These five traces are referred to as DEC, DFN, CANARIE, Univ. Sask., and Univ. Do., respectively. The DEC and DFN traces are used for evaluating the performance of proxy cache replacement schemes under current workload conditions. The characteristics of the remaining traces are employed for deriving workload forecasts. The CANARIE and DFN traces were collected at the primary-level proxy cache in the core of the Canadian CA* Net II and of the German Research Network, respectively. The DEC, Univ. Sask., and Univ. DO. traces were collected at institutional-level Web proxy caches functioning as secondary-level Web proxy caches.

Preprocessing the DEC and DFN traces, we excluded uncachable documents by commonly known heuristics, e.g. by looking for string “cgi” or “?” in the requested URL. From the remaining requests, we considered responses with HTTP status codes 200 (OK), 203 (Non Authoritative Information), 206 (Partial Content), 300 (Multiple Choices), 301 (Moved Permanently), 302 (Found), and 304 (Not Modified) as cacheable [AFJ00], [CI97], [JB99]. Details on trace preprocessing are given in Appendix B. Table 4 summarizes the properties of the DEC and DFN trace. We brake down the request stream of documents according to their content type as specified in the HTTP header. If no content type entry is specified, we guess the document class using the file extension. We omit documents which could not be classified in this way. We distinguish between three main classes of Web documents: HTML documents (e.g., .html, .htm), image documents (e.g., .gif, .jpeg), and multimedia documents (e.g., .mp3, .ram, .mpeg, .mov). Text files (e.g. .tex, .java) are added to the class of HTML documents. Typical multimedia documents are static audio and video files. A few compressed binary downloads (.gz, .zip) as well as a small number of application documents (.ps and .pdf) contained in the traces are also categorized as multi media documents. Table 4 states the properties of the DEC and DFN traces. We observe that in current workloads HTML and image documents together account for about 95% of documents seen and of requests received. This observation has also been observed in [MW99] for a number of other proxy traces among which are CANARIE and Univ. Sask.

The key property for the performance of Web caching constitutes *temporal locality* in the request stream. Temporal locality can be quantified by the relationship between the

	Trace	DEC	DFN
	Date	1996	2000
	Classification of cache	Institutional Proxy	Backbone Proxy
All cachable documents	**Number of documents**	1,226,350	2,841,790
	Overall size (MB)	19,420.16	39,434.24
	Mean document size (KB)	16.21	14.55
	Variance of document size	55.45	268.62
	Number of requests	3,643,328	6,686,409
	Requested data (MB)	45,396.99	81,337.55
HTML	**Number of documents**	301,926 (24.6%)	626,418 (22.0%)
	Overall size (MB)	1,945.60 (10.0%)	8,755.20 (22.2%)
	Mean document size (KB)	6.84	14.63
	Variance of document size	3.96	4.28
	Number of requests	574,551 (15.7%)	1,346,231 (20.1%)
	Requested data (MB)	3,997.70 (8.8%)	17,431.93 (21.4%)
Images	**Number of documents**	875,700 (71.1%)	2,063,076 (72.6%)
	Overall size (MB)	8,448,00 (43.5%)	13,957.12 (35.4%)
	Mean document size (KB)	10.22	7.10
	Variance of document size	7.66	7.38
	Number of requests	2,994,068 (82.2%)	5,096,117 (76.2%)
	Requested data (MB)	21,240.52 (46.8%)	25,265.22 (31.1%)
Multi media	**Number of documents**	48,724 (4.0%)	152,296 (5.4%)
	Overall size (MB)	9,026.56 (46.5%)	16,721.92 (42.4%)
	Mean document size (KB)	189.71	115.23
	Variance of document size	25,003	43,593
	Number of requests	74,709 (2.1%)	244,061 (3.7%)
	Requested data (MB)	20,158.77 (44.4%)	38,640.31 (47.5%)

Table 4. Properties of DEC and DFN traces

probability of an access to a Web document and the time passed since the last access to this document. As discussed in [JB00], temporal locality in the request stream is caused by two different sources: The *popularity* of Web documents and the *temporal correlation* in the request stream. A popular Web document is seen often in a request stream. Therefore, popular documents are referenced more often in a short time interval than less popular documents. Temporal correlation take into account the time between two successive references to the same document. A hot Web document is requested several times in a short intervals whereas

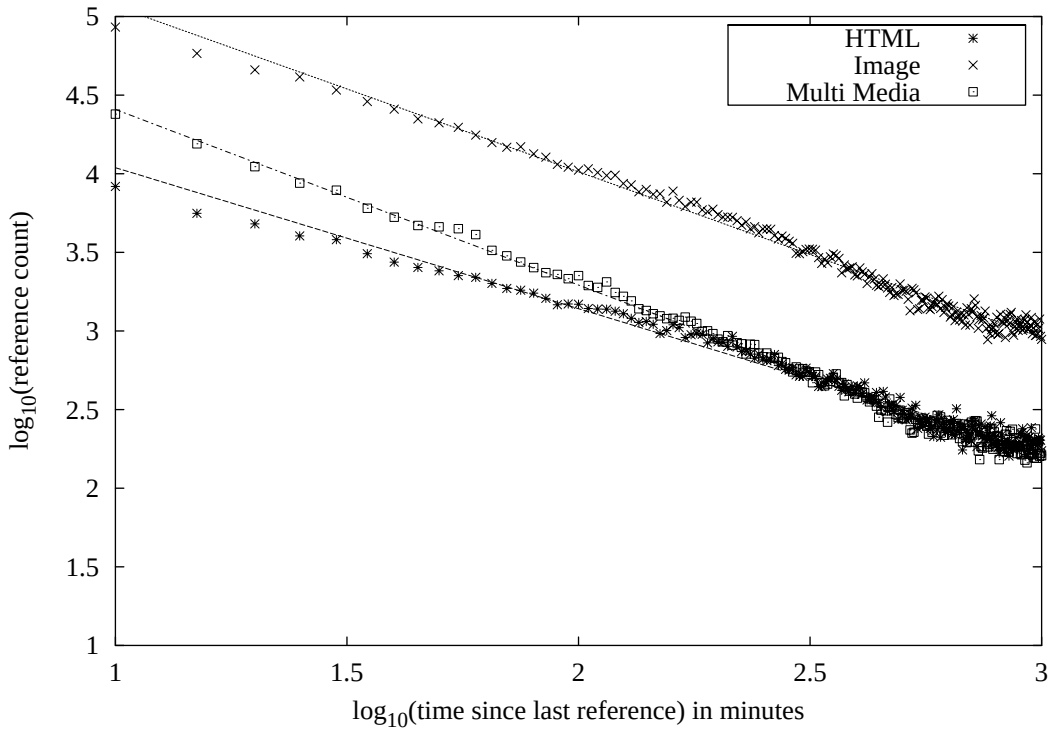


Figure 4. Breakdown of interreference times by document class in DEC trace

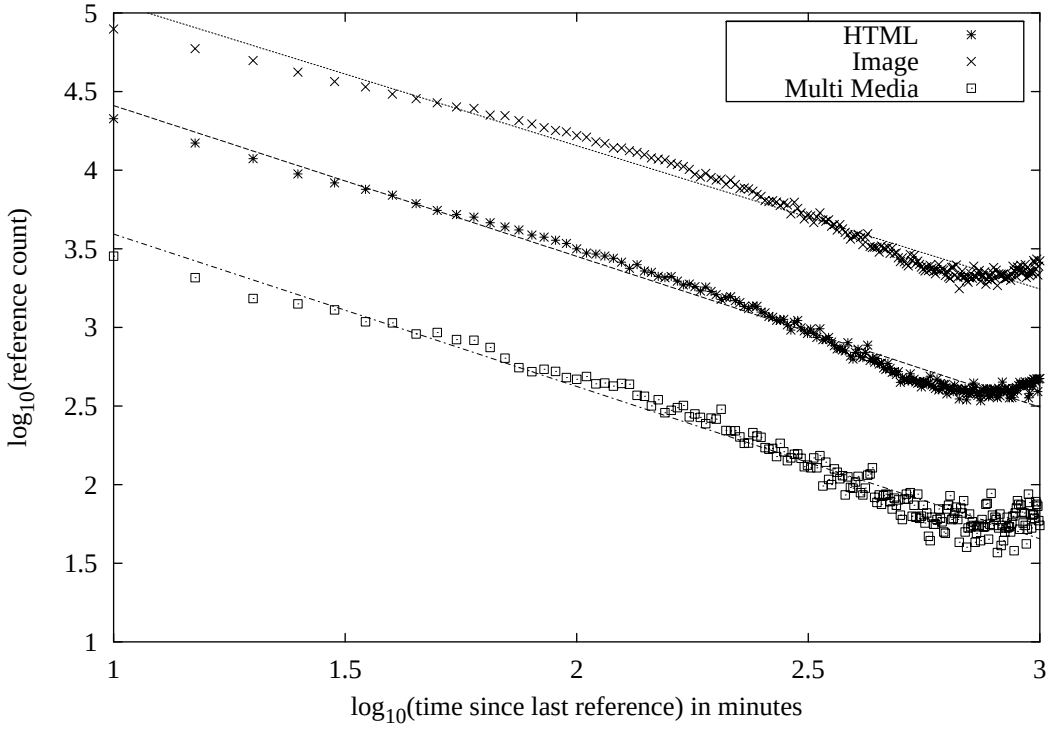


Figure 5. Breakdown of interreference times by document class in DFN trace

the average document is referenced just a few times. Temporal locality can be characterized by two parameters. The first parameter, denoted as the popularity index α describes the distribution of popularity among the individual documents. The number of requests *N* to a Web document is proportional to its popularity rank ρ to the power of $-\alpha$, that is: $N \sim \rho^{-\alpha}$. The popularity index α can be determined the slope of the log/log scale plot for the number of references to a Web document as function of its popularity rank.

The second parameter, denoted as β measures the temporal correlation between two successive references to the same Web document. The probability *P* that a document is requested again after n requests is proportional to n to the power of $-\beta$, that is: $P \sim n^{-\beta}$. Temporal correlation between successive accesses to the same document can be measured by plotting the reference count as a function of *reference interarrivals*. That is the number of requests seen in the request stream between successive access to one particular document. To eliminate the influence of popularity on such a plot (i.e., more popular documents are likely to be accessed after shorter periods of time) the plot is done for equally popular document, e.g. by plotting reference interarrivals after a document has been accessed *k* times.

For the DEC and DFN traces, the calculated values for α and β are shown in Tables 5 and 6. These values indicate that there are some extremely popular images whereas popularity is more wide spread for text documents and multi media documents. Figures 4 and 5 plot for the DEC and DFN traces the *interreference times* broken down for each document class. The interreference time is given by the time elapsed between two successive accesses to a particular Web document. Note that distribution of interreference times reflects both popularity and temporal correlation [JB99]. As shown in Figures 4 and 5, the degree of temporal locality in Web request streams is different for the three considered document classes.

5.2 Forecast of Future Web Proxy Workloads

For forecasting the workload of institutional Web proxy caches, besides the DEC trace we additionally consider Univ. Sask. and Univ. Do. traces. Table 4 presents the characteristics for each document class. The values of the Univ. Sask. trace are derived from Table 5 and Figure 5 of [MW99]. From Table 5, we observe the following trends: The percentages of requests to multi media documents increases more than linear. The popularity of multi media documents increases, that is the parameter α of the Zipf-like distribution decreases. Furthermore, temporal correlation increases and, thus, the parameter β increases. The percentages of requests to HTML documents also increases more than linear.

Due to clearly observable trends, linear regression is employed for determining the forecast for popularity index and temporal correlation for each document class. That is the forecasted value y_3 is derived from the observed values y_1 and y_2 by $y_3 = y_2 + (y_2 - y_1)$. The forecasted

		1996	1998	2000	2002
		DEC	Univ. Sask.	Univ. Do.	Forecast
HTML	**Number of requests (%)**	15.69	19.72	24.15	28.47
	Mean document size (KB)	6.84	8.96	7.49	7.76
	Variance of document size	3.96	–	–	5.39
	Popularity index, α	0.79	0.78	0.76	0.74
	Temporal correlation, β	0.42	??	0.51	0.56
Image	**Number of requests (%)**	82.24	77.45	72.03	66.35
	Mean document size (KB)	10.22	5.63	8.31	8.05
	Variance of document size	7.66	–	–	9.95
	Popularity index, α	0.75	0.76	0.78	0.80
	Temporal correlation, β	0.50	??	0.54	0.56
Multi Media	**Number of requests (%)**	2.07	2.81	3.82	5.17
	Mean document size (KB)	189.71	49.15	124.81	121.22
	Variance of document size	25,003	–	–	19,549
	Popularity index, α	0.78	0.75	0.73	0.71
	Temporal correlation, β	0.65	??	0.78	0.85

Table 5. Workload forecast for institutional Web proxy caches

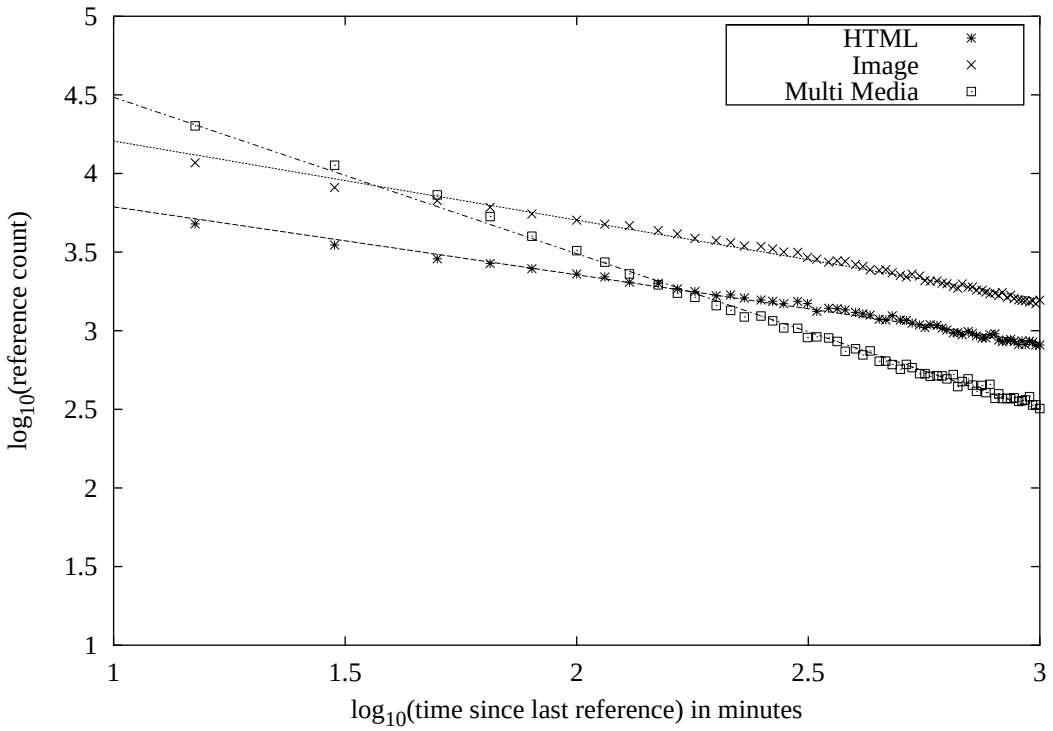


Figure 6. Breakdown of interreference times by document class in workload forecast for institutional proxy caches

		1998	2000	2002
		CANARI	**DFN**	**Forecast**
HTML	**Number of requests (%)**	17.27	20.10	22.61
	Mean document size (KB)	10.30	14.29	12.29
	Variance of document size	–	4.28	2.83
	Popularity index, α	0.60	0.54	0.48
	Temporal correlation, β	0.49	0.65	0.81
Image	**Number of requests (%)**	80.67	76.20	70.73
	Mean document size (KB)	6.25	6.93	6.59
	Variance of document size	–	7.10	7.47
	Popularity index, α	0.61	0.65	0.69
	Temporal correlation, β	0.51	0.60	0.69
Multi Media	**Number of requests (%)**	2.05	3.70	6.66
	Mean document size (KB)	122.67	115.23	118.95
	Variance of document size	–	43,593	42,943
	Popularity index, α	0.73	0.70	0.67
	Temporal correlation, β	0.58	0.71	0.84

Table 6. Workload forecast for backbone Web proxy caches

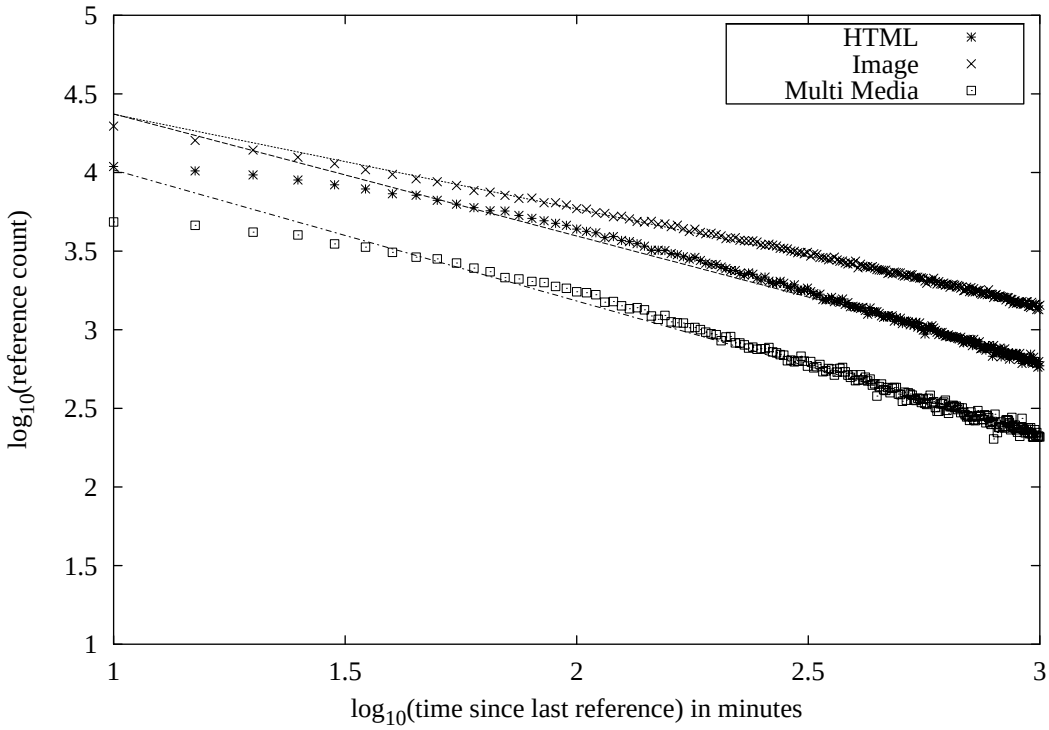


Figure 7. Breakdown of interreference times by document class in workload forecast for backbone proxy caches

percentages of requests is derived using a linear logarithmic regression for representing exponential growth of Web users. That is the forecasted percentage values y_3 is derived by $\ln y_3 = \ln y_2 + (\ln y_2 - \ln y_1)$. Subsequently, the forecasted percentage values are normalized, so that they sum up to 100%. Since for all three classes of Web documents no trends can be observed, the forecasts for the mean document sizes are determined using the method of moving average, that is $y_3 = ½ (y_1 + y_2)$. Subsequently, based on these characteristics, the reference stream of the DEC trace is altered and the corresponding variances are determined based on the modified trace data. Figure 6 plots the interreference times for individual document classes for the workload forecast derived in this way. The different slopes describe how the temporal locality in the request streams have been modified.

Using the same kind of data of the CANARIE and DFN traces, we can derive with the same regression methods a workload forecast for proxy caches located in backbone networks. Table 6 presents the corresponding characteristics for HTML, image, and multi media documents. The log/log plot of the interreference times for individual document classes is shown in Figure 7.

5.3 Deriving the Workload Forecasts from the DEC and DFN Traces

To analyze the performance of Web replacement schemes for the workload forecasts introduced in Section 5.2, synthetic workloads rather than measured data are needed as input for our simulator. These synthetic traces are based on current traces: Forecast 1 is based on DEC trace, Forecast 2 on DFN trace, respectively. To obtain the characteristics specified in Tables 5 and 6, we need to modify the number of requests to the different document classes, the distribution of document sizes, and the document popularity and temporal correlation in the reference stream. Timestamps of incoming requests are kept from original traces, avoiding the need for a reasonable model of interarrival times. The mean document sizes specified in Table 5 and 6 can be achieved by individual scaling document sizes for each document class by a constant factor. Number of requests to each class can be achieved by randomly selecting the document class for an outstanding request according to the probability distribution specified by the fraction of requests to this class.

It remains to show how the documents within a class can be referenced according to the distributions of the two sources of temporal locality specified by α an β. The *independent reference* model [BCF+99], [JB99] considers only one source of temporal locality, i.e., the popularity. The independent reference model chooses a document with popularity rank ρ with probability $P \sim \rho^{-\alpha}$ As stated in [MEW00], temporal locality resulting from short term temporal correlations is important for performance of small caches. To generate a request stream considering both sources of temporal locality, we used the method described below.

To keep correlations between document size and request count [MW99], for the DEC and DFN traces we number all documents d_ρ of a document class by their popularity rank ρ. We calculate relative frequency $\overline{N}(d_\rho)$ according to the distribution specified by the popularity index α. That is $\overline{N}(d_\rho) = \lfloor R\rho^{-\alpha} \rfloor$. Here, R is the number of references to the most popular document scaled according to the overall reference count for the document class in the workload forecast. The documents are divided into (possibly empty) *popularity classes* C_j of equally popular documents, that is $C_j = \{d_\rho | \overline{N}(d_\rho) = j\}$. To generate a request, we select a popularity class C with probability $P(C = C_j) = |C_j| j^{-\alpha}$. Here $|C_j|$ denotes the cardinality of popularity class C_j. Among the documents $d_\rho \in C$, we choose a document d with $P(d = d_\rho) \sim t_{c_i}(d_\rho)^{-\beta}$. Here, $t_{c_i}(d_\rho)$ is the number of references to documents in class C_i since the last reference to d_ρ. The correctness of this algorithm can be verified by plotting the distribution functions of popularity and temporal correlation on a log/log scale and fitting the slopes α and β by a least square fit. Empirical tests show that the resulting request stream yields the same overall characteristics, e.g., the fraction of one-timers as reported in [MW99].

6 Performance Experiments

6.1 Investigation of the Adaptability of Greedy Dual *

In a first experiment, we evaluate the ability of the GD* replacement scheme to adapt to the actual workload seen at the proxy cache. Under the constant cost model, the optimal case constitutes that for each document class (i.e., HTML, images, and multi media) the fraction of cached documents is equal to the fraction of requests to this document class in the request stream. Figures 7 and 8 plot the fraction of cached image and multi media documents for GD*(1) and LRU. As workload the DEC trace is considered. The cache size is assumed to be 1 GByte.

Figure 4 and 5 show that for each document class GD*(1) quickly reaches the optimal fraction of cached documents specified in Table 4 (i.e., 82% images and 2.1% multi media). Opposed to that, in LRU the fraction of cached image documents is smaller (i.e., 40%) and the fraction of multi media documents is substantially larger (i.e., 50%). Similar results have been observed for the DFN trace. These observations explain why GD*(1) achieves high hit rates: GD*(1) does not waste space of the Web cache by keeping large multi media documents that will not be requested again in the near future.

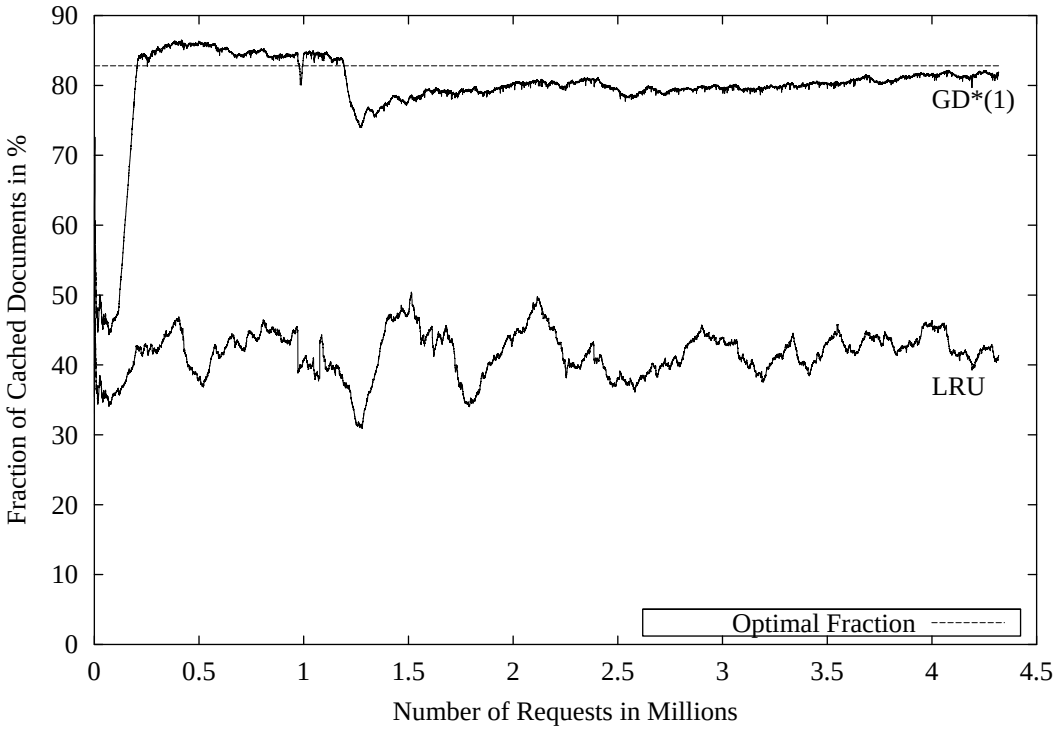


Figure 7. DEC trace: Fraction of Web cache occupied by images for LRU and GD*(1)

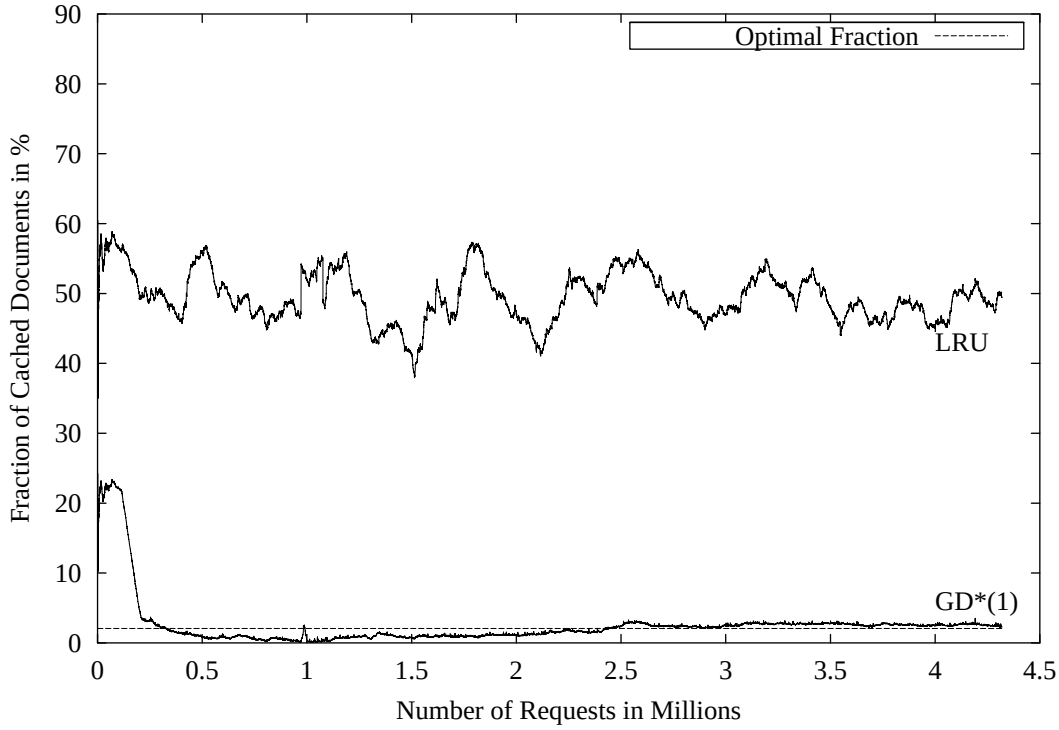


Figure 8. DEC trace: Fraction of Web cache occupied by multi media documents for LRU and GD*(1)

6.2 Performance for Current Workloads

In a second experiment, we provide a comparative study for the Web replacement schemes LRU, LFU-DA, GDS(1), and GD*(1) for current workloads of institutional and backbone Web proxy caches. Other replacement schemes are not considered, since in [CI97] it has been shown that GDS outperforms these schemes. As performance measures, the hit rate and byte hit rate are considered. In Figures 9 to 12, we plot the hit rate (left) and byte hit rate (right) for increasing cache sizes. Cache sizes are set to 0.05%, 0.10%, 0.20%, 0.50%, 1%, 2%, 5%, 10%, and 20% of overall trace size mentioned in Table 4. Recall that the DEC trace was recorded at an institutional Web proxy cache whereas the DFN trace was recorded

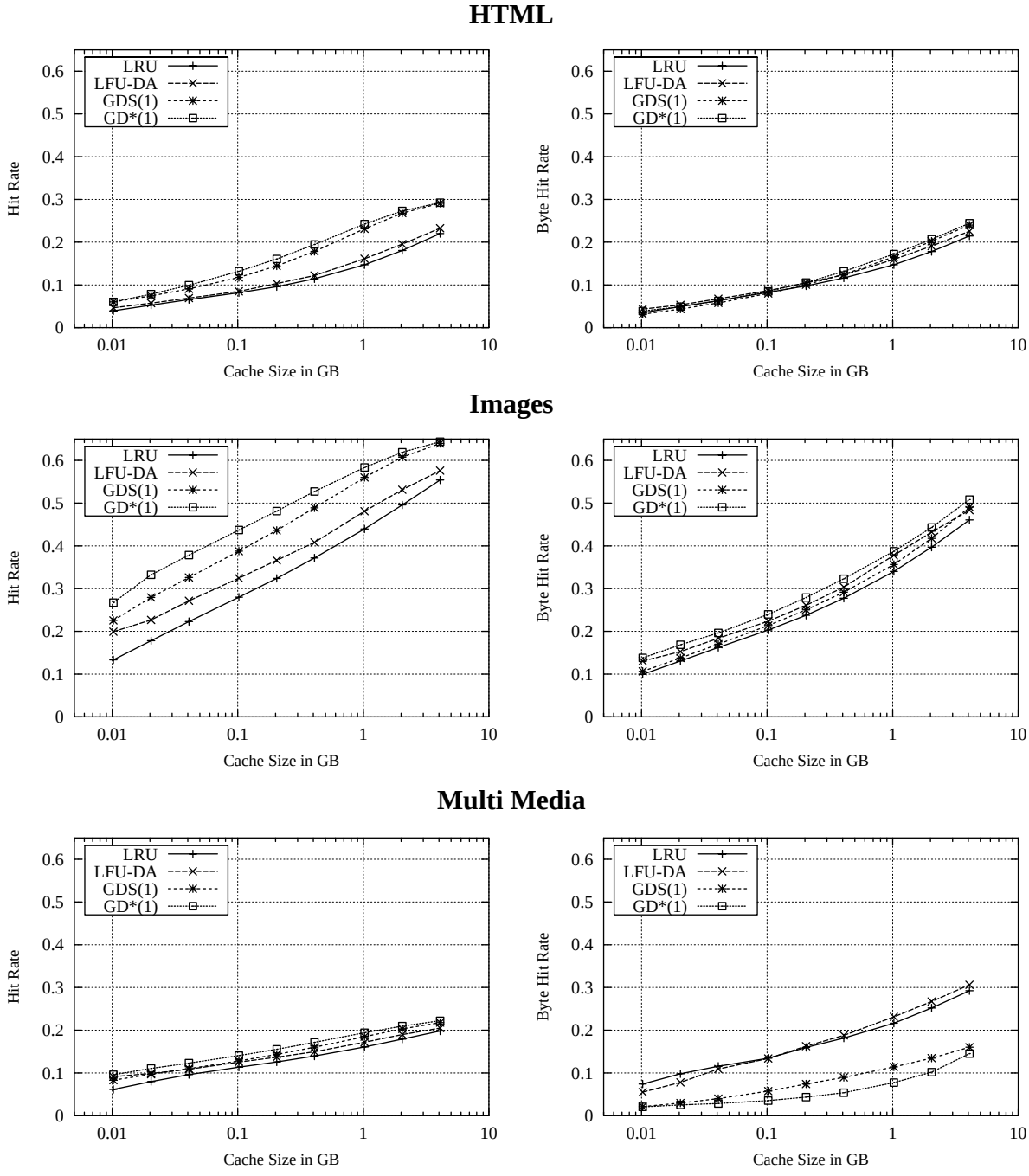


Figure 9. DEC trace: Breakdown of hit rates for different document classes

in a backbone network. Thus, the recorded request streams of the DEC and DFN traces contain different degrees of temporal locality. This leads to different maximal achievable hit rates and byte hit rates. For example, for the DEC trace, the maximal achievable hit rate is about 63% for images, while it is only about 27% for the DFN trace. In the following, we relate our observations to the results of [JB00] in which GD* has been introduced.

Consistent with [JB00], we observe that frequency based replacement schemes outperform recency-based schemes in terms of hit rates. As shown in Figures 9 and 10, GD*(1) outperforms GDS(1) and LFU-DA outperforms LRU in terms of hit rate. This holds for each document class. It is most obvious for images while there are only a small advantage

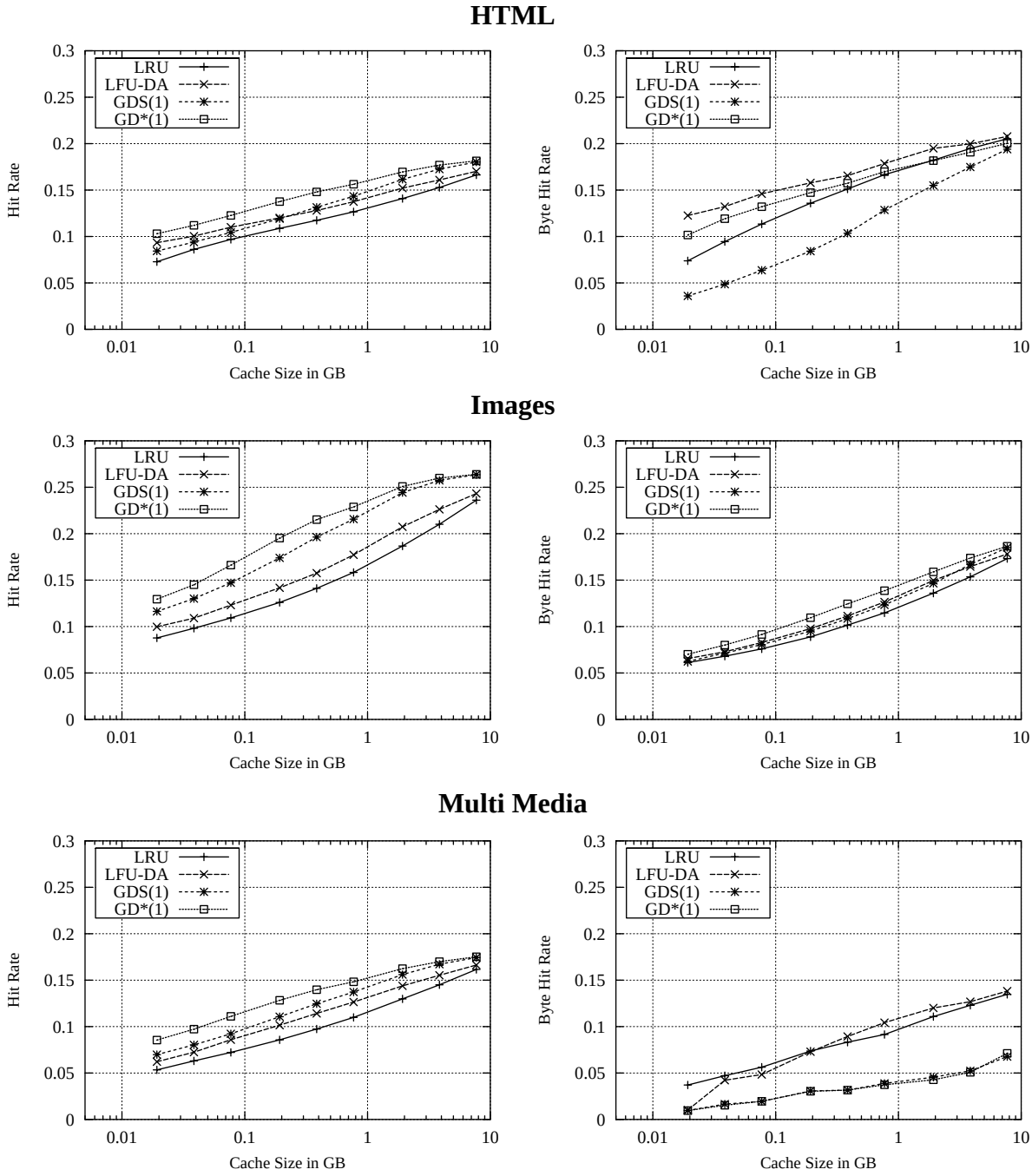


Figure 10. DFN trace: Breakdown of hit rates for different document classes

for HTML and multi media documents. Consistent with [JB00], we observe that in terms of hit rate LRU and LFU-DA perform worse than GDS(1) and GD*(1). This observation is significant for HTML and image documents because of their small document sizes, while there are only small advantages for large multi media documents. This observation can be explained by the fact that LRU and LFU-DA do not take into account document sizes.

Opposed to [JB00], we do not observe in Figure 13 that GD*(1) achieves competitive performance in terms of byte hit rate. As shown in Figure 9 and 7 for HTML and image documents the byte hit rate achieved by GD*(1) is competitive. However, for multi media documents GD*(1) performs significantly worse in terms of byte hit rate than LRU and LFU-DA. Since the byte hit rate for multi media documents dominate the overall byte hit rate, this observation leads to a poor byte hit rate for GD*(1).

As novel aspect of our study, Figures 9 and 10 plot curves for the achieved hit rates and byte hit rates broken down by document class. Comparing the curves of Figures 9 and 10 with corresponding curves of Figure 13, illustrate that the overall hit rate is mainly influenced by the overall hit rate for images. The overall byte hit rate is mainly determined by the overall byte hit rate for multi media documents. The first result can be explained by the fact that about 70% of the requests in the DEC and DFN traces are requests for images. The second result is due to the fact that multi media documents determine nearly 50% of the requested data in the DEC and DFN traces.

6.3 Performance for Future Workloads

As a third experiment, we investigate performance of replacement schemes on the workload forecasts specified in Tables 5 and 6. Recall that in these workload forecasts, the mean file sizes for HTML, image, and multi media documents as well as the fraction of requests to individual document classes have been modified. As a consequence, the overall size of the trace representing the forecast for institutional Web proxies is 18.7 GB instead of 19.2 GB of the DEC trace. The overall size of the trace representing the forecast for backbone proxies is 38.5 GB instead of 39.4 GB of the DFN trace. As before, cache sizes are set to 0,05%, 0,10%, 0,20%, 0,50%, 1%, 2%, 5%, 10%, and 20% of overall trace sizes.

Consistent with [JB00], we observe in Figures 11 and 12 that LRU and LFU-DA perform significantly worse than GDS(1) and GD*(1) in terms of hit rate. As already observed for current workloads in Section 6.2, the gap between GD*(1) and LRU is significant for HTML and images while it diminishes for multi media documents. Opposed to [JB00], Figures 11 and 12 show that the gap between frequency-based and recency- based schemes in terms of hit rates vanishes for the workload forecasts. That is, LRU performs almost as good as LFU-DA and GDS(1) performs even better than or GD*(1). This can be explained by the short term temporal correlation assumed for the future workloads. Increasing the parameter β let

temporal correlation become a more important factor of temporal locality than document popularity. Recency-based replacement schemes make use of temporal correlation, while frequency-based replacement schemes make use of document popularity. Also opposed to [JB00], we observe in Figure 13 that the byte hit rate of GD*(1) is not competitive for the workload forecasts. Because of the higher temporal correlation, the byte hit rate of GD*(1) for HTML and images looses ground to other schemes, while byte hit rates on multi media documents stays low resulting from discrimination of large documents. Low byte hit rates on multi media have even larger impact on overall byte hit rates because of the higher fraction of such requests.

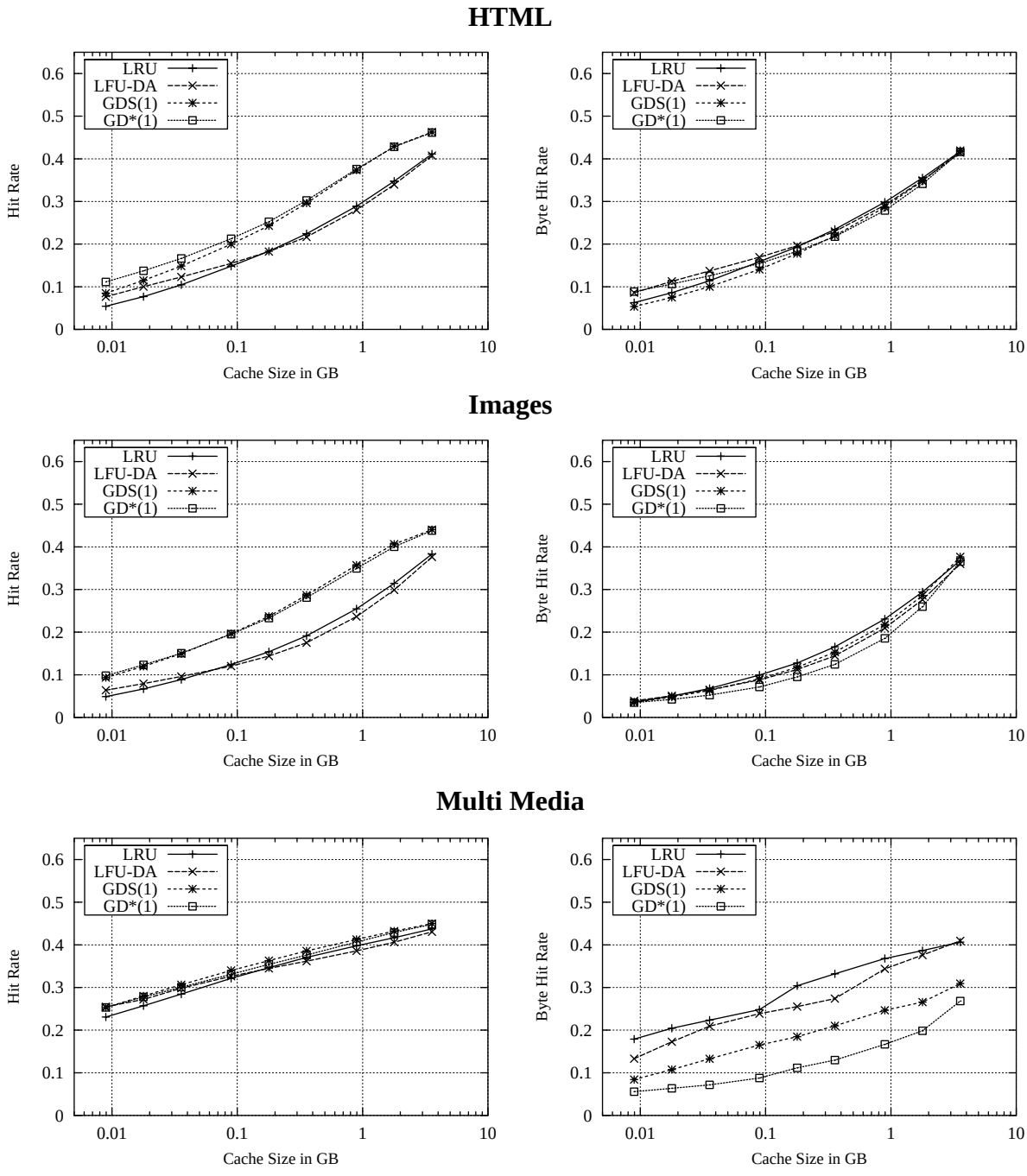


Figure 11. Workload forecast for institutional proxy caches: Breakdown of hit rates for different document classes

Furthermore, our studies show that the hit rate on HTML and multi media documents increase whereas the hit rates on images decreases. This effect is due to the smaller fraction of requests to images in the workload forecasts. In terms of byte hit rate LRU and GDS(1) perform for the workload forecasts significantly better than for the current workloads. In fact, LRU outperforms the frequency-based schemes LFU-DA and GDS(1) outperforms GD*(1). This is due to the assumption that the temporal correlation specified by the parameter β is higher in future workloads than in current workloads.

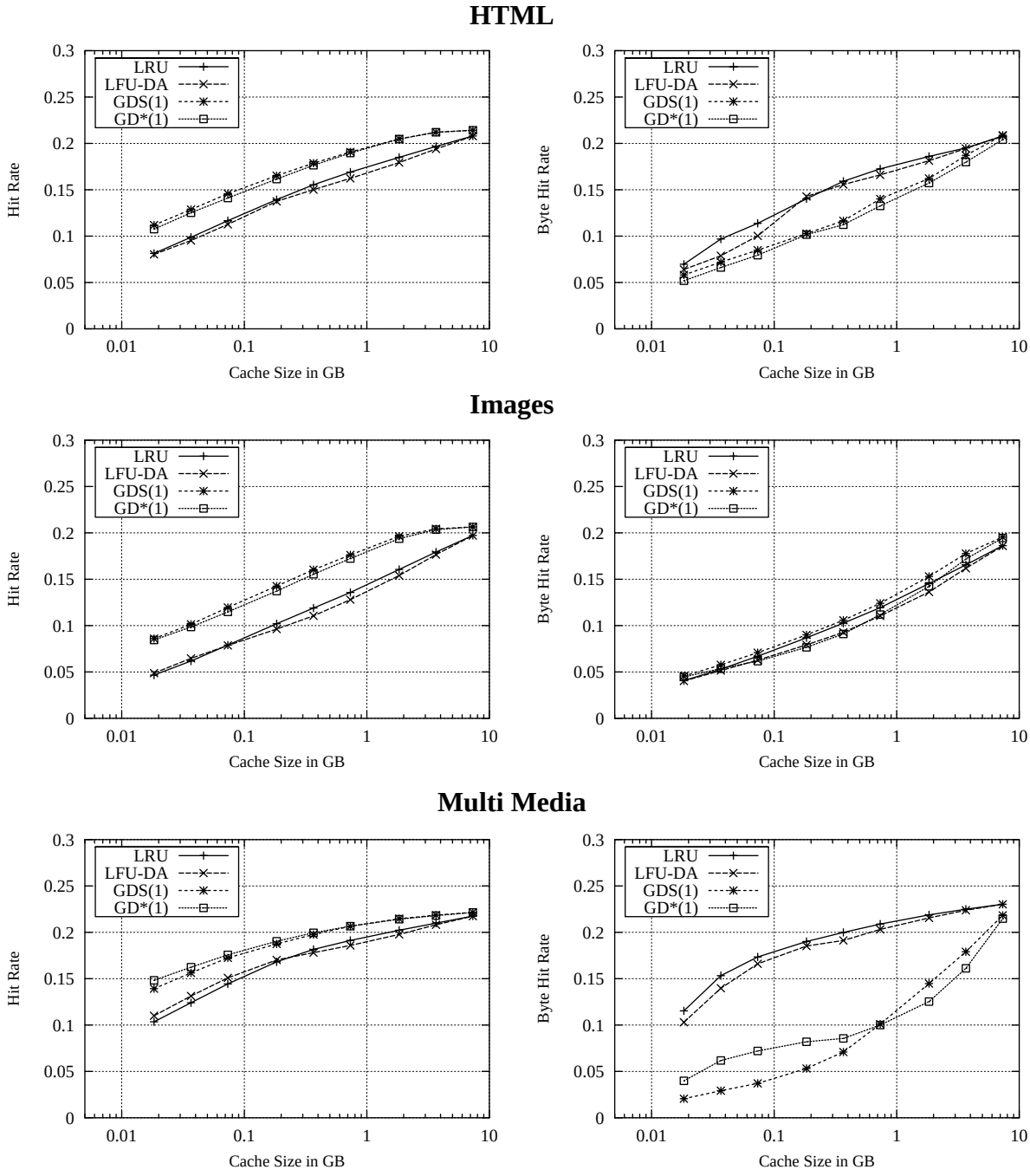


Figure 12. Workload forecast for backbone proxy caches: Breakdown of hit rates for different document classes

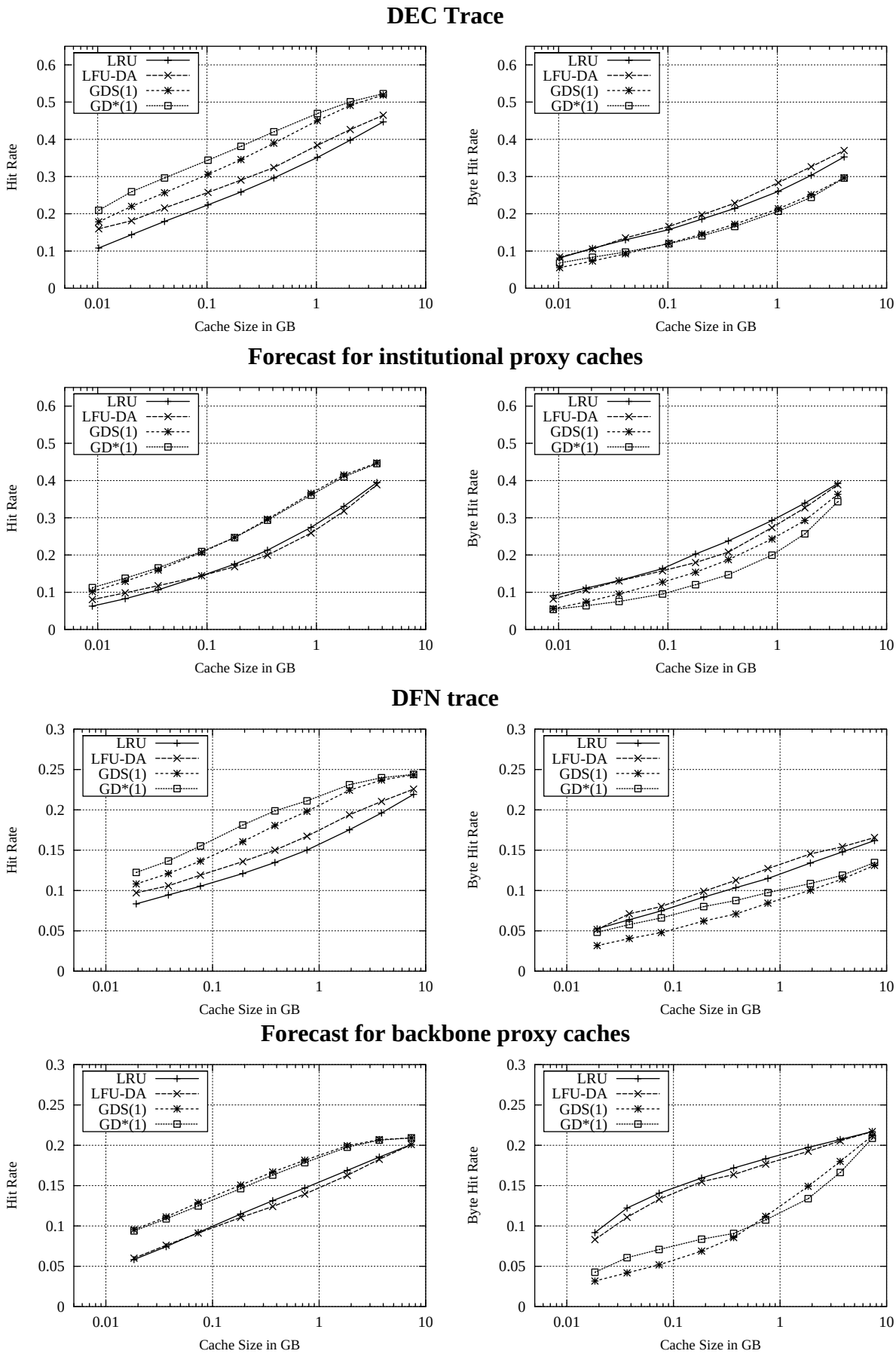


Figure 13. Overall hit rates and byte hit rates for current and future workloads

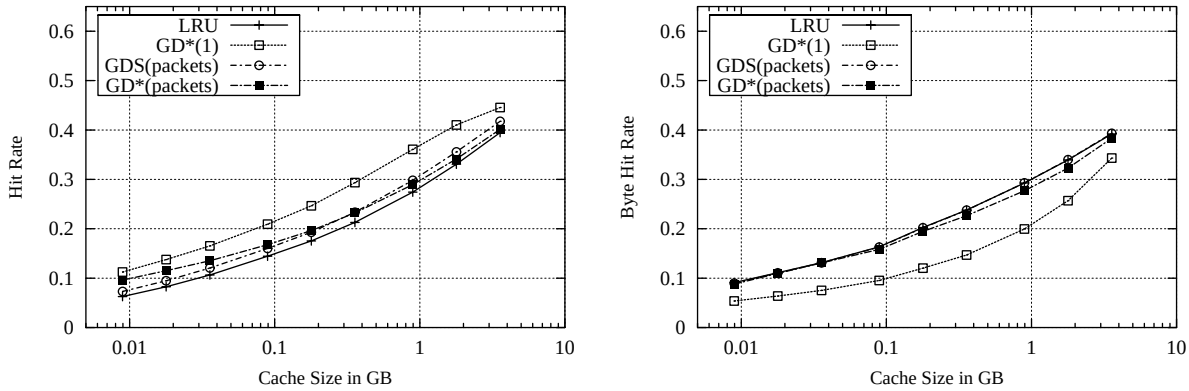


Figure 14. Performance of GD*(packets) and GDS(packets) for institutional proxy caches

As a last experiment we studied the performance of GD* and GDS for the workload forecasts under packet cost model. Figures 14 and 15 compare GD*(packets) and GDS(packets) with GD*(1) and LRU which has shown in Figure 13 best hit rates and byte hit rates, respectively. For our simulation runs, we used the cache sizes as mentioned in Section 5.3.

Opposed to [JB00], we observe that GD*(packets) does not outperform LRU in terms of byte hit rates. The increasing importance of temporal correlation in the request streams of the workload forecasts and the lack of size awareness of LRU close the gap in byte hit rate. As described in [JB00], large values for β put more weight on frequency decisions, which are not suited for workloads with high temporal correlation. Therefore, GD*(packets) looses ground to LRU, which is tailored to capture temporal correlation in form of recency-based replacement decisions. In term of hit rate, GD*(packets) outperforms LRU only for small cache sizes. This is due to taking into account the document popularity in terms of frequency of access to certain Web documents.

Figures 14 and 15 also show that for future workloads GDS(packets) achieves the highest byte hit rates (i.e., as high as LRU) while outperforming LRU in terms of hit rate. In an integrated evaluation considering both hit rate and byte hit rate GDS(packets) performs slightly better than GD*(packets).

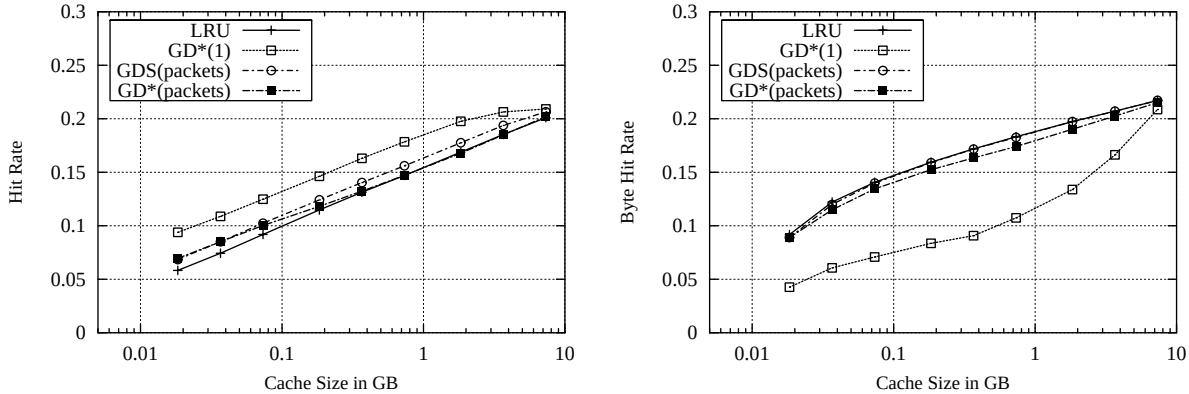


Figure 15. Performance of GD*(packets) and GDS(packets) for backbone proxy caches

6.4 Partitioned Web Proxy Caches

As last experiment, we evaluated performance of the replacement schemes LRU and SLRU on a partitioned organization for Web proxy caches. Thus, the cache memory is split up in several partitions of different sizes. Each partition is assigned to a certain class of web documents. E.g., there are three partitions, one is assigned to HTML document, one to images and one to multi media documents. On each partition an autonomous replacement scheme is applied. That is, for the replacement schemes LRU one LRU stack is implemented each for HTML documents, images, and multi media documents. Size of partitions can be determined by the fraction of requests for documents belonging to the class managed by the partition.

Partitioned Web caches have several application areas. First, statically partitioned caches can be implemented by running several cache processes on a single machine. As results of our experiments show, this can improve hit rate of traditional replacement schemes as LRU, SLRU and LFU-DA. Second, the individual partitions can be distributed on work stations connected by a local area network, each running a cache process. Small partitions, e.g. the HTML partition, can be managed by small workstations. Large partitions, e.g. the multi media partition can be managed by workstations with sufficient disk space. Partitions with high access frequencies, e.g. the Image partition, can be managed by workstations with high processing power.

Figure 16 and 17 show that a partition organization of the cache can improve hit rate of the cache for replacement schemes LRU and SLRU. On the same time, there are small losses in byte hit rate compared to a unpartitioned organization. In the figures, we put the results in relation to the best stable implemented replacement scheme (i.e., GDS in Squid) and to the best known replacement scheme (i.e. GD*). This shows, that partitioned organization makes LRU and SLRU more competitive to GDS and GD* in terms of hit rate. In the same time, byte hit rate of partitioned LRU and SLRU remains superior to the byte hit rate of GDS and GD*.

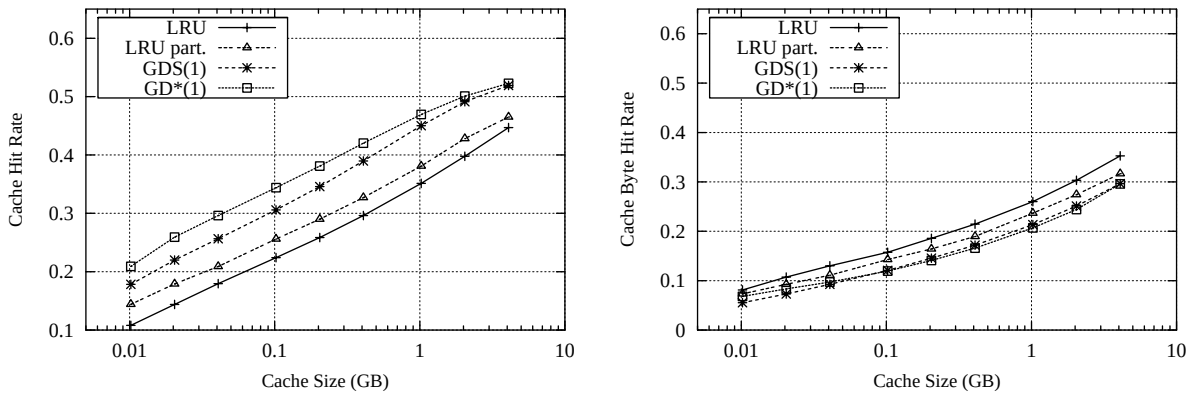


Figure 16. Performance of partitioned LRU

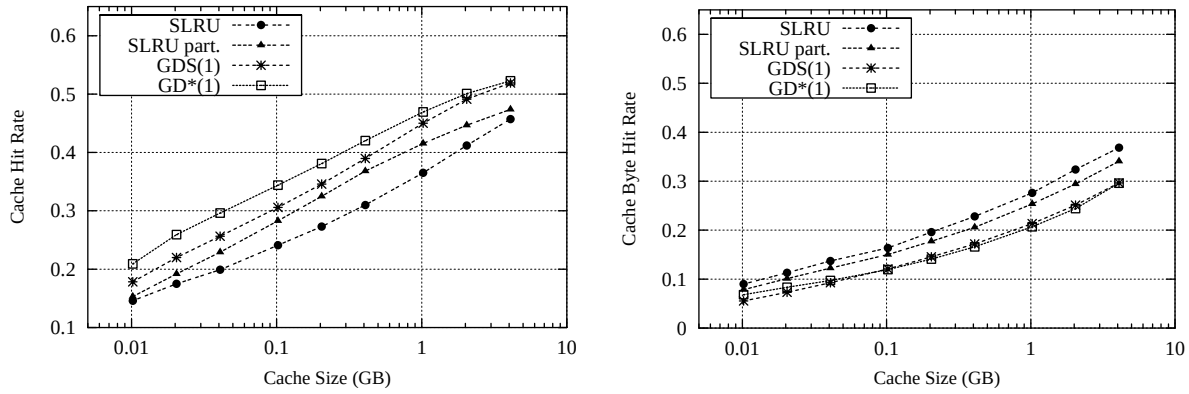


Figure 17. Performance of partitioned SLRU

For LFU-DA we achieved results comparable to SLRU. It is not reasonable to implement a partitioned organization of a cache managed by the replacement schemes GDS and GD*. Those replacement schemes adapt the fraction of cached documents very well to the number of request for the distinct classes. Our experiments have shown, that partitioned organization of cache will always decrease the performance of GDS and GD*.

Part 2: Evaluating Cooperative Web Caching for Emerging Network Technologies

7 Overview

Cooperative Web caching means the sharing and coordination of cached Web documents among multiple communicating proxy caches in an IP backbone network. Cooperative caching of data has its roots in distributed file and virtual memory systems in a high-speed local area network environment. Cooperative caching has shown to substantially reduce latencies in such distributed computing systems because network transfer time is much smaller than disk access time to serve a miss. While bandwidth for previous IP backbone networks deployed by Internet Service Providers typically has been limited to 34 Mbps, current and future IP networks provide bandwidth ranging from 155 Mbps to 2.4 Gbps (see e.g., CA*Net-3 [CA01], G-WiN [GW01], or Internet-2 [IN01]). Thus, it is important to investigate the impact of emerging network technologies on the performance of cooperative Web caching protocols.

Protocols for cooperative Web caching can be categorized as message-based, directory-based, hash-based, or router-based [CMT01]. Wessels and Claffy introduced the Internet cache protocol, ICP [WC98], which has been standardized and is widely used. As a message-based protocol, ICP supports communication between caching proxies using a simple query-response dialog. It has been reported that ICP scales poorly with increasing number of caches. Directory-based protocols for cooperative Web caching enable caching proxies to exchange information about cached content. The information is compressed using arrays of bits, so called Bloom filters. Notable protocols of this class include Cache Digests by Rousskov and Wessels [RW98] and Summary Cache by Fan, Cao, Almeida, and Broder [FCAB00]. The most notable hash-based cooperative Web caching protocol constitutes the cache array routing protocol, CARP, introduced by Valloppillil and Ross [Ros97], [VR98]. The rationale behind CARP constitutes load distribution by hash routing among Web proxy cache arrays. Recently, Karger et al. proposed hash-based routing using URL resolution at the domain name service as another protocol of this class [KBB+99]. In recent work, Wu and Yu introduced several improvements to hash-based routing, considering network latency and allowing local replication [WY99], [WY00]. Cieslak, Foster, Tiwana, and Wilson introduced the Web cache coordination protocol, WCCP, as a router-based protocol. WCCP transparently distributes requests among a cache array [CFTW00]. Very recently, the caching neighborhood protocol, CNP, has been introduced by Chiang et al. [CLLM00], [CULM99]. CNP allows request forwarding among caching proxies in a dynamically changing hierarchy controlled by the origin server.

In previous work, the performance of cooperative Web caching protocols has mostly been studied just in comparison to ICP. Performance results comparing Cache Digests versus ICP based on the NLANR cache hierarchy have been reported in [RW98]. The performance of CARP versus ICP has been studied using a Markov model [Ros97]. The performance of CPN, Cache Digests, and CARP has also been analyzed by high-level analytical models [CULM99]. A first comprehensive performance study of cooperative Web caching was conducted by Wolman et al. [WVS+99]. They studied upper bounds achievable through cooperative Web caching under the assumption that no communication overhead is introduced by inter cache communication and no cache space is wasted by holding multiple copies of the same document in several caches. They derived the results by trace-driven simulation of a single Web proxy cache and provide sensitivity analysis using a Markov model. The Markov model also provides a comparison of a Squid-like hierarchical Web caching system, a hash-based caching system, and a directory-based caching system inspired by Summary Cache. In another recent paper, Rodriguez, Spanner, and Biersack developed analytical models for comparing the performance of hierarchical and distributed Web caching [RSP99]. Feldmann, Cáceres, Douglis, Glass, and Rabinovich investigated the performance of caching proxies in environments with different network bandwidth between client and proxy and between proxy and server, respectively [FCD+99].

To best of our knowledge, a comprehensive performance study of the protocols ICP, CARP, Cache Digests, and WCCP based on the same IP backbone network topology and workload characteristics has not been reported so far. Furthermore, the effect of rapidly increasing bandwidth availability to these cooperative Web caching protocols has not been investigated. We are also not aware of any performance study of WCCP v2.0. Opposed to previous work [FCD+99], [RSP99], [WVS+99], the goal of this part of the project lies in understanding the behavior and limiting factors of specific protocols for cooperative Web caching under measured traffic conditions. Based on this understanding, we give recommendations for Internet Service Providers (ISPs), Web clients, and Application Service Providers (ASPs).

In Section 10, we present a comprehensive performance study for the cooperative Web caching protocols ICP, Cache Digests, CARP, and WCCP. The performance of the considered protocols is evaluated using measured Web traffic from DFN [GW01] and NLANR [NL01]. The presented curves illustrate that for ISPs operating IP networks with high bandwidth availability (622 Mbps and 2.4 Gbps), clearly either CARP and WCCP is the protocol of choice. From the clients' point of view, ICP is most beneficial because ICP achieves lowest latency. For ASPs, WCCP is the protocol of choice because WCCP achieves the best cost/performance ratio with respect to cache utilization. Sensitivity studies show that temporal locality and low cache utilization due to low participation to cooperative Web caching make considerably impact to the performance of individual protocols. The presented results are

derived using a discrete-event simulator of an IP backbone network implemented with the simulation library CSIM [Sch95].

The part of the report is organized as follows. To make the report self-contained, Section 8 provides an introduction to cooperative Web caching and recalls the functionality of the protocols ICP, Cache Digests, CARP and WCCP. The simulation environment for evaluating the considered protocols for cooperative Web caching is introduced in Section 9. In Sections 10, we present performance curves for the considered protocols for cooperative Web caching derived from the simulator and the measured trace data.

8 Protocols for Cooperative Web Caching

The aim of Web proxy caching lies in reducing both document retrieval latency and network traffic. Cooperative Web caching provide means that if a requested document is not contained in the queried Web cache, other caches are queried first before the document is downloaded from the origin Web server. Protocols for cooperative Web caching can be categorized as message-based protocols, directory-based protocols, hash-based protocols, and router-based protocols. Message-based protocols define a query/response dialog for exchanging information about cached content. An example for a message based protocol is the Internet cache protocol, ICP. Directory based protocols summarize information into frequently exchanged directories. Cache Digests constitutes an example for a directory-based protocol. Hash-based protocols as e.g., the cache array routing protocol, CARP, employ hash functions to distribute the URL space among cooperating Web caches. Router-based protocols intercept Web traffic on IP layer and redirect it to a caching proxy. An example for a router-based protocol constitutes the Web cache coordination protocol, WCCP.

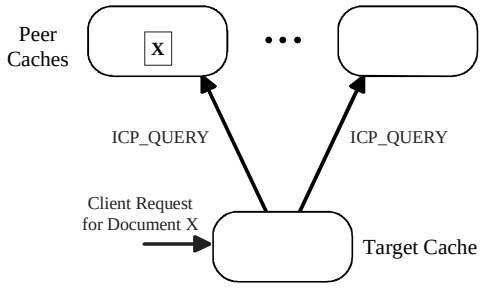
In this Section, we recall the major functionality of these protocols for cooperative Web caching in a mesh of loosely coupled Web proxy caches. Most protocols include further functionality, e.g., for dynamic reconfiguration of the caches or fault tolerance. This functionality is beyond the scope of our study and is omitted in the description. We describe the actions performed by a cache after a miss for a client request. We call the queried Web cache the *target cache*, all other caches in the mesh are denoted as *peer caches* [CMT01]. Web caches holding a valid copy of the queried document are marked with *X* in Figures 18 to 21.

ICP is an application layer protocol based on the user datagram protocol/internet protocol, UPD/IP. It was originally introduced by the Harvest Web cache for coordinating hierarchical Web caching. ICP defines a set of lightweight messages used to exchange information about cached documents among caches. Figure 18 illustrates the functionality of ICP. If a target cache suffers a miss on a client request, it queries its configured peers using a special *ICP query* message as shown in Figure 18 (a). A peer cache replies with an *ICP hit* message, if it holds the requested document. Otherwise, the peer cache reports an ICP miss message as

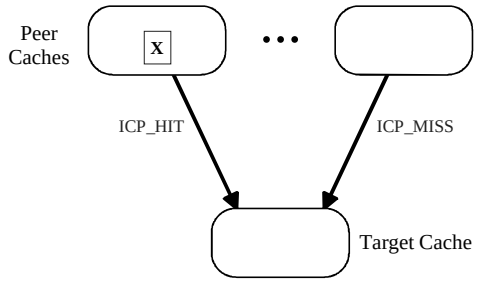
shown in Figure 18 (b). The target cache waits either an ICP hit is received or all configured siblings reported a miss. Since ICP is based on UDP, messages are not reliably delivered. A timeout prevents a cache from infinite waiting for lost messages. The target cache fetches the document from the first peer cache signaling a hit; see Figure 18 (c). If no peer cache signals a hit, the document is fetched from the origin Web server or a configured parent cache. The document is stored locally at the target cache and delivered to the client ; see Figure 18 (d). Note that with ICP multiple copies of a particular document may be stored in a cache mesh. ICP can adapt to network congestion and cache utilization by locating peer caches which send the fastest response. The disadvantage of ICP lies in introducing additional latency on a cache miss due to waiting until receiving replies from all peer caches or reaching the timeout.

Cache Digests defines a protocol based on the hypertext transfer protocol, HTTP. As ICP, Cache Digests operates on the application layer of the TCP/IP protocol stack. Cache Digests was introduced by Rousskov and Wessels and is implemented in the Squid Web cache [RW98]. Cache Digests enables caching proxies to exchange information about cached content in compact form. A summary of documents stored by a particular caching proxy is coded by an array of bits; i.e., so called *Bloom filter*. To add a document to a Bloom filter, a number of hash functions are calculated on the document URL. The results of the hash functions specify which bits of the bit array have to be turned on. On a lookup for a particular document the same hash functions are calculated and the specified bits are checked. If all bits are turned on, the document is considered to be in the cache. With a certain probability, a document is erroneously reported to be in the cache. The probability depends on the size of

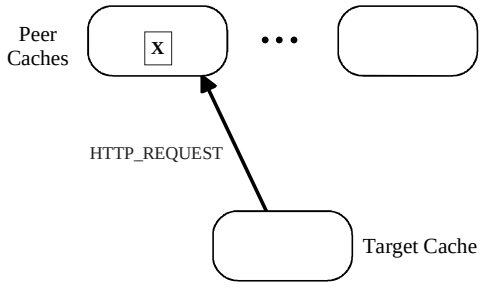
(a) miss at target cache



(b) replies of peer caches



(c) fetching document at target caches



(d) storing document at target caches and delivering document to client

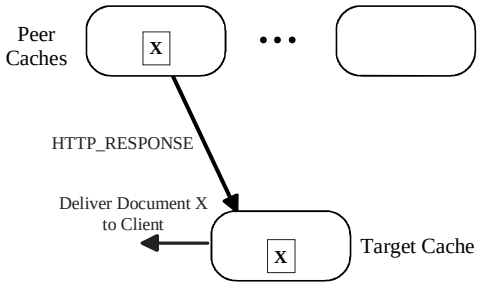


Figure 18. Illustration of the functionality of ICP

the Bloom filter. Cooperating caching proxies build Cache Digests as a summary of locally cached content. Figure 19 illustrates the functionality of Cache Digests. Each target cache requests digests from all peer caches on a regular basis as shown in Figure 2 (a). If a target cache misses on a client request, it searches the digests of its peer caches; see Figure 19 (b). If the requested document is reported to be cached by any digest, the document is requested form the corresponding peer cache; see Figure 19 (c). Otherwise, the document is fetched from the origin Web server. In both cases, a copy of the requested document is stored by the target cache and the document is delivered to the client; see Figure 19 (d). Note that as in ICP, multiple copies of a particular document may be stored in a cache mesh.

An advantage of Cache Digests lies in only generating network traffic on the digest exchange and not on each document request. The disadvantage of Cache Digests lies in causing *false cache hits*. False hits can occur in two ways: First, a digest reports that a particular document is cached, but the document has been already evicted since the generation of the digest. Second, a bloom filter may report a hit when the document is not in the cache. The number of false hits influences the performance of a cache mesh by causing unnecessary network traffic [RW98].

CARP constitutes also a cooperative Web caching protocol on the application layer of the TCP/IP protocol stack. CARP is based on HTTP and was introduced by Valloppillil and Ross [VR98]. As Cache Digests, CARP is based on hash functions. The version of CARP we consider in Section 10 implements hashing inside the caches [Ros97]. Thus, the considered version of CARP does not require to change the client software. Note that another version of

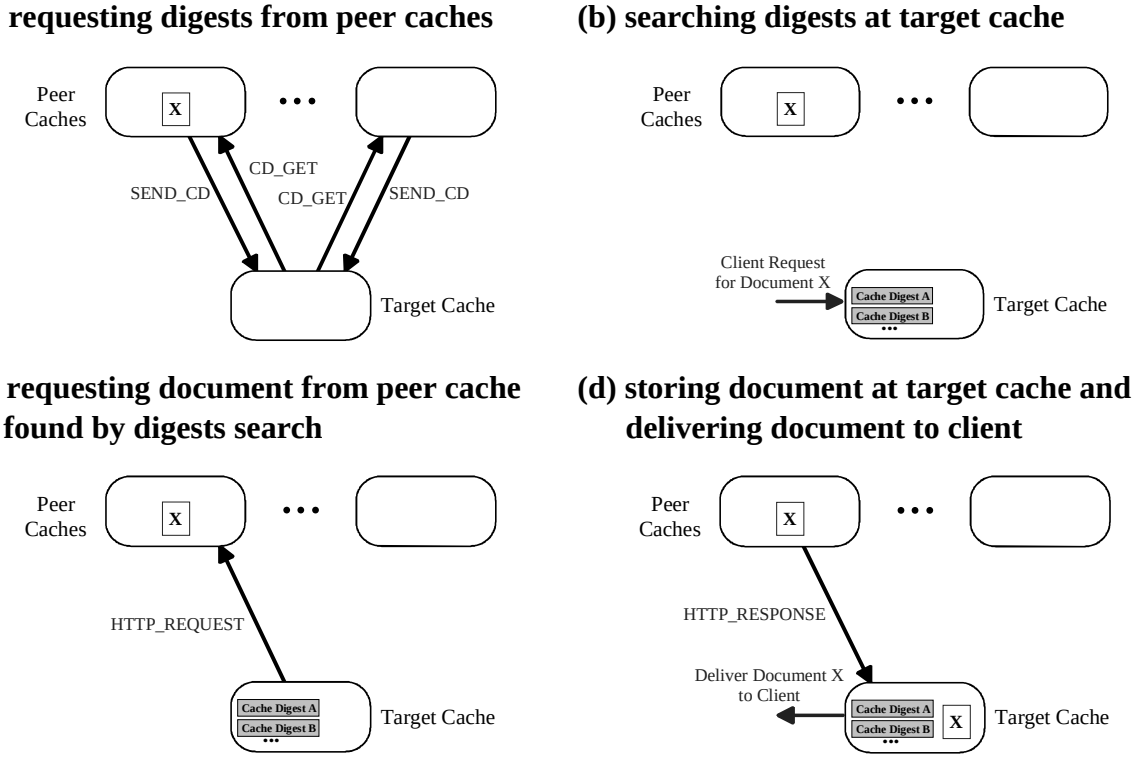


Figure 19. Illustration of the functionality of Cache Digests

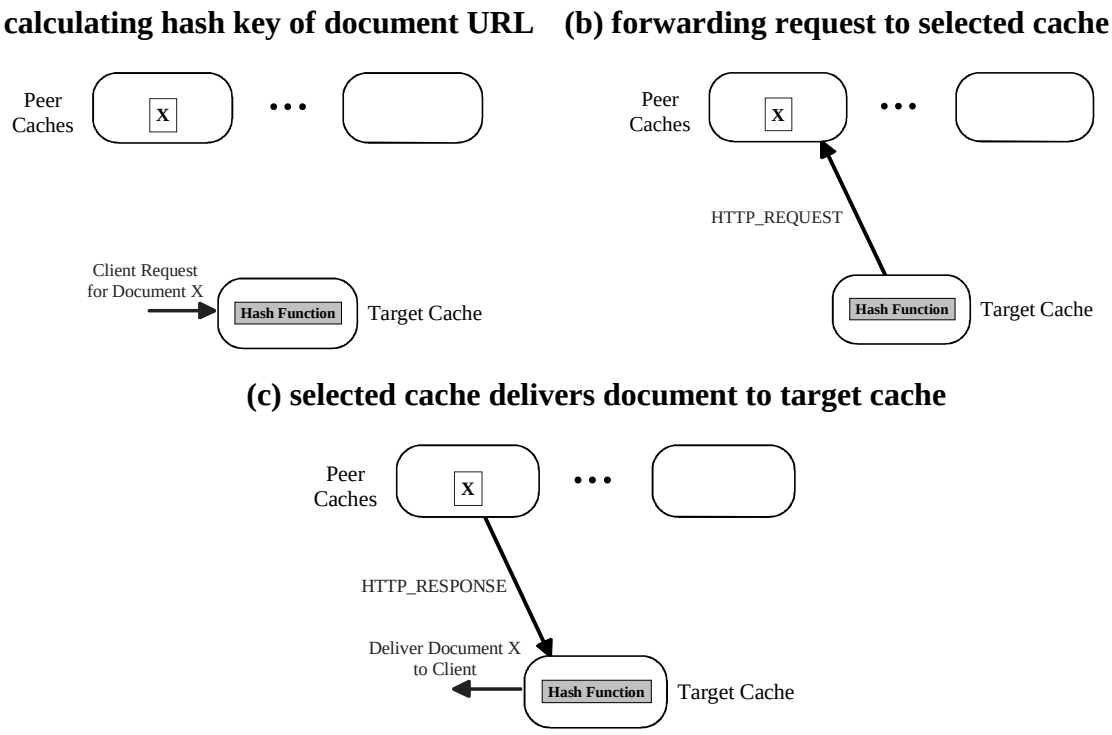


Figure 20. Illustration of the functionality of CARP

CARP is implemented such that hashing is performed in the client software [CMT01]. Each cache in the cache mesh stores an unique hash function, which maps the URL space to a hash space. Each element of the hash space is associated with a particular caching proxy. Figure 20 illustrates the functionality of CARP. If a target cache receives a client request, it calculates the hash key of the document URL; see Figure 20 (a). The result is combined with the hash keys of the names of all caches in the mesh. The request is forwarded to the cache which achieves the smallest value of the combined hash key; see Figure 20 (b). We refer to this cache as the *selected cache*.

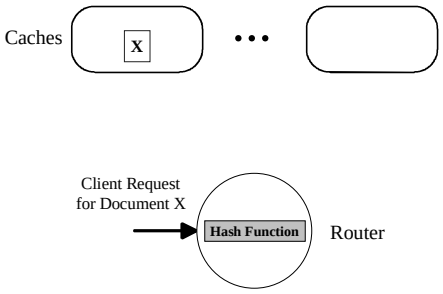
The selected cache can be any member of the cache mesh including the target cache. On a hit, the selected cache delivers the document to the target cache, if both are different as shown in Figure 20 (c). On a miss, the selected cache retrieves the document from the origin Web server, stores a copy and delivers it to the target cache. The target cache delivers the document to the client. Note that the target cache does not store a copy of the document. Each document is stored only in the selected cache. This unifies several physically distributed caching proxies to one logical cache. The advantage of CARP lies in not wasting cache memory for replicated documents. As a disadvantage, CARP employs expensive HTTP communication among the caching proxies on each request.

WCCP is a router-based protocol on the network layer of the TCP/IP protocol stack. Recently, the specification of WCCP v2.0 has been made public available in an Internet draft [CFTW00]. WCCP takes the responsibility for the distribution of requests away from the caches. It allows a Web cache to join a *service group*. A service group contains one or more caches and one ore more routers. Figure 21 illustrates the functionality of WCCP. The routers

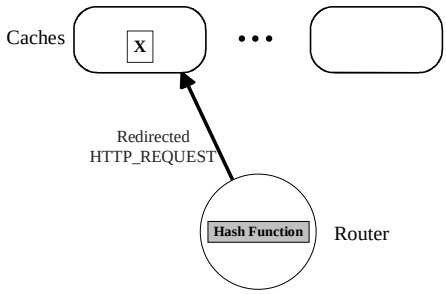
of a service group intercept IP packets of HTTP requests sent from a client to the origin Web server as shown in Figure 21 (a). The packets are redirected to a particular caching proxy in the service group. As in CARP, the caching proxy is chosen by a hash key. Opposed to CARP, in general the router does not know the complete URL of a requested document. Therefore, it uses the IP address of the destination of intercepted packets for the hash function, i.e., the IP address of the origin Web server of the document. The result of the hash function yields an index into a redirection hash table. This redirection hash table provides the IP address of the Web cache to which the request is forwarded as shown in Figure 21 (b). Due to hashing based on IP addresses, all objects of a particular site are serviced by the same caching proxy. This constitutes the main difference to the version of CARP we consider. The selected cache services the request from cache memory or the origin Web server. The requested document is delivered directly to the client by the cache; see Figure 21 (c). Note that as in CARP, at most a single copy of a document is stored in a local cache mesh. As a further advantage, WCCP does not increase the load on caching proxies by distributing documents via the routers. As a disadvantage, WCCP increases the load on routers due to the calculation of hash functions and packet redirection.

As mentioned above, we use implementations that do not require changes in user agents. That is the client has to be configured to issue document request to a statically assigned caching proxy or the origin Web server.

(a) intercepting IP packets by a router



(b) locating cache by a redirection hash table



(c) deliver the document to the client

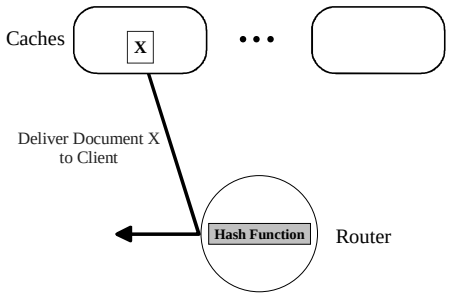


Figure 21. Illustration of the functionality of WCCP

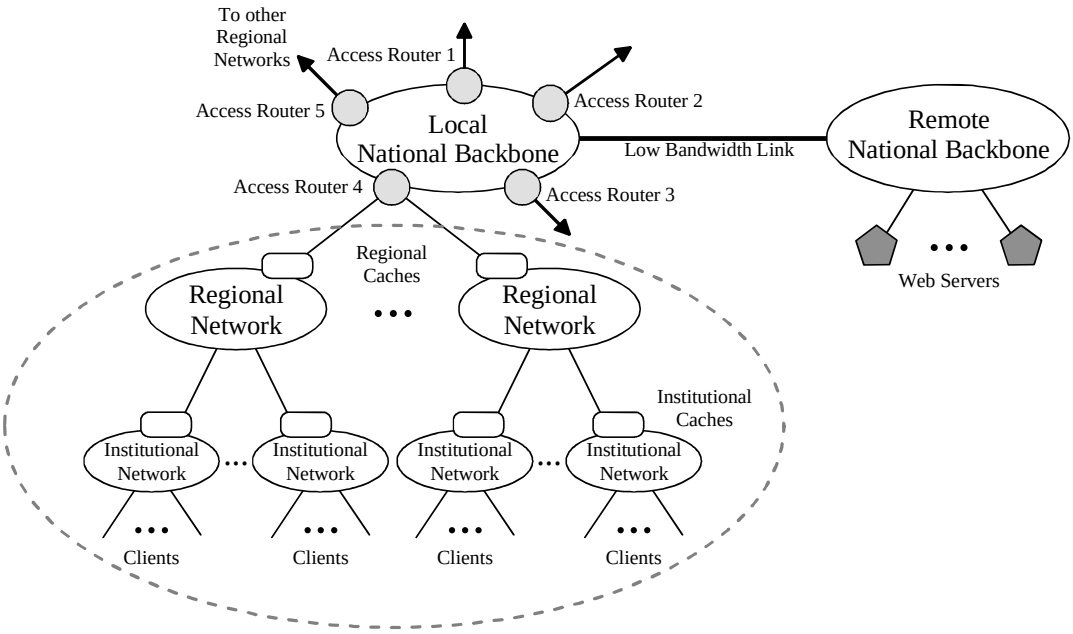


Figure 22. Considered network configuration

9 Simulation Environment

9.1 Network Model

In our experiments, we investigate the performance of cooperative caching for caching proxies distributed across the backbone network of a national Internet service provider (ISP). To simulate a particular network topology, we adopt the modeling approach for IP networks connecting clients and servers presented in [RSP99]. They model the internet as a hierarchy of ISPs as shown in Figure 23. All clients (i.e., user agents) are connected to institutional networks which are connected via regional networks to a national backbone. National backbones are also connected. Caches are located at the access points between two networks to reduce the consumption of network bandwidth. As in [RSP99], the simulator represents just one local and one remote national backbone network. The hierarchical structure of the local network comprises of several regional networks. One or more institutional networks are connected to each regional network. All user agents reside in the institutional networks. All original servers are assumed to be located in the remote backbone network.

Opposed to [RSP99], the goal of our simulation study constitutes the comparative performance evaluation of the protocols for cooperative Web caching introduced in Section 8 rather than evaluating distributed versus hierarchical Web caching. Therefore, we replace the single national cache used in [RSP99] by a cache mesh distributed across the national backbone as shown in Figure 24. We assume that caches are placed at five access routers which connect one or more regional networks to the backbone. User agents are allowed to peer directly with national caches located at the access router connecting them via institutional and regional networks to the local national backbone, or to use institutional or

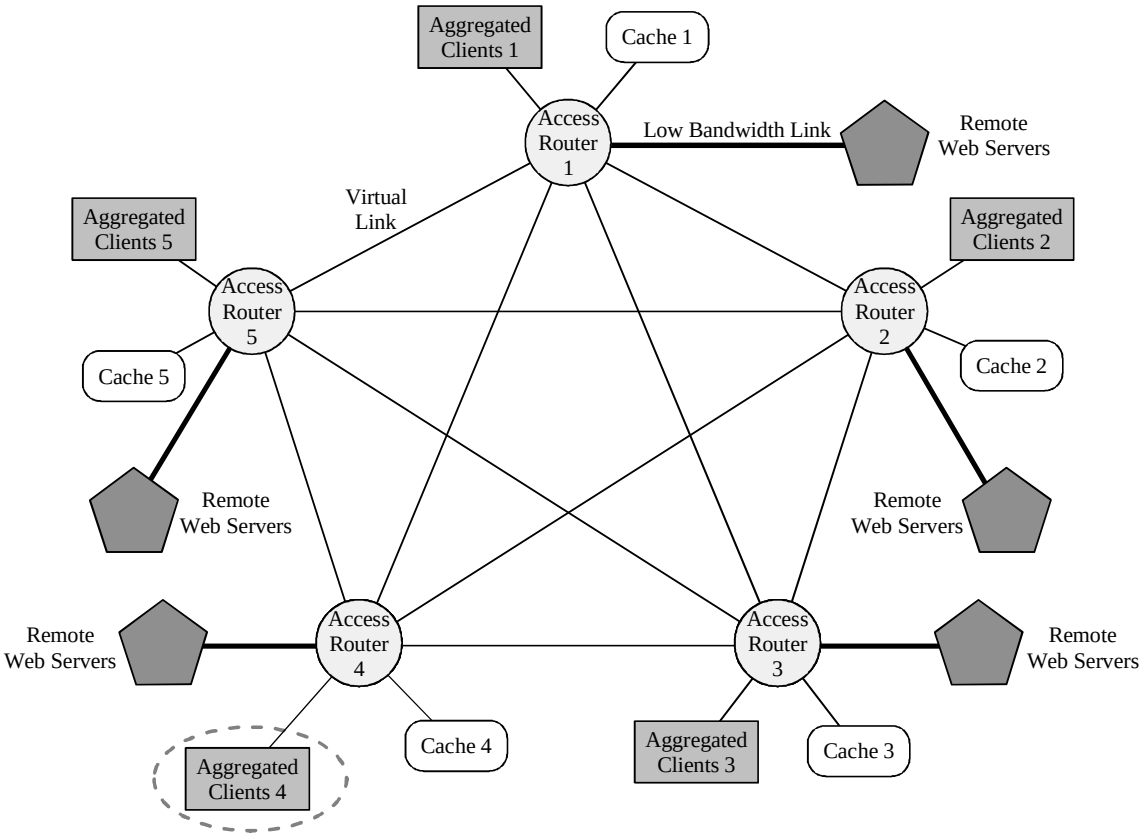


Figure 23. Model of network configuration with virtual links and aggregated clients

regional caches on the intermediate levels of a cache hierarchy. Institutional and regional caches are allowed to peer with the national cache at their access point to the national backbone. Therefore, clients of a national cache consist of user agents, institutional and regional caches, which are directly connected to the associated access router via institutional and regional networks. Without loss of generality, these clients are aggregated to a single component called *clients*. This component is directly connected to an access router.

Figure 24 shows the configuration of the local backbone network considered for the comparative performance study presented in Section 10. The configuration comprises of five caching proxies, each of them connected to an access router. The access routers are fully connected by virtual links. Clients and a local Web server are connected to each access router. Note that all clients located in the dashed circle in Figure 23 are aggregated in the client component denoted as “Clients 4” in Figure 24. The simulator assumes the network configuration to be fixed. Thus, we do not take into account failures and down times of any network component.

The simulator comprises of several building blocks which can be utilized to assemble arbitrary configurations for backbone networks. The following describes the behavior and simplifying assumptions of the building blocks of the simulator. These building blocks are CSIM simulation components modeling virtual links, access routers, clients, caches, and Web servers. Table 7 provides an overview of the parameter settings of the simulator.

Parameter	Description	Value
RTT	Average round trip time in local backbone network	varying
P_{loss}	Packet loss probability in local backbone network	0.01 %
T_{HTTP}	Time for of HTTP connection	3.0 msec.
T_{Cache}	Time for cache lookups/updates $(0.5*T_{HTTP})$	1.5 msec.
T_{ICP}	Time for processing an ICP query/response $(0.1*T_{HTTP})$	0.3 msec.
T_{CARP}	Time for calculation of destination cache $(0.2*T_{HTTP})$	0.6 msec.
T_{WCCP}	Time for calculation of target IP address and processing encapsulated IP packets $(0.1*T_{HTTP})$	0.3 msec.

Table 7. Parameters of the simulator

Virtual links

The simulator represents connectivity of basic components by virtual links. That is as simplifying assumption, we do not represent each physical link in the local national backbone network. A virtual link connects each pair of access routers. Each virtual link is associated with a round trip time RTT, i.e., the time which is needed by an IP packet to be transmitted from the source router of the virtual link to the destination and back. Furthermore, a packet loss probability P_{loss} is assigned to each link. This is the probability that a packet is lost while being transmitted on a virtual link. Virtual links are used to transmit two types of messages. The first type are ICP messages which use UDP/IP as underlying transport protocol. We assume an ICP message to get lost with probability P_{loss} and to get delayed with a mean of $RTT/2$ otherwise. The second type of transmission is a HTTP request/response dialog. HTTP uses the transmission control protocol/internet protocol, TCP/IP as underlying transport protocol. To capture the mean delay introduced by TCP/IP, we employ the analytical model introduced in [CSA00]. This model takes RTT and P_{loss} as well as some parameters of the TCP/IP protocol stack together with the size of the transmitted message as input for deriving the mean delay for connection setup and data transmission. To model the request part of HTTP, we calculate the mean time for connection set up as well as the transmission time for the request in TCP's slow start mode. For the response, we assume the mean delay for document transmission consisting of the slow start phase and a following steady state transmission phase if the document is large enough. We make the assumption that RTT and P_{loss} are not significantly influenced by traffic originating from intercache communication, i.e., they are constant during the simulation run. This assumption holds for intercache traffic in most national backbone networks because of low cache utilization.

To evaluate cooperative Web caching for emerging network technologies, we need to configure virtual links for different bandwidth available in the local backbone network. In our

experiments, we examined network bandwidth of 34 Mbps, 155 Mbps (STM-1 connection), 622 Mbps (STM-4 connection), and 2.4 Gbps (STM-16 connection). Following [FCD+99], we estimate round trip times for links offering different bandwidth. For a 155 Mbps and 622 Mbps bandwidth, we assume an average round trip times of 15 msec. and 10 msec., respectively. These delays are observed in the Gigabit research network G-WiN [GW01]. To estimate round trip times for 34 Mbps and 2.4 Gbps connections, we employ linear regression. From the measured delays, we observe that increasing network bandwidth by factor four approximately decreases average round trip time by 5 msec. Thus, we assume average round trip times of 20 msec. and 5 msec. for 34 Mbps and 2.4 Gbps connections, respectively.

Local Web Caches

Web proxy caches are connected to the access routers connecting regional networks to the local national backbone. The simulator implements the basic functionality of a caching proxy similar as described in [WY99], [WY00]. Each cache implements a cache manager using the LRU replacement scheme and a CPU server servicing requests in a FIFO queue. The cache manager can be configured to provide the functionality of ICP, Cache Digests, or CARP as described in Section 8. The core functionality of WCCP is implemented in the routers and, therefore, is not part of the cache manager. The simulator does not represent modifications of Web documents. Thus, the cache manager does not expire documents as real Web caches do. Therefore, the simulator slightly overestimates the amount of traffic saved by the cooperative Web caching. The service time of the CPU server depends on the operation performed. For processing a HTTP request time T_{HTTP} is required. Time for cache lookups and updates is denoted by T_{Cache}. Following [WY99], we assume that $T_{Cache} = 0.5 \cdot T_{HTTP}$. A single ICP query or response is processed in time T_{ICP}. It holds $T_{ICP} < T_{HTTP}$, since ICP messages are short and simple UDP transmissions [WC98]. Therefore, we assume that $T_{ICP} = 0.1 \cdot T_{HTTP}$. Calculation of hash functions takes time T_{CARP} for CARP. The hash function defined by CARP uses several arithmetic operations as 32 bit multiplication [VR98]. Therefore, we assume that hashing is more expensive than processing ICP messages, i.e., $T_{CARP} = 0.2 \cdot T_{HTTP}$. We assume that calculation of an entry of a cache digests based on hash functions also takes the delay T_{CARP}. Requesting and sending digests is performed based by HTTP and takes the delay T_{HTTP}.

The delay T_{HTTP} is determined experimentally as follows. Following [WY00], we perform simulation runs for various values of T_{HTTP} and monitor the utilization of the simulated caches for each value of T_{HTTP}. Since the correct cache utilization has also been measured during the trace recording, the values for cache utilization corresponding to different values of T_{HTTP} are used to calibrate the delay T_{HTTP}. This calibration yields T_{HTTP} = 3.0 msec.

Access routers

We refer to a router connecting one or more regional networks to the national backbone network as an *access router*. Access routers receive transmissions from a client, Web cache, or link component and pass it to an other Web cache, client, or link. Because all network transmission delays are included in the round trip time associated with virtual links, a transmission is not further delayed by an access router. The transmission redirected by WCCP constitutes an exception to this. In WCCP, an access router has to calculate the new target cache of a client request using a hash function and encapsulate the IP package for redirection. The combined time needed for these operations is denoted by T_{WCCP}. Opposed to CARP, the hash function defined by WCCP is based on simple bit shifting and XOR operations, which can be easily calculated by the router [CFTW00]. Redirection is done by rewriting a IP packet with an additional header, which is also a fast operation. Therefore, it holds $T_{WCCP} < T_{CARP}$, and we assume $T_{WCCP} = 0.1 \cdot T_{HTTP}$.

Clients

Several user agents, institutional, and regional caches can be connected to an access router via local and regional networks. The comparative simulation study presented in Section 10 focuses on distributed caching in a national backbone network. Thus, we refer to all these sources of requests as clients. We assume that all clients are configured to peer with the closest national cache, i.e., the cache located at the access router connecting their regional network to the national backbone network. We aggregate all clients connected to one access router in one clients component. The clients component assumed to be connected to the access router via a client link. Client links are used to transmit HTTP responses and introduce the same delay to a transmission as a virtual link does. The clients component issues requests to the caching proxy located at the same router. The request stream consists of the aggregated request streams of all clients located in the lower level networks connected to the central router. The request interarrival times are given by the timestamps of the requests recorded in the trace. A detailed description how client request streams are obtained from the trace files is given in Section 9.2.

Origin Web Servers in Remote Backbone Network

In the simulator, all origin Web servers are assumed to be located in a remote national backbone network. This remote network is connected via a low bandwidth connection to the local backbone network in which distributed Web caching using the considered protocols is explicitly represented. This low bandwidth connection to the remote backbone clearly dominates the delay for receiving a document from its origin Web server in the remote network. To reach the origin Web server, additional delays are introduced by passing the national, regional and institutional networks under the remote backbone network. However,

these delays are negligible compared to the delay between two backbone networks. Finally, the utilization of the origin Web server constitutes another important factor for the overall document retrieval latency. The sum of these latencies is denoted as the download time of a Web document. Estimates for these mean delays are derived from the considered traces as described in Section 9.2.

9.2 Characteristics of the Considered Workloads

To derive meaningful performance results for distributed Web caching in a national backbone network, we need to feed our simulator with representative workloads collected at top-level caches. Request streams for top-level caches show significantly different characteristics than request streams for institutional caches [MWE00]. The performance studies presented in Section 10 are based on traces from log files of two different networks: (1) four top-level proxy caches of the German Gigabit research network, G-WiN [GW01] and (2) ten top-level proxy caches of the National Laboratory for Applied Network Research (NLANR) cache hierarchy [NL01]. At the time of trace collection, 44 universities all around Germany configured their local caching proxies to use the top level caching proxies of the G-WiN as parents. For NLANR, at time of trace collection 584 individual clients peered to the caches. For both networks, we evaluated the trace files for a period of one week. Due to space limitations, we present only the results for a single day in the particular week. For all other days recorded in the trace files, similar performance results will be achieved.

To make the trace files usable for our performance study, some preprocessing has to be performed. First, from request recorded in the trace file we consider only GET requests to cacheable documents. We exclude uncachable documents by commonly known heuristics, e.g., by looking for string “cgi” or “?” in the requested URL. From the remaining requests, we consider responses with HTTP status codes 200 (OK), 203 (Non Authoritative Information), 206 (Partial Content), 300 (Multiple Choices), 301 (Moved Permanently), 302 (Found), and 304 (Not Modified) as cacheable. To determine the correct size of data transmissions with status code 304, we scanned the trace in a two pass scheme. Furthermore, we exclude all log file entries indicating intercache communication, because intercache communication is performed by the simulator. Trace characteristics after preprocessing are shown in Table 8.

Recall that the modeled network configuration contains five cooperating Web caches whereas we have traces from a single Web cache. Following [WVS+99], the overall request stream recorded in a measured trace is divided into fractional request streams issued by individual clients (i.e., 44 request streams for DFN). Subsequently, these fractional request streams are agglomerated into five subtraces, one for each aggregated clients of Figure 24, such that the total number of requests issued by clients is approximately equal for each subtrace.

Trace	**DFN**	**NLANR**
Date	June 7, 2000	December 6, 2000
Duration (hours)	24	24
Number of Web documents	2,208,527	1,935,226
Overall document size (GB)	42.75	23.07
Number of requests	4,310,753	3,361,744
Requested data (GB)	67.45	64.11
Average requests/sec.	49.89	38.90
Number of clients	44	584

Table 8. Properties of traces measured in DFN and NLANR

Table 9 states the properties of the subtraces for DFN and NLANR. To estimate the mean delays for retrieving documents from the origin Web server, we consider requests recorded with a TCP_MISS/200 status written by the Web proxy cache Squid. The transmission of a document from a cache to the client can be widely overlapped with the delay for transmitting the document form the origin Web server to the cache. Therefore, the time needed by a top level cache to retrieve a document from the origin Web server and deliver it to the client is a close approximation for the download delay specific for the document. If a document appears in several log file entries with status code TCP_MISS/200, we calculate download delay as mean value of the recorded time intervals. By scanning log files for an entire week, we were able to determine download delays for about 98% of the requested documents.

The important factor for the performance of cooperative Web caching in the backbone of a national ISP is the ratio between the document transmission time in the local backbone network to the document download time from the origin Web server. Table 10 provides numerical results for the average download times derived from the DFN and NLANR traces as well as mean document transmission times for different network bandwidth. These mean document transmission times are derived by the performance modeling for TCP latency of [CSA00]. Note that the average download time in the DFN trace is significantly lower than in

	DFN	**NLANR**
Average number of requests	862,151	672,349
Average requested data (GB)	13.49	12.82
Average requests/sec.	9.97	7.78

Table 9. Properties of DFN and NLANR subtraces for modeling aggregated clients

	Bandwidth	**DFN**	**NLANR**
Document transmission time in local backbone network	2.4 Gbps	225.32 msec.	224.21 msec.
	622 Mbps	245.73 msec.	243.72 msec.
	155 Mbps	266.14 msec.	263,28 msec.
	34 Mbps	286.54 msec.	282.74 msec.
Document download time	unknown	2681.66 msec.	3633.88 msec.

Table 10. Document transmission and document download times derived from trace data

the NLANR trace. However, corresponding document transmission times are almost equal for both traces. From Table 10, we conclude that for a bandwidth of 622 Mbps in the local backbone network, the ratio between the document transmission time and the document download time is about 1/11 for DFN while this ratio is about 1/15 for NLANR.

10 Comparative Performance Study of Considered Protocols

10.1 Performance Measures

Performance measures of interest for evaluating cooperative Web caching protocols include document retrieval latency, bandwidth consumption, and average cache utilization. For ISPs the bandwidth consumption of a cache mesh constitutes the most important measure. Bandwidth consumption can be split up into two parts: intercache traffic and saved traffic. The intercache traffic specifies the traffic used by communication and document transfers among the caches in a mesh. This part of bandwidth consumption constitutes the overhead introduced by cooperative Web caching. The simulator measures intercache traffic by counting the volume transferred via the virtual links. The saved traffic is the volume of all documents which can be delivered by a caching proxy of the mesh. That is the traffic which can be kept within the local backbone network. This part of bandwidth consumption determines the benefit of cooperative Web caching. Saved traffic can be determined by measuring the amount of data delivered by the local Web caches in the mesh. To relate traffic saved by cooperative Web caching to the overhead introduced by intercache communication, we define *protocol efficiency*. We denote the saved traffic due to cooperative Web caching by SV_{coop}, the traffic saved without cooperative Web caching by SV_{no_coop}, and the traffic for intercache communication by V_{icc}. Protocol efficiency is given by $SV_{coop} - SV_{no\_ccop} / V_{icc}$.

Document retrieval latency is the most important performance measure for clients. To be beneficial for clients, cooperative Web caching should significantly decrease document retrieval latency [CULM99]. The average retrieval latency specifies the mean time a client

has to wait until the entire document is delivered. Latency is measured at the client side. Whenever a client establishes a connection to the target cache, a timer is started. The timer is stopped when the client has received the requested document, entirely. Recall that we assume the caches to be in a cut-through mode, i.e., a cache instantly forwards to the client IP packets received from another cache or the origin Web server.

The performance measure most interesting for Internet enterprises like Application Service Providers (ASPs) constitutes the average cache utilization because this measure immediately implies cost/performance trade-offs. Average cache utilization indicates the number of requests supplied by a given Web cache. The average cache utilization is determined by measuring the fraction of time the Web cache CPU is busy.

Recall from Table 8 that in the considered traces the overall amount of requested data is about 65 GB. In the experiments presented below, relative cache sizes range from about 0.4% to more than 20% of the overall amount of data requested by all clients. Note that for larger cache sizes all requested documents of the considered traces can be stored in one cache. Thus, curves for individual protocols are independent from further increasing cache size.

10.2 Bandwidth Consumption and Protocol Efficiency

In a first experiment, we study bandwidth consumption in the cache mesh of the local backbone network for the considered cooperative Web caching protocols. Figures 25 and 27 plot the amount of saved traffic as a function of individual cache size for the DFN trace and the NLANR trace, respectively. The results show that without cooperative Web caching an amount of 15 GB is saved for DFN, i.e., 22% of the overall requested data. For NLANR, 26 GB are saved, i.e., 39% of the requested data. This difference can be explained by the different client populations of the caches underlying the traces. Clients of the DFN caches are institutional level proxies whereas clients of the NLANR caches can be user agents, institutional level proxies, and regional proxies like e.g., the proxies of the CANARII cache hierarchy [CA01]. As described in [MWE00], locality of reference is affected by intermediate levels of a cache hierarchy. Thus, user agents peering a cache raise locality and increase hit rate in the NLANR trace. Cooperative Web caching increases saved volume up to 22 GB for the DFN trace, i.e. 29% of the total requested data. This constitutes an increase of 39% relative to the saved data volume among the caches without cooperative Web caching. For the NLANR trace, cooperative Web caching increases saved volume by 17% to about 30 GB, i.e., 46% of the total amount of requested data. As above, the difference can be explained by the different client population. Higher locality leads to higher hit rates in individual proxies and leaves smaller space for improvements by cooperative Web caching.

Figures 26 and 29 plot the intercache traffic as a function of cache size for the DFN and the NLANR trace, respectively. Note that without cooperative Web caching no intercache communication occurs. Thus, these figures do not contain curves for this case. For CARP, we

observe that the amount for intercache communication is about 80% of the requested total amount of data. This can be explained by the fact that the URL space is equally partitioned among the five caches by the hash functions. Only 20% of the requested documents are serviced by the Web cache to which the request was issued. The remaining 80% must be delivered from another cache in the mesh. Due to simple hashing, WCCP does not achieve optimal distribution of requests among the caches. This causes for WCCP the higher intercache traffic than for CARP. ICP generates overhead traffic for every cache miss in a target cache [RW98]. ICP also causes intercache traffic when retrieving a document from a peer cache. The overhead traffic decreases with increasing cache size, because hit rates at the target cache increase. On the opposite, traffic caused by document retrieval increases because more misses in the target cache can be resolved by hits in the peer caches. Cache Digests cause the smallest amount of intercache communication for because Cache Digests does not introduce communication on every request as CARP or on every miss as ICP. Consistent with [Ros97], CARP and WCCP save most traffic. For small caches, WCCP saves slightly less traffic than CARP because of uneven load balancing. CARP distributes documents from the same site equally among all caches in the local mesh. CARP and WCCP are tightly followed by ICP because of sufficient bandwidth. Cache Digests performs worst because of false misses.

Figures 29 and 30 plot the efficiency of the considered cooperative Web caching protocols as a function of cache size. CARP yields low efficiency of about 10%, the efficiency achieved by WCCP is even lower. As explained above, this is due to the high rate of document transmissions between the caches which occur on about 80% of all requests. On the opposite, ICP yields efficiency of about 80%, mainly because of the high amount of UDP communication for documents not in the caches. Cache Digests yield best efficiency because digests are rarely exchanged and request issued to other caches result in cache hits with high probability.

The results for bandwidth consumption presented in Figures 25 to 30 are measured for a bandwidth of 622 Mbps in the local backbone. In further experiment, we performed the same simulation study for 155 Mbps and 2.4 Gbps bandwidth. These curves have basically the same shape than the curves of Figures 25 to 30. Thus, bandwidth consumption is almost independent from the bandwidth available in the local backbone.

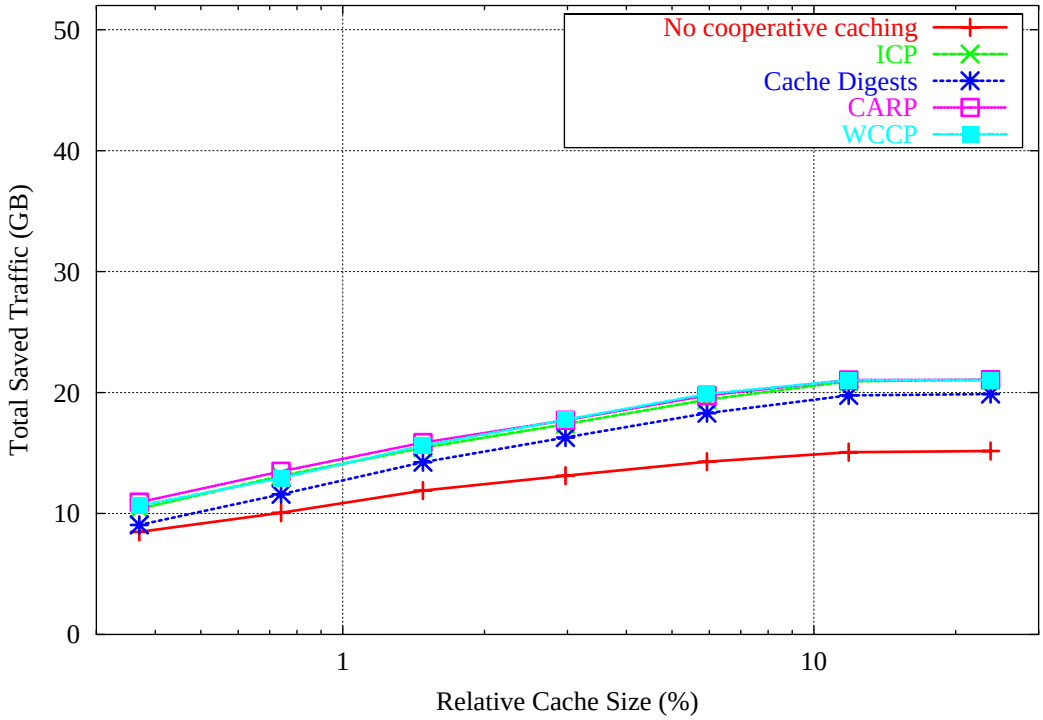


Figure 24. DFN trace: Bandwidth consumption of different protocols; saved traffic; 622 Mbps bandwidth

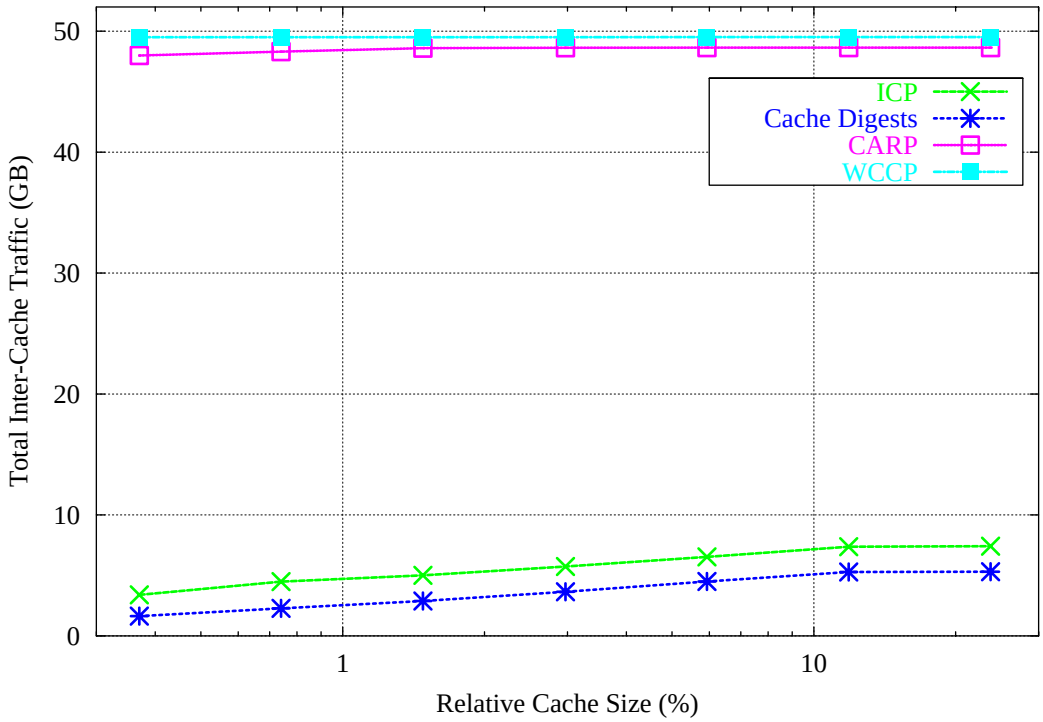


Figure 25. DFN trace: Bandwidth consumption of different protocols; intercache traffic; 622 Mbps bandwidth

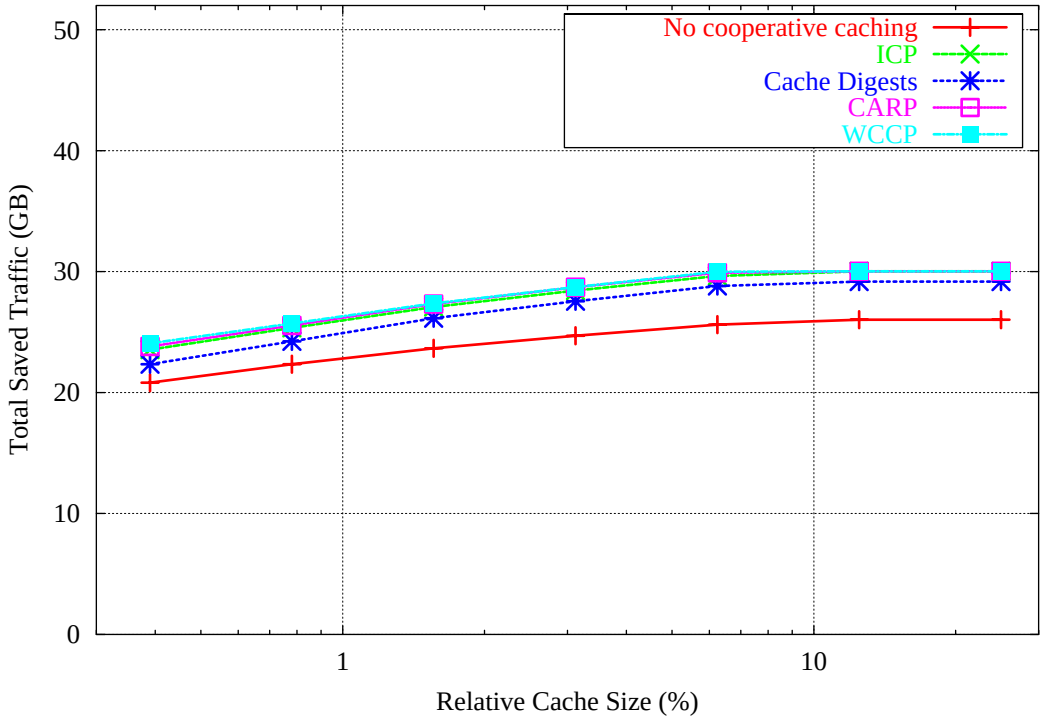


Figure 26. NLANR trace: Bandwidth consumption of different protocols; saved traffic; 622 Mbps bandwidth

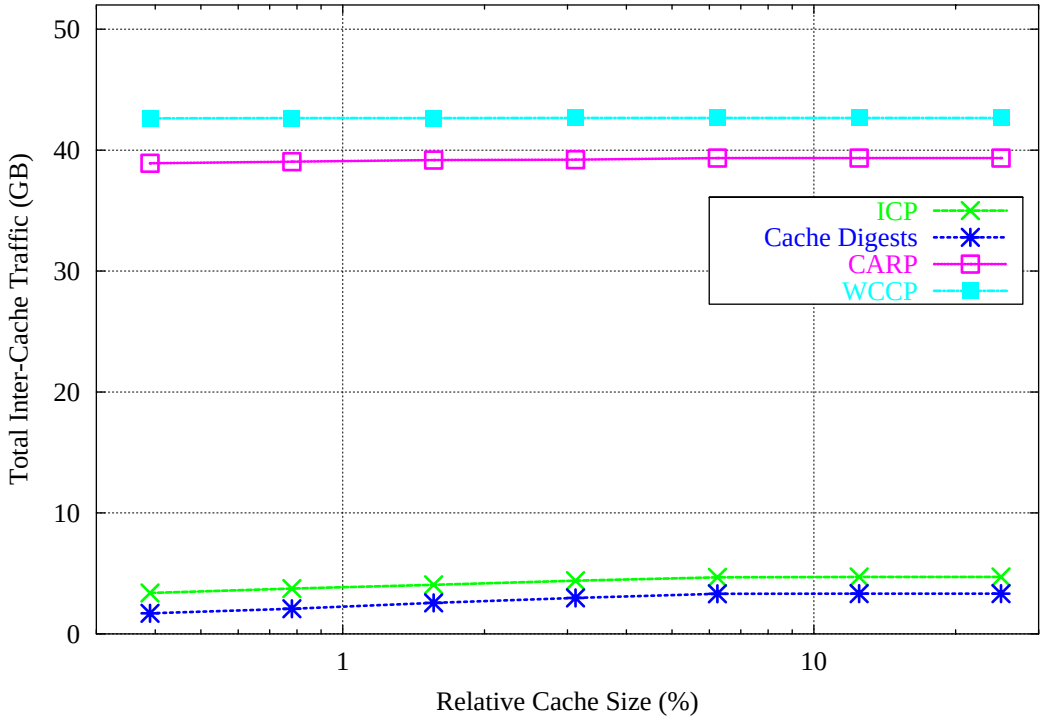


Figure 27. NLANR trace: Bandwidth consumption of different protocols; intercache traffic; 622 Mbps bandwidth

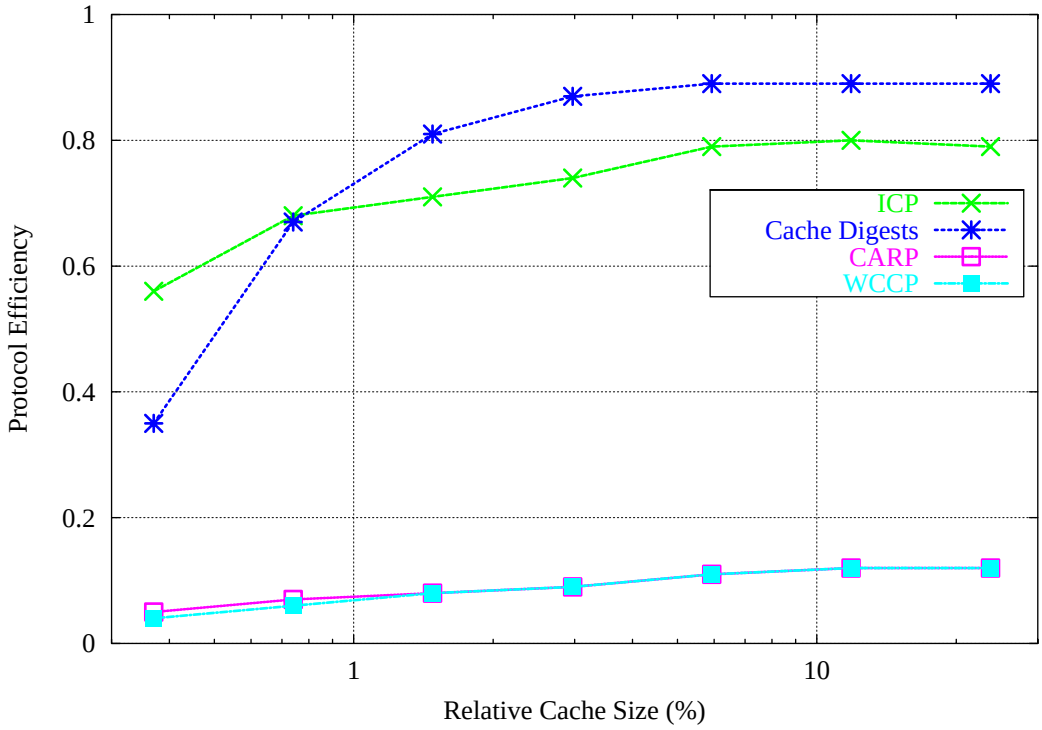


Figure 28. DFN trace: Protocol efficiency versus cache size; 622 Mbps bandwidth

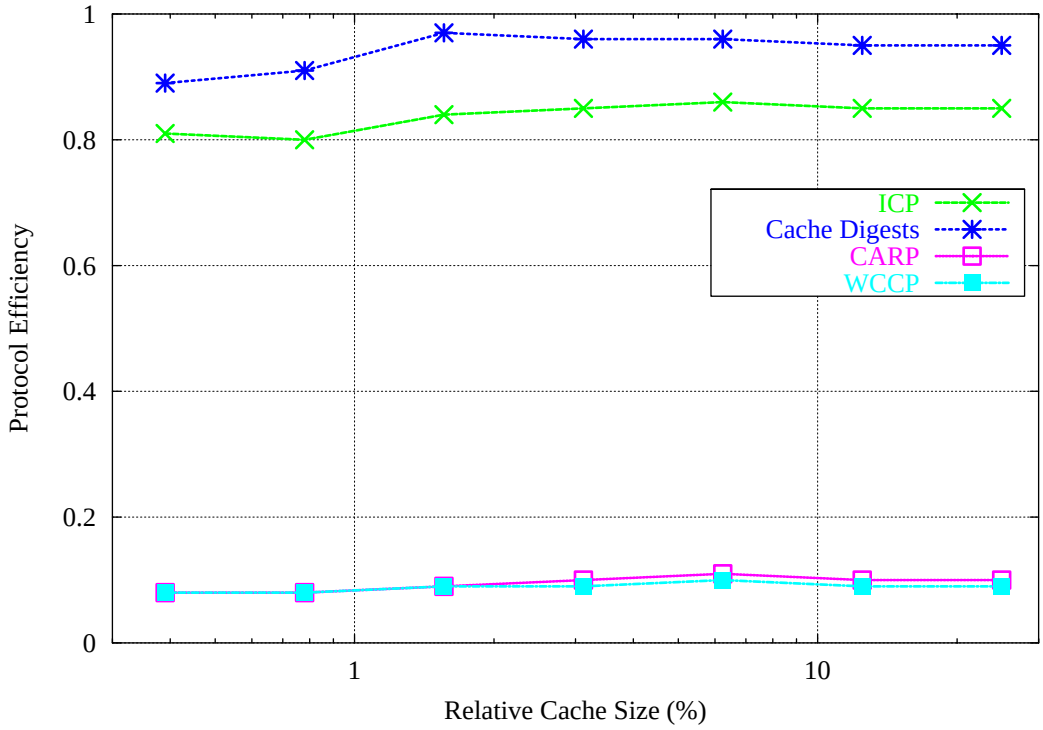


Figure 29. NLANR trace: Protocol efficiency versus cache size; 622 Mbps bandwidth

11 Document Retrieval Latency

Figures 31 to 34 provide a comparison of the latencies introduced by the protocols for increasing cache sizes. The experiments are performed for bandwidths of 155 Mbps and 2.4 Gbps in the local backbone. To illustrate the relative performance difference of the protocols, the origin of the y-axis is not zero in Figures 31 to 38. For very small caches in DFN, no cooperative Web caching outperforms all protocols except ICP in terms of latency. In fact, the benefit from receiving documents from the local mesh due to cooperative Web caching is less than the overhead introduced by the protocols. An exception constitutes ICP because of its rather low overhead for discovering copies of a particular document. If the target cache misses on a request, the probability for finding the requested document in any other cache in the local mesh is rather low for small cache sizes. With increasing cache size, cache hit rate increases, too. For 155 Mbps bandwidth, CARP yields almost the same to document retrieval latency as no cooperative Web caching. For 2.4 Gbps bandwidth, CARP performs slightly better than no cooperative Web caching. However, the benefit of any cooperative Web caching protocol is not significant for clients, i.e., a reduction of document retrieval latency of at most 10%.

Comparing corresponding curves in Figures 33 and 34, we observe that higher locality caused by different client population in the NLANR trace causes all protocols to be beneficial even for small cache sizes. Cache Digests shows worst performance of all protocols. This can be explained by the fact that Cache Digests is not capable of exploiting the high temporal locality in the NLANR trace because of low actuality of the digests. Opposed to [CULM99], [RW98], ICP achieves lower document retrieval latency than Cache Digests. CARP performs better than Cache Digests because of more effectively exploiting temporal locality. The low document retrieval latency of WCCP is due to low overhead of redirecting requests by routers and a high probability for cache hits.

Comparing the curves of the DFN and NLANR in Figures 31 to 34, we conclude that the performance gain of CARP and WCCP over no cooperative Web caching is significantly influenced by the locality in the workload. Low locality in DFN yields relatively high latencies for CARP and WCCP. For good locality in NLANR, Figures 33 and 34 show that the performance of CARP and WCCP is close to Cache Digests and ICP, respectively.

Comparing the curve shown in Figures 31 and 32 with corresponding curves of Figures 33 and 34 for NLANR, we observe that the impact of bandwidth availability in the local backbone network on document retrieval latency is rather low. In order to further illustrate this effect, we keep in Figures 35 and 36 the relative cache size fixed to 15 % and investigate document retrieval latency for network bandwidth of 34 Mbps, 155 Mbps, 622 Mbps and 2.4 Gbps. We observe that document retrieval latency scales linear when bandwidth availability in the backbone network scales by factor four. Different slopes of the graphs show different

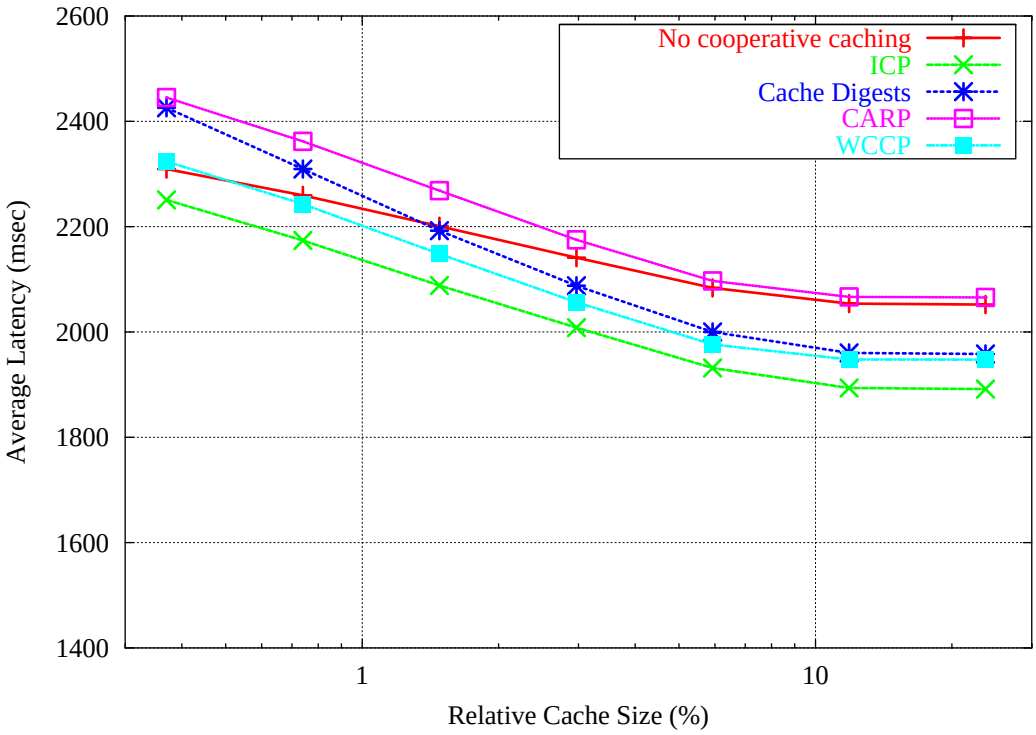


Figure 30. DFN trace: Document latency of different protocols; 155 Mbps bandwidth

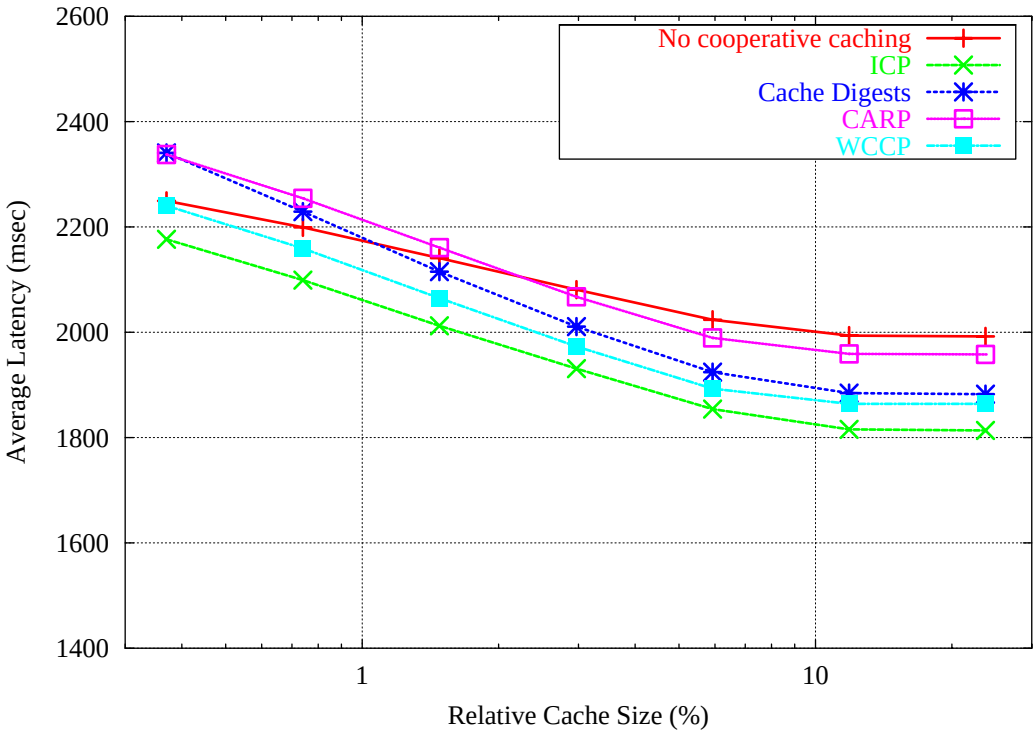


Figure 31. DFN trace: Document latency of different protocols; 2.4 Gbps bandwidth

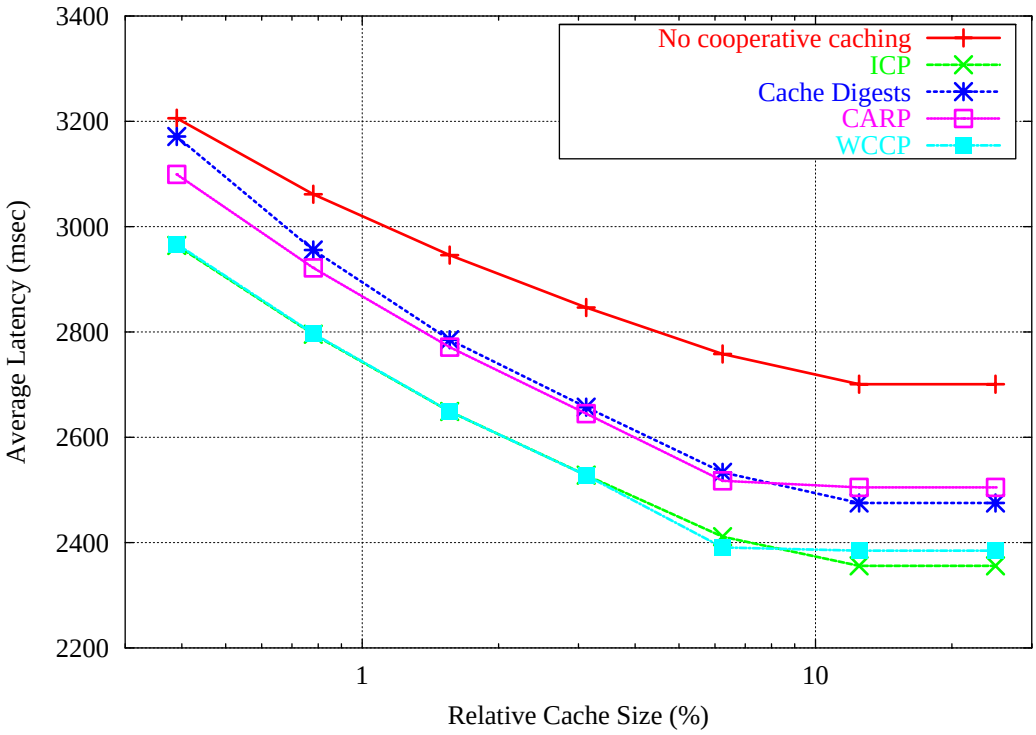


Figure 32. NLANR trace: Document latency of different protocols; 155 Mbps bandwidth

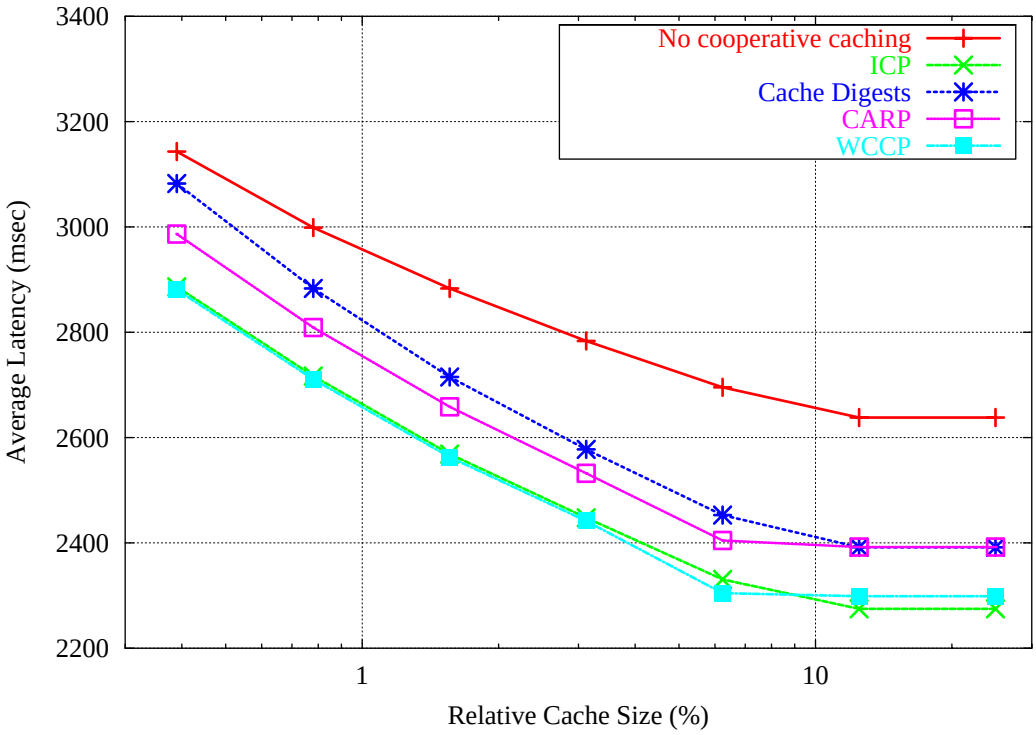


Figure 33. NLANR trace: Document latency of different protocols; 2.4 Gbps bandwidth

sensitivity of the protocols to network round trip time. Consistent with [WVS+99], we find that CARP and WCCP show greatest sensitivity because the retrieval of more than 80% of the data from other caches introduces substantial traffic in the network. ICP is only a slightly less sensitivite. This can be explained by the fact that the duration of the query response dialog introduced by ICP depends mainly on network round trip time. Cache Digests show least sensitivity, because of its small amount of intercache traffic.

From Figures 35 and 36, we conclude that the availability of additional bandwidth in the local backbone network has little impact on document retrieval latency. Currently, document retrieval latency is dominated by document download time observed in the traces (see Table 10). Recall that document download time is determined by the bandwidth of the connection between local and remote backbone and by the delay at the origin Web servers. These delays are independent from cooperative Web caching protocols in the local backbone. To show the impact of the ratio between document download time and document transmission time, Figures 37 and 38 present a sensitivity study. Consistent for both DFN and NLANR, we observe that document retrieval latency depends linearly on the ratio between document transmission and document download time. Different slopes in the curves for individual protocols show different sensitivity of the protocols. The slopes depend on the fraction of documents which can be delivered form the local cache mesh due to cooperative caching with the considered protocols. Thus, no cooperative Web caching achieves the steepest slope while CARP and WCCP achieve lowest slope. Comparing results for DFN and NLANR, we find again that effectiveness of cooperative Web caching heavily depends on locality observed in the workload. For the DFN trace showing low temporal locality, no cooperative Web caching outperforms CARP and WCCP for a ratio between document transmission time and document download time of 1/8. For the NLANR trace which exhibits higher temporal locality than DFN trace no cooperative Web caching performs worse than all cooperative Web caching protocols for all considered ratios.

11.1 Cache Utilization

Figures 39 and 40 plot the average cache utilization as a function of cache size for the different protocols. Without cooperative Web caching low cache utilization is achieved because besides a constant number of client requests no further messages are generated. Higher overhead for processing requests at the origin Web server cause slightly higher utilization for small cache sizes. Opposed to this, ICP yields the highest utilization due to its overhead on a cache miss. Consistent with [Ros97], we conclude that ICP scales poorly when the number of peer caches increases. CARP achieves little less cache utilization because CARP forces caches to calculate a hash sum on every request. Opposed to ICP, in CARP the load of retrieving a document is only added to the target cache and the selected cache. In fact, the additional load introduced by CARP is independent of the number of caches in the local mesh. Cache Digests yield rather low cache utilization because Cache Digests exchange

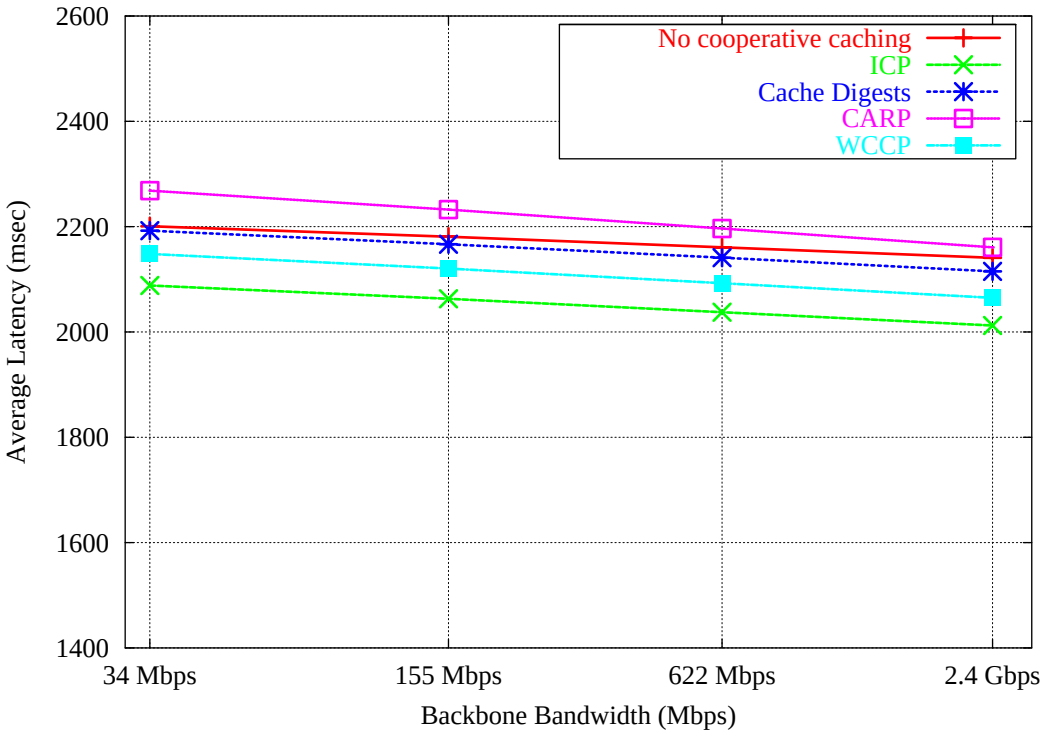


Figure 34. DFN trace: Document latency for different bandwidth availablity; relative cache size 15%

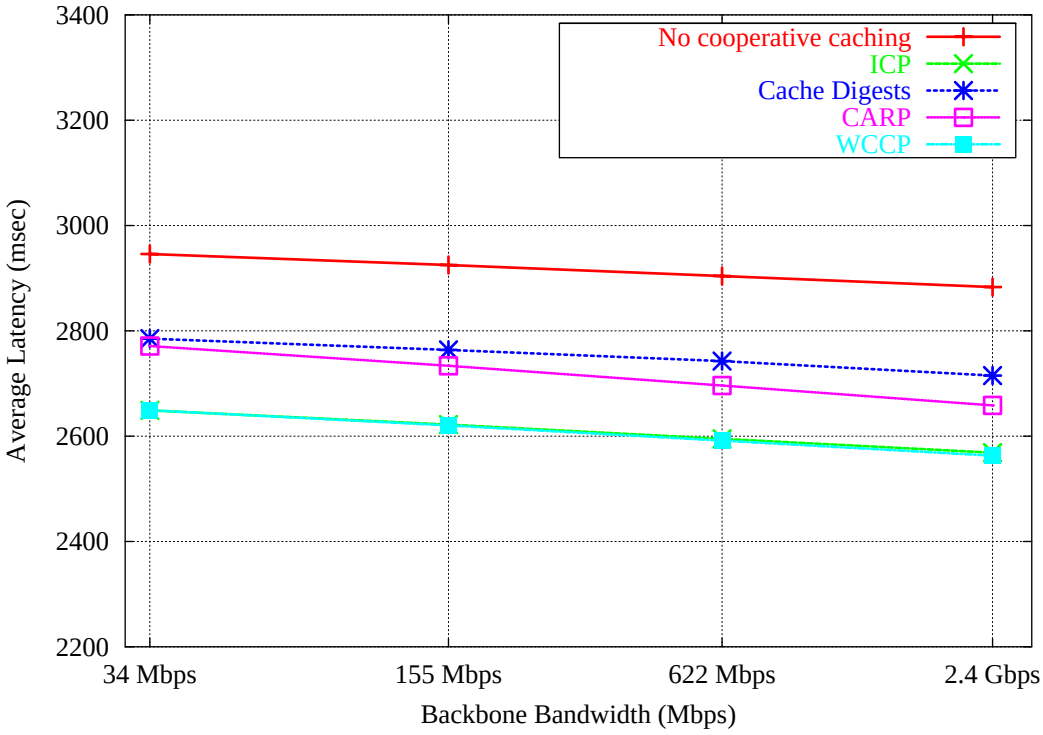


Figure 35. NLANR trace: Document latency for different bandwidth availablity relative cache size 15%

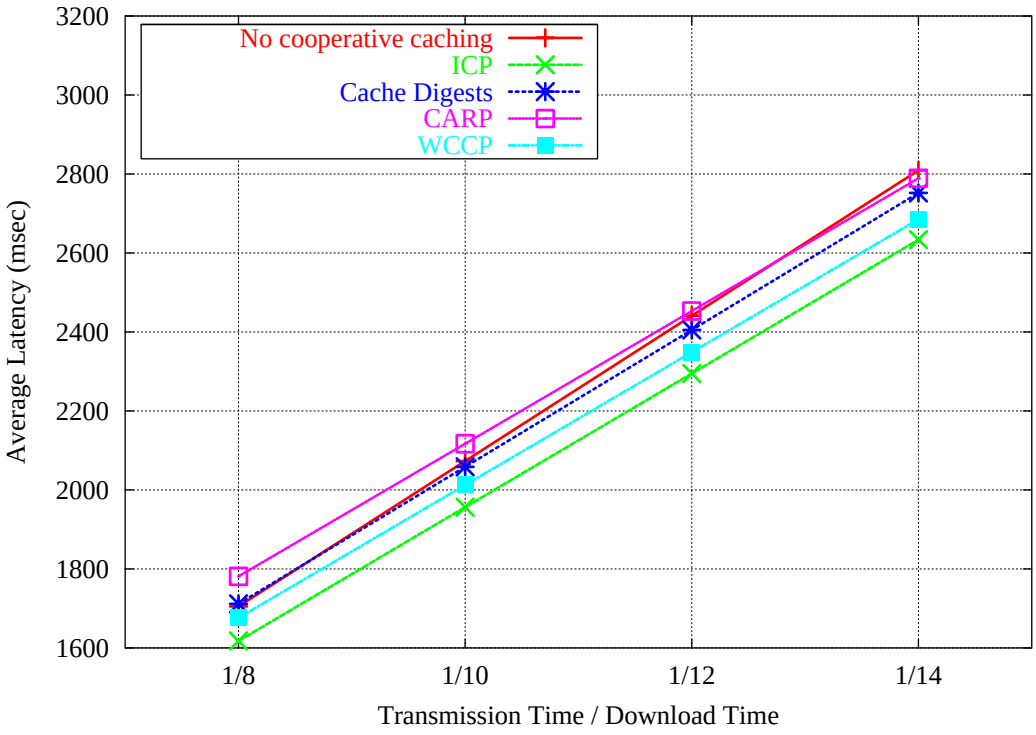


Figure 36. Sensitivity study for DFN trace: Latency vs. transmission/download ratio; 622 Mbps bandwidth, relative cache size 15%. Ratio observed in DFN trace is 1/11.

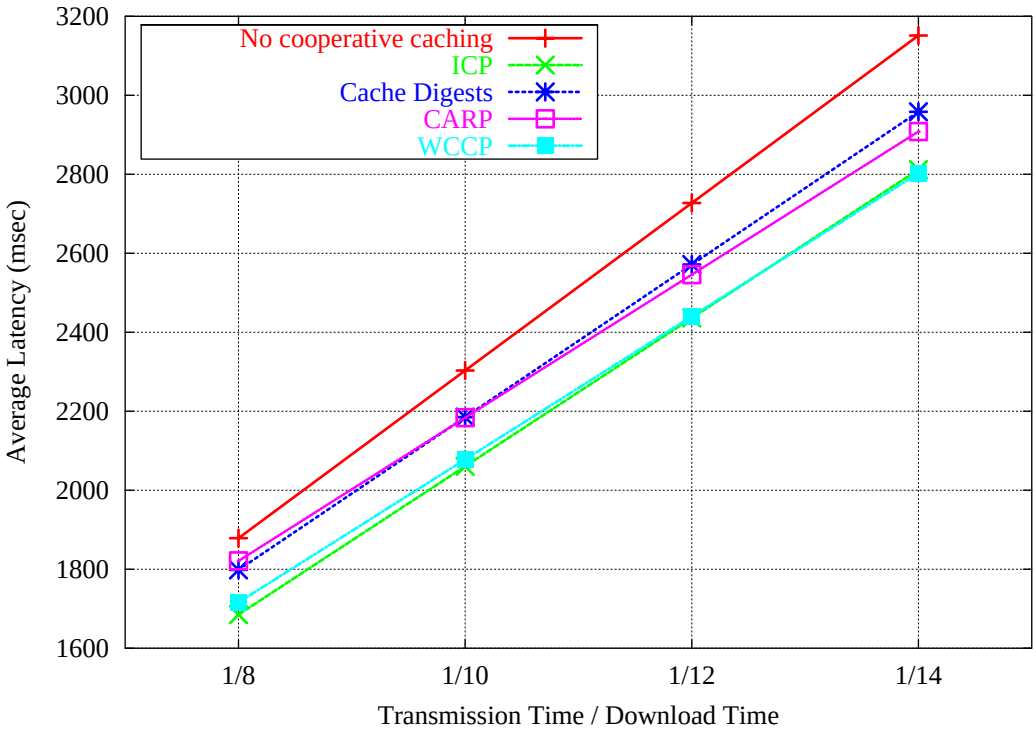


Figure 37. Sensitivity study for NLANR trace: Latency vs. transmission/download ratio; 622 Mbps bandwidth, relative cache size 15%. Ratio observed in NLANR trace is 1/15.

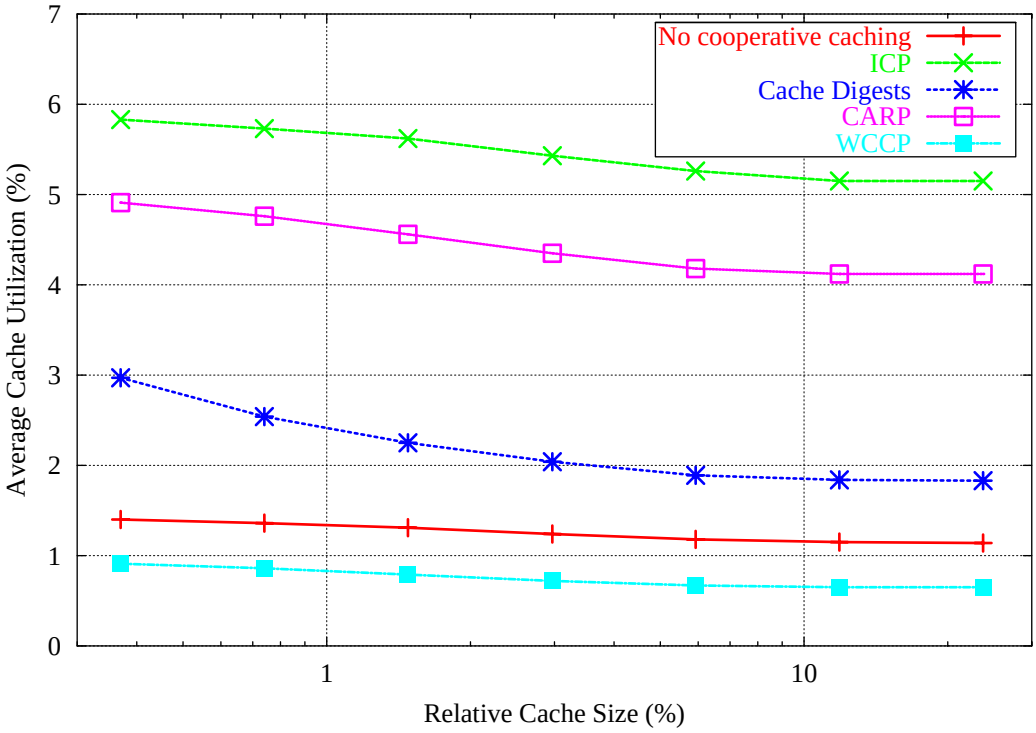


Figure 38. DFN trace: Cache utilization versus cache size; 622 Mbps bandwidth

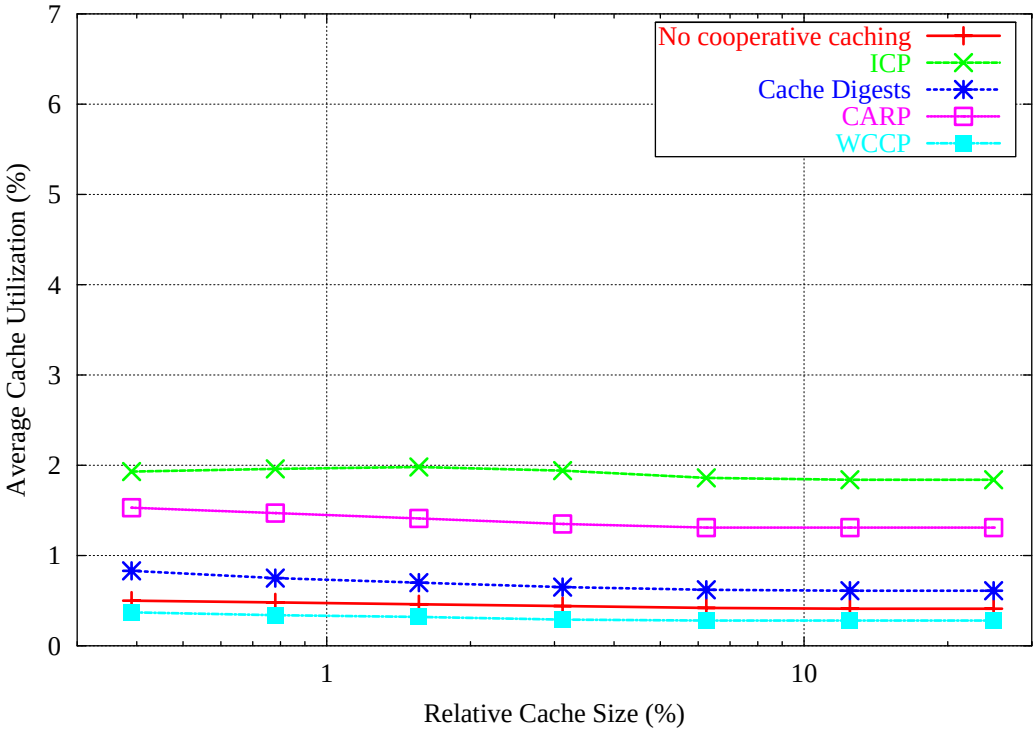


Figure 39. NLANR trace: Cache utilization versus cache size; 622 Mbps bandwidth

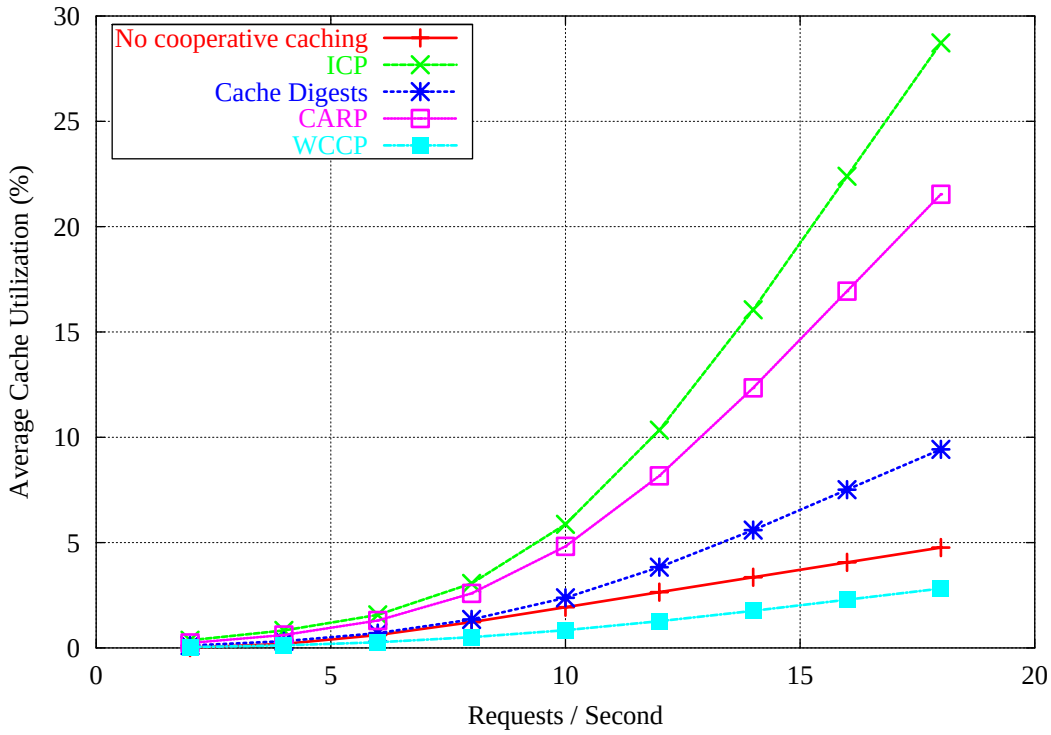


Figure 40. Sensitivity study for DFN trace: Cache utilization vs. request rate; 622 Mbps bandwidth, relative cache size 15%. 10 requests/sec. are observed in DFN.

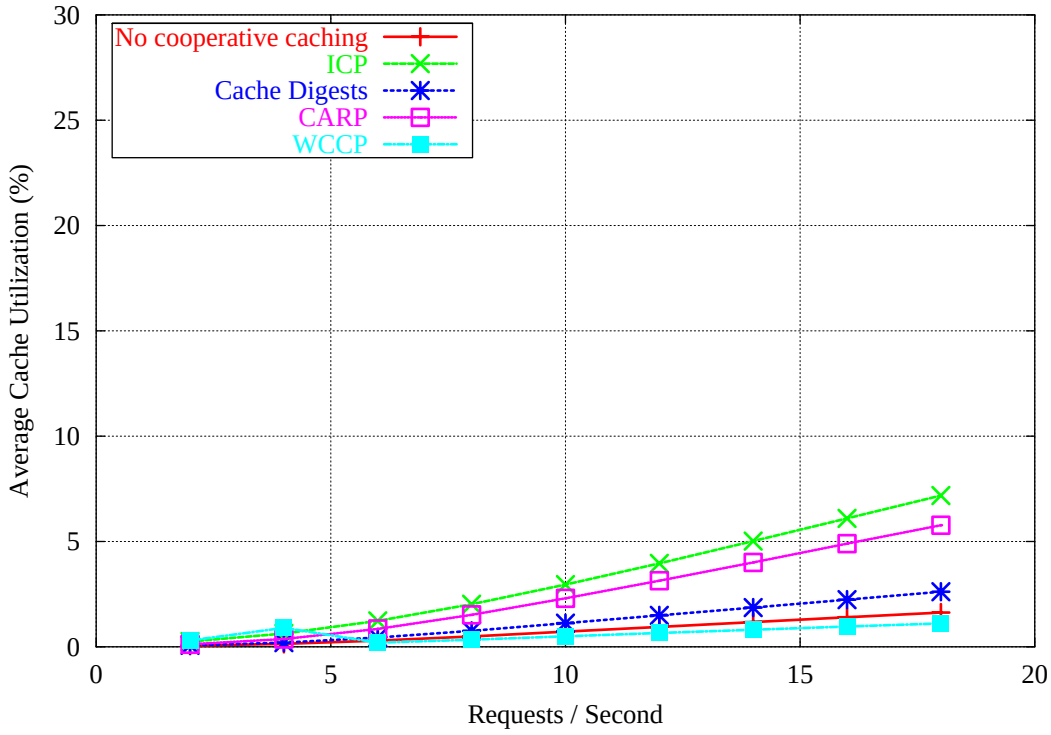


Figure 41. Sensitivity study for NLANR trace: Cache utilization vs. request rate; 622 Mbps bandwidth, relative cache size 15%. 8 requests/sec. are observed in NLANR.

messages only on a regular basis. WCCP offers lowest load to the caches due to balancing requests in the routers. In fact, average cache utilization with WCCP is even lower than for no cooperative Web caching.

From Figures 39 and 40, we also observe that both the DFN and NLANR trace offer a moderate load to the caches. In fact, DFN has an average of 10 request/sec. and NLANR 8 requests/sec. To investigate protocol performance for increasing request rates, we perform a sensitivity study shown in Figures 41 and 42. The relative cache size is kept fixed to 15%, network bandwidth is fixed to 622 Mbps and the interrequest times in the DFN and NLANR traces are varied. For both DFN and NLANR, we find that relative order in cache utilization between the protocols does not change with increasing workload. ICP achieves highest cache utilization because of its overhead on each miss. CARP scales slightly better than ICP. WCCP achieves even better scalability than no cooperative Web caching because of its load balancing among the caches. Consistent with [RW98], we conclude that Cache Digests yields high scalability while ICP scales poorly. To ensure scalability, clearly the protocol of choice is WCCP. Comparing Figures 41 and 42, we find that the higher locality in the NLANR trace has substantial impact on cache utilization. High hit rates at target caches reduce network traffic. Thus, all cooperative Web caching protocols scale considerably better in environments offering high temporal locality.

12 General Conclusions Drawn from Performance Studies

In this project, we provided an in-depth analysis of behavior and design issues of standalone and cooperative Web caching environments. We presented several performance studies based on current and future workload characteristics. To enable long-term design, we presented sensitivity studies, which show the behavior of state-of-the-art algorithms and protocols under changing user behavior, workload characteristics and network technology. The results can be directly transferred into recommendations for operators of local area networks, Internet service provider and application service provider.

In Part 1, we presented comprehensive performance studies of the Web cache replacement schemes LRU, LFU-DA, Greedy-Dual-Size (GDS) and Greedy-Dual * (GD*). While all commercial Web caching solutions solely rely on LRU, the newly proposed schemes LFU-DA, GDS, and GD* can be used in Squid software Web cache. Opposed to previous studies, we not only consider current workloads based on measured trace data, but also two forecasts for future workloads seen at Web proxy caches. This workload forecasting is motivated by the rapidly increasing number of digital audio (i.e., MP3) and video (i.e., MPEG) documents in the Web. To derive synthetic workloads for the workload forecasts, we introduced an effective method for modifying given trace data so that the modified request stream represents the workload characteristics of the forecast. To understand how Web cache replacement schemes deal with different Web document classes, we presented curves plotting hit rate and byte hit rates broken down for HTML, images, and multi media documents.

The investigation of the adaptability of GD*(1) presented in Section 6.1 evidently shows that GD*(1) does not waste cache space by keeping large multi media documents that are likely not to be referenced in the near future. This observation explains why GD*(1) almost always achieves the highest hit rate. The breakdown of hit rates and byte hit rates per document class shows that the overall hit rate is mainly influenced by the hit rate on images. The overall byte hit rate is mainly influenced by the byte hit rate on multi media documents.

Recall that current workloads consist of about 70% images and only about 2% multi media documents. As a consequence, GD*(1) performs significantly better that the other schemes in terms of hit rate. For small proxy caches, GD*(1) also stays competitive with LRU and LFU-DA in terms of byte hit rate. In an overall evaluation considering both hit rates and byte hit rates, the software Web caching solution Squid with the replacement scheme GD*(1) should be the choice for current workloads. Recall that our workload forecasts are based on the assumption that the fraction of multi media documents significantly increases, the popularity of some multi media documents also increases and that the time between two successive references to the same Web document decreases. These assumptions are motivated by the trends derived from five traces measured in 1996, 1998, and 2000. For future workloads, GDS(1) achieves the same performance as GD*(1) in terms of hit rate. Furthermore, the

difference in hit rate achieved by GD*(1) over LRU and LFU-DA became considerably smaller. On the other hand, the disadvantage of GD*(1) over LRU and LFU-DA in terms of byte hit rate clearly became significant. In an overall evaluation considering both hit rates and byte hit rates the software Web caching solution Squid with the replacement scheme GDS(1) should be the choice for future workloads.

In Part 2, we presented a comprehensive performance study of the cooperative Web caching protocols ICP, CARP, Cache Digests, and WCCP. We investigated performance of individual protocols from viewpoints of Internet Service Providers (ISPs), clients, and Internet enterprises like Application Service Providers (ASPs). Consequently, as performance measures we considered bandwidth consumption, user latency, and cache utilization.

Recall that ISPs are most interested in the amount of saved traffic and in protocol efficiency. The curves presented in Figures 24 to 29 indicate that ISPs clearly benefit from cooperative Web caching. For currently operating backbone networks having a bandwidth of 155 Mbps, ICP is the protocol of choice because of its high protocol efficiency. For future backbone networks having bandwidth of 2.4 Gbps, WCCP is superior to ICP because WCCP yields higher saved traffic than ICP while the low protocol efficiency of WCCP does not matter. Recall that ASPs are most interested in low cache utilization because this implies good cost/performance trade-offs. As illustrated in Figures 39 to 40, ASPs benefit from cooperative Web caching in case of future backbone networks providing bandwidth of 622 Mbps or 2.4 Gbps. In this case, WCCP yields the lowest cache utilization of all protocols and also lower cache utilization than no cooperative Web caching. Recall that clients are most interested in low document retrieval latency. We observe only little differences in document retrieval latencies achieved by the individual protocols. Moreover, these latency curves are in the neighborhood of the latency curve for no cooperative Web caching. Thus, clients have not much benefit from cooperative Web caching regardless which protocol is employed. As illustrated in a sensitivity study, clients will benefit most from reducing the ratio between transmission time and document download time. Therefore, providing higher bandwidth in links to remote backbone networks or deploying a content delivery network are considerably more effective approaches for reducing document retrieval latency than cooperative Web caching.

In all experiments, we found that the performance of cooperative Web caching protocols heavily benefits from temporal locality. Since temporal locality is more likely to occur on a lower level of a cache hierarchy, cooperative Web caching is most beneficial among institutional caching proxies. Thus, corresponding curves of NLANR show better performance than for DFN. Furthermore, both the DFN trace and NLANR trace indicate a rather low participation to cooperative Web caching among their subscribers. Furthermore, we found that the impact of low cache utilization due to low participation in cooperative Web caching make considerably impact to the performance of individual protocols.

13 Recommendations for DFN-Verein

In this final chapter, we give general recommendations drawn from our performance studies. We sum up how the customers of the DFN-Verein as well as the DFN in its function as an ISP can take advantages from the lessons learned in this project.

Recommendations for Operators of Local Web Caches at DFN Customer Sites

In the performance studies presented in Part 1 we investigated the performance of locale Web caches. We showed that usage of a state-of-the art replacement scheme, e.g. Greedy Dual Size or Greedy Dual * can save up to 40% of the WWW traffic volume for current and future workloads. This studies assumes that all clients inside an institution make use of the Web caching service, as given in the DEC trace. However, if the cache is only used by a subset of all potential clients, as it is usually in all German universities by now, the amount of saved traffic reduces to less than 20%. The gap in cache performance caused by different usage patterns is much bigger than the gap caused by the application of different caching technologies and algorithms.

As a result of our study, we recommend to the operators of local caches taking measures to ensure high usage of their caching services. For example an appropriate measure is the installation of transparent web caching solutions, e.g. by employment of the Web Cache Coordination Protocol WCCP. High cache acceptance and usage are the building blocks for a sufficient performance of al presented caching solutions.

Recommendations for the DFN-Verein as Internet Service Provider

The performance studies presented in Part 2 show that, given the current usage pattern, the highest bandwidth savings achievable by cooperative web caching in the G-WiN Backbone is about 22%. As investigated for local caching solutions, the reason for this poor performance is low usage of the caching service by the clients. Opposed to the results investigated for the DFN-trace, the NLANR-trace shows better performance due to high acceptance and utilization of the NLANR cache hierarchy.

As a result of our study, one can argue that the DFN-Verein should take measures to ensure sufficient cache usage by the clients. For example clients could be forced to make use of the caching service by transparent caching solutions in local institutions. Nevertheless, caching of every WWW request issued from inside the G-WiN puts tremendous challenges to WWW caches and protocols. Caching Hardware capable of managing workloads of this dimension, if available, would have problems to gain a sufficient cost-performance-ratio.

A reason for low cache utilization is the little impact of cooperative Web caching on end user latency, as shown in Part 2. A primary goal of a caching solution must be to optimize this performance measure in order to get widely accepted by the clients. To develop a scalable an

cost efficient Web caching service, we recommend to the DFN-Verein to focus future efforts on transparent WWW replication techniques and content routing solutions, e.g. as employed by Content Delivery Networks.

General Recommendations

The results presented in Part 1 and 2 show how performance studies can be employed to evaluate the benefit of the installation of new technological approaches. Our studies showed that web caching is only effective, if widely used by the clients. The results of the studies were derived based on workload-measurements and –forecasts which were available without building a complex Web caching infrastructure, neither at local institutions nor inside the G-WiN backbone. We conclude that in-depth performance studies should be used before the installation of new technological solutions, because they can a priori discard several design alternatives and identify the framework for efficient use of a technological approach.

Proposals for Future Projects

The majority of work done in this project constitutes the development of the simulation environment for local and distributed Web caching solutions as well as the workload characterization and modeling. The developed components could be reused in a short-term project, which provides economic evaluations of different Web caching solutions. Using the existing components, the expected bandwidth savings for an arbitrary cache configuration can be calculated based on a given workload trace. The simulation results can be used to perform a detailed cost / benefit analysis considering the investment in hardware and labor. By providing such combination of simulation software and economic calculations, the project results can easily be transferred from network performance measures (i.e., byte hit ration and end user latency) to economic performance measures (i.e., return of investment).

In a long-term project, the current project results can build a theoretical foundation for the development of an efficient ISP-centric content delivery solution. To increase client acceptance for content delivery solutions in the Gigabit Research Network G-WiN, to issues must be addressed: First, End user latency has to be substantially reduced. As shown in Part 2, this can be achieved by reducing Web server delays. Second, transparent methods for redirection of user requests to cache servers have to be employed. Request must be addressed to the server, which can serve the requested content optimal from two different points of view. An optimal delivery from the client’s point of view is the fastest possible delivery of a requested Web document. From the point of view of an Internet service provider, an optimal delivery saves most bandwidth on external (i.e. expensive) links. To meet these conflicting goals, in-depth understanding of cache cooperation and the sensitivity of distributed caching systems to workload characteristics is needed. Such understanding is provided by the results the current project.

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