

BIND 9 performance while serving large zones under update

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Abstract

(A PDF version of this document is available at ftp://ftp.isc.org/isc/dns_perf/ISC-TN-2008-1.pdf

An HTML version that does not use frames is at http://ftp.isc.org/isc/dns_perf/ISC-TN-2008-1.html)

ISC has built a testbed out of Commercial Off-The-Shelf (COTS) servers that can perform full-scale tests of the performance of DNS protocols using real data from TLD and root servers, or synthetic data to test the performance of different mixes. We have been particularly interested in the performance of **DNSSEC** mechanisms within the DNS protocols and on the use of BIND as a production server for major zones.

High-end name service is typically provided by a battery of 13 servers, any one of which could be selected by the client that received the reply identifying them. Our testbed houses 13 servers and a framework that simulates an adequately-fast internet connection to them, so that our tests mirror as closely as possible the operating environment used by TLD and root name service operators. Test clients issue requests to the servers in the testbed, and outboard measurement systems track the requests and the responses.

We have measured raw query processing speed, DDNS update speed, and the speed of query processing while simultaneously updating via DDNS protocols. We used the COM zone from 5 October 2007 for these tests, and we used a 48-hour trace of the Palo Alto F-Root node as a source of query data.

This work was sponsored in part by the National Science Foundation via grant NSF OARC DNS SCI CISE SCI-0427144.

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1. Introduction

ISC has built a testbed that can perform full-scale tests of the performance of DNS protocols using real data from TLD and root servers, or synthetic data to test the performance of different mixes. We have been particularly interested in the performance of **DNSSEC** mechanisms within the DNS protocols and on the use of BIND as a production server for major zones.

Ordinary DNS traffic uses UDP datagrams. The protocol standard specifies that the replies be restricted to 512 bytes of payload (**RFC1035**, #4.2.1). In such a packet, the responding name

server can fit 13 answers to a question. If the question asked is 'what are the name servers for domain example.com?', the answer will identify no more than 13 name servers. For this reason, high-end name service is typically provided by a battery of 13 servers, any one of which could be selected by the client that received the reply identifying them.

Our testbed houses 13 servers and a framework that simulates an adequately-fast internet connection to them, so that our tests mirror as closely as possible the operating environment used by TLD and root name service operators. Test clients issue requests to the servers in the testbed, and outboard measurement systems track the requests and the responses.

There probably exist enough supercomputers in the world for us to have built a cluster of 13 supercomputers that would have adequate performance under almost any conditions. But an important purpose of our testbed is to test with affordable commercial off-the-shelf server hardware. There is more value in testing the performance of servers that can be used around the world in DNS operations than in testing the performance of experimental servers that never leave a laboratory. So every component of our testbed has been moderately-priced **COTS** equipment that realistically can be used by full-scale name service operators.

Although we have tested with both signed and unsigned zones, we did not measure the performance of zone signing or re-signing as part of this project.

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1.1. Project outline

The DNS Performance Testing Project was conceptually divided into these phases:

1. Design and document testbed. Identify the proper server hardware through benchmarks and order necessary hardware. Testbed will allow simulation of a universe of 13 TLD servers, using computers of appropriate speed interconnected by a non-blocking switch. Testbed will include enough client computers to present a full simulated load, and will have a control machine and a separate logging machine.
2. Acquire a test request stream by recording 72 hours of **F root** traffic. Subsets of this test stream will be used for performance measurements.
3. Build testbed. Install and configure the servers and interconnects. Try various operating systems under various configuration settings, including at a minimum FreeBSD, Linux, NetBSD, and Solaris. Get the testbed working with BIND under each such OS using a copy of the live .com database, and measure performance under each.
4. Filter the test request stream to produce a TLD test stream for COM by removing all queries that are not asking about .com domains. Modify the "nsupdate" program so that it can generate and send a synthetic test update stream that is 1/3 NS record changes, 1/3 domain-add requests, and 1/3 domain-delete requests, and so that it has a speed-control option that can be used to adjust the rate at which it sends such requests.
5. Set up the testbed so that each of the 13 servers is running as an authoritative server for a recent copy of the COM zone, and that each is processing the filtered test request stream produced in Task 4. Set up the 13 servers so that each uses Notify and IXFR to keep its COM zone up to date. Set up a 14th server as a "Stealth master" (see RFC1996 #2.1) as an authoritative server for the COM zone, and then make a series of tests that use nsupdate to update this 14th server with the synthetic update stream. There will be 3 tests in this series, corresponding to "low", "medium", and "high" rates of update. A low rate is 1% of COM changing every day; a medium rate is 3% of COM changing every day, and a "high" rate will be the maximum speed at which we are able to make it run.
6. Make the testbed hardware available to approved organizations for research measurement projects. Any significant software developed will be provided as open source.

1.2. Staffing

- David Boggs, PhD: principal investigator
- Brian Reid, PhD: associate investigator and research programmer
- Paul Vixie: associate investigator
- Peter Loshier: system administrator

2. Identifying appropriate server hardware

Our experience as authors and maintainers of BIND is that the performance of BIND is limited primarily by the processor and memory performance of the server computer, and by bottlenecks in the operating system. Vendors normally advertise processor speeds, but the performance of a computer's memory subsystem is not readily available. We have identified several candidate server computer configurations based on price and availability and have measured the memory performance (bandwidth, latency, and cache performance) of each.

2.1. Candidate computers

We selected computers from various vendors that were priced such that we might be able to buy 16 of them for about \$100K. We also included computers that we know were unacceptably slow, so that we could have a wider spectrum of results from the measurement suites. This included:

Computers tested

ID	Vendor	Model	Code	Processor(s)	Memory	Bus	Comments
Sun 1	Sun	Sun Fire	X4200	4x AMD254/2.8GHz	DDR-400	PC3200	
Sun 2	Sun	Sun Fire	X4200	4x AMD285/2.6GHz	DDR-400	PC3200	
Iron 1	Iron Systems	I-class	I1525HS	2x Xeon/2.4GHz	DDR-400	PC3200	Intel E7505 chipset
Iron 2	Iron Systems	M-class	MS3520HS	4x AMD280/2.4GHz	DDR-400	PC3200	Tyan S3870
Cel 1	Celestica		A8440	2x AMD846/2.0GHz	DDR-333	PC2700	desktop
DEC	Compaq			1x Celeron/1.25GHz	SD-133	PC133	desktop
HP 1	Hewlett Packard	Proliant	DL 140g3	4x Xeon/3.0GHz	DDR2-667	PC5400	1U system

We measured a number of other less-powerful systems, primarily to help us be confident in our measurement methodology. None of them was a realistic candidate to be our server choice.

2.2. Measurement methodology

We began with the **memtest86** measurement suite (v3.2), by means of a bootable CD that did not involve the subject computer's installed OS. This program claims to measure transfer rates in megabytes/sec to and from memory and caches. We followed with **the calibrator** (v0.9e), which measures cache and memory latency and TLB performance, and with **lmbench** (v3.0a4). Combined results are shown below, separated by CPU maker (Intel or AMD). We were suspicious of the memory bandwidth number for the HP 1 unit, presumably because the memtest86 program is not interfacing properly with its hardware. We investigated further using the **STREAM** system (v1.0), which shows bandwidth numbers similar to those from memtest86 for all units except HP 1.

	AMD processors				Intel processors		
	Sun 1	Sun 2	Iron 2	Cel 1	HP 1	Iron 1	DEC
Bandwidth in MBytes/sec							
L1 memtest86	22886	21251	19717	16331	49058	19607	12375
L2 memtest86	5686	5280	4899	4230	--	14675	5610
Memory mt86	2237	2202	2237	972	19559	1460	342
lmbench	2316	2368		1303	2984	2047	652
Latency in nanoseconds (miss/replace)							
L1 calibrator	3.48/3.47	3.73/3.73	4.08/4.07	5.07/5.05	3.07/3.80	6.82/6.94	4/4
L2 calibrator	99/99	98/98	116/116	165/165	64/104	114/116	102/102
lmbench	83	83		155	72	109	109
STREAM benchmarks in MBytes/sec							
Copy	1724	1816		1122	2586	1309	285
Scale	1785	1885		1175	2751	1194	310
Add	1896	1994		1254	2884	1329	394

On the basis of these benchmarks, and of vendor prices, we selected the HP 1 system ([DL 140g3](#)) to use for our testbed. We began this benchmark assuming that AMD systems would be faster in our price range, but the data shows otherwise.

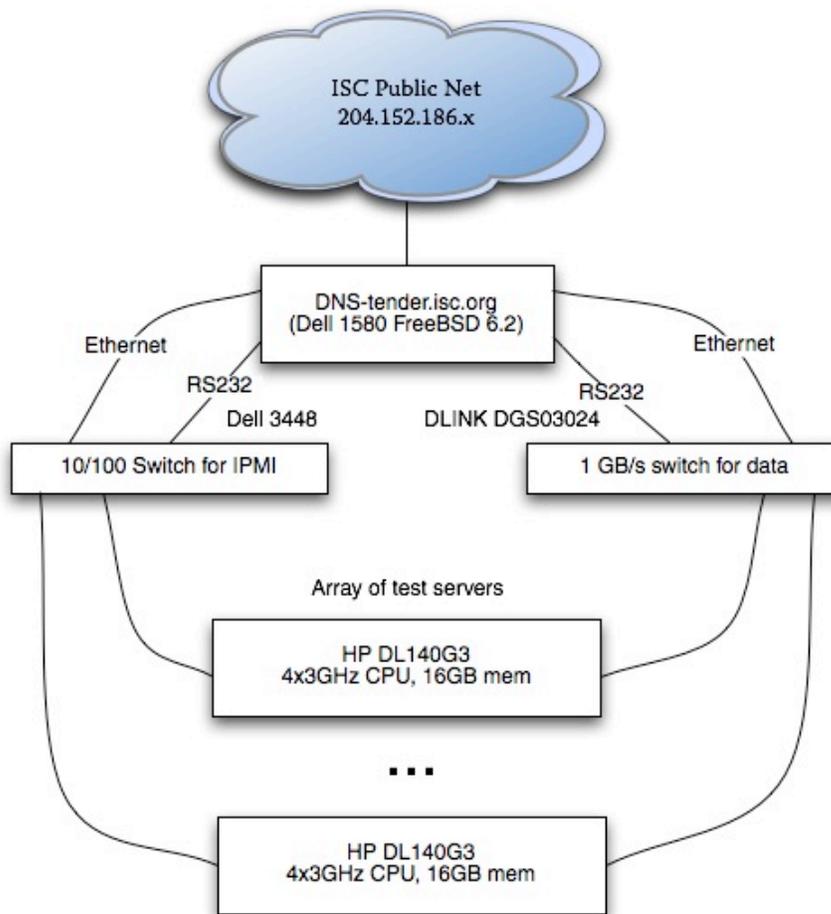
3. Operating system evaluations

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Having benchmarked the hardware for maximum performance in the kind of load to be offered, we now benchmark various operating systems for their suitability to run BIND 9. The same query stream is sent to the same version of the application software running on several different operating systems, and the processing speed is noted.

3.1. Description

The testbed configuration is as follows:



Using several machines in our testbed (one for each OS), we are running an instance of these operating systems:

- FreeBSD 6.2-RELEASE
- FreeBSD 7.0-CURRENT
- Linux Gentoo 2.6.21
- Linux Fedora Core 2.6.18
- NetBSD 4.0
- OpenBSD 4.1
- Windows 2003 Server
- Windows XP Professional

On each of the server test computers, we installed BIND 9.4.1-P1 and configured it to be authoritative for PT, COM.BR, and NL. We configured BIND to act as an authoritative server, with the following configuration:

```
options {
  listen-on { 204.152.187.83; };
  check-sibling no;
  recursion no;
  fetch-glue no;
  allow-recursion { none; };
  acache-enable yes;
  max-acache-size 128M;
};
```

3.2. Test methodology

We began with some preliminary tests to determine whether or not the size of the zone file being served had an effect on server performance. We were not able to measure any difference in server response rates over a 50:1 ratio of zone file size. We believe that if we had used a zone file that was larger than the amount of physical memory on the server, there would have been significant performance degradation. After concluding that zone file size did not matter, we used the .PT zone for further testing because it was not tedious to copy it from machine to machine during server reconfiguration.

We used a 1-hour test data stream that was captured from queries to ns-ext.isc.org. We extracted those queries that enquired of the .PT zone. There were 1.13 million such queries in the test stream. We sent this query stream in turn to each of the test servers using the [queryperf](#) program. We measured the length of time that it took each server to answer all of the queries in this query stream, and from that determined the average query response rate at which the server breaks down and is no longer able to process further requests, for each operating system.

3.3. Results

This table shows the approximate average number of queries per second processed by BIND 9.4.1-P1 running on the listed operating system using the testbed hardware in the configuration shown at the beginning of this page. The query rate shown is the 'breaking point' capacity such that the server would be forced to drop queries if it received them any faster (on average).

Server capacity at breaking point	
OS	Queries/second
Linux Gentoo 2.6.20.7	93,000
Linux Fedora Core 2.6.20.7	87,000
FreeBSD-7-CURRENT 200708	84,000
FreeBSD-6-stable 200708	55,000
FreeBSD 6.2-RELEASE	51,000
Solaris-10 DevelExpr 5/07	50,000
NetBSD-4.0-Beta 200708	42,000
OpenBSD 4.1-snap-20070427	35,000
Windows 2003 Server	22,000
Windows XP Pro64 5.2.3790 SP2	20,000

To determine whether or not there were performance differences in serving signed zones, we performed these tests using both signed and unsigned zone files. We did not test signed zones under all operating systems; we did this test using FreeBSD 6.2, making the assumption that relative speed differences would be the same across operating systems. Our test version of the unsigned zone file for .PT is 4.8 MB; the signed version of that file is 33.9 MB. In our test stream of 1.13 million queries we found no difference in the speed at which BIND 9.4.1-P1 responds to queries served from a signed version or unsigned version of the zone. There were differences in query size and total network traffic:

Network byte count per test (entire 1.13 million queries)

	requests	replies
unsigned zone	71.3 MB	141.2 MB
signed zone	83.7 MB	391.3 MB

Average packet size in bytes

	requests	replies
unsigned zone	63 bytes	125 bytes
signed zone	74 bytes	346 bytes

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4. Testbed physical construction

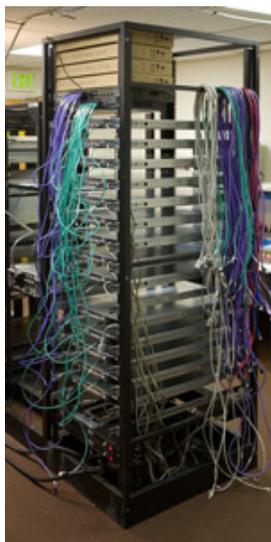
The logical design for ISC's DNS performance testbed is described in [ISC technote TN-2006-2](#). The equipment fits in a single 7-foot 19-inch four-post rack, and requires 3 15-amp 120VAC power circuits. Because the engineers performing tests can be located anywhere in the world, we are using [IPMI](#) to administer and control the computers. This requires having a separate Ethernet to carry the IPMI signalling, requiring each server to have two Ethernet connections. Although IPMI was devised and popularized by Intel, several open-source IPMI clients are available.

4.1. Description

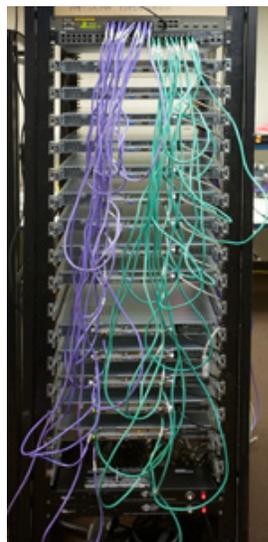
We mounted the power controllers at the bottom of the rack and the Ethernet switches at the top of the rack. Because IPMI is a 10MBPS protocol, we used a (less expensive) 10/100 switch for the IPMI network, and a nonblocking Gigabit switch for the data transport network. The servers are mounted on slide rails, and use every second slot in the rack for better cooling.

4.2. Photographs

Click on a photograph to pop up a larger view. These photographs were taken 4 April 2007.



DNS performance testbed rack seen from left rear corner. The cardboard boxes at the top hold racking supplies.



Testbed from the back. Lavender wires (left) are to the Gigabit data network; turquoise wires (right) are to the IPMI network. Power lines run inside a channel built in to the right edge of the rack.



Testbed seen from the front. Two of the servers are removed for OS testing. A power controller is visible at the bottom edge of this picture.



Close-up of the front panel of the servers, showing vendor model number (HP ProLiant DL140 G3). Note the air vent above the CD-ROM drive. Such vents are not common in 1U servers, but because of high CPU speeds, these servers need more air flow over the CPU heat sinks than a typical 1U.

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5. Test data stream

The purpose of this project is to test the performance of DNS servers under various conditions. This requires a baseline test stream, to which we will make various adjustments. A 48-hour baseline test stream was captured from the F-root server in Palo Alto on 15-17 November 2006.

5.1. Characteristics of baseline stream

We used tcpdump to capture all packets transmitted by the Palo Alto F-root server. UDP name service replies include the question to which they are the reply. The baseline tests will be run by reproducing the questions in this stream, one question per query packet. Other tests will require augmenting these queries with others (to increase the load) and replacing some of these queries with a different mix (to change the load without increasing it).

Below is the output from [this characterization program](#) run over the 15-17 November baseline stream.

```
Start: Wed, 15 Nov 2006 06:00:00 +0000, duration: 172800.00 seconds.
414931073 requests (38.8% failed)

Avg rate (requests/second) = 2401.2, 95%ile burst = 3011.0, Max burst = 3921.9
414342756 recursive queries (38.7% failed); 171887553 authoritative replies

23587274 TCP packets in 7906809 sessions (0 never closed) not analyzed (5.7% of total packets)

By type of query in default class:
251892742/ 60.7%  A          107157854 failed (42.5%)
41508116/ 10.0%  PTR         6860091 failed (16.5%)
34088345/  8.2%   AAAA        7343865 failed (21.5%)
23454402/  5.7%   SOA         21453572 failed (91.5%)
23030654/  5.6%   MX          6186641 failed (26.9%)
20844336/  5.0%   A6          166356 failed (0.8%)
7440925/  1.8%   SRV         7211917 failed (96.9%)
4729932/  1.1%   TXT         1613960 failed (34.1%)
3715926/  0.9%   NS          537492 failed (14.5%)
1902492/  0.5%   ANY         860207 failed (45.2%)
1111659/  0.3%                   1111659 failed (100.0%)
1020917/  0.2%   CNAME       193925 failed (19.0%)
50697/  0.0%   NAPTR       39748 failed (78.4%)
31239/  0.0%   TXT CHAOS   50 failed (0.2%)
22763/  0.0%   MAILB       22763 failed (100.0%)
19929/  0.0%   A HS        19929 failed (100.0%)
6004/  0.0%   X25         5917 failed (98.6%)
4225/  0.0%   Type0       485 failed (11.5%)
```

([click here](#) for the full chart, including the long tail)

Class ANY:

34296/ 0.0%

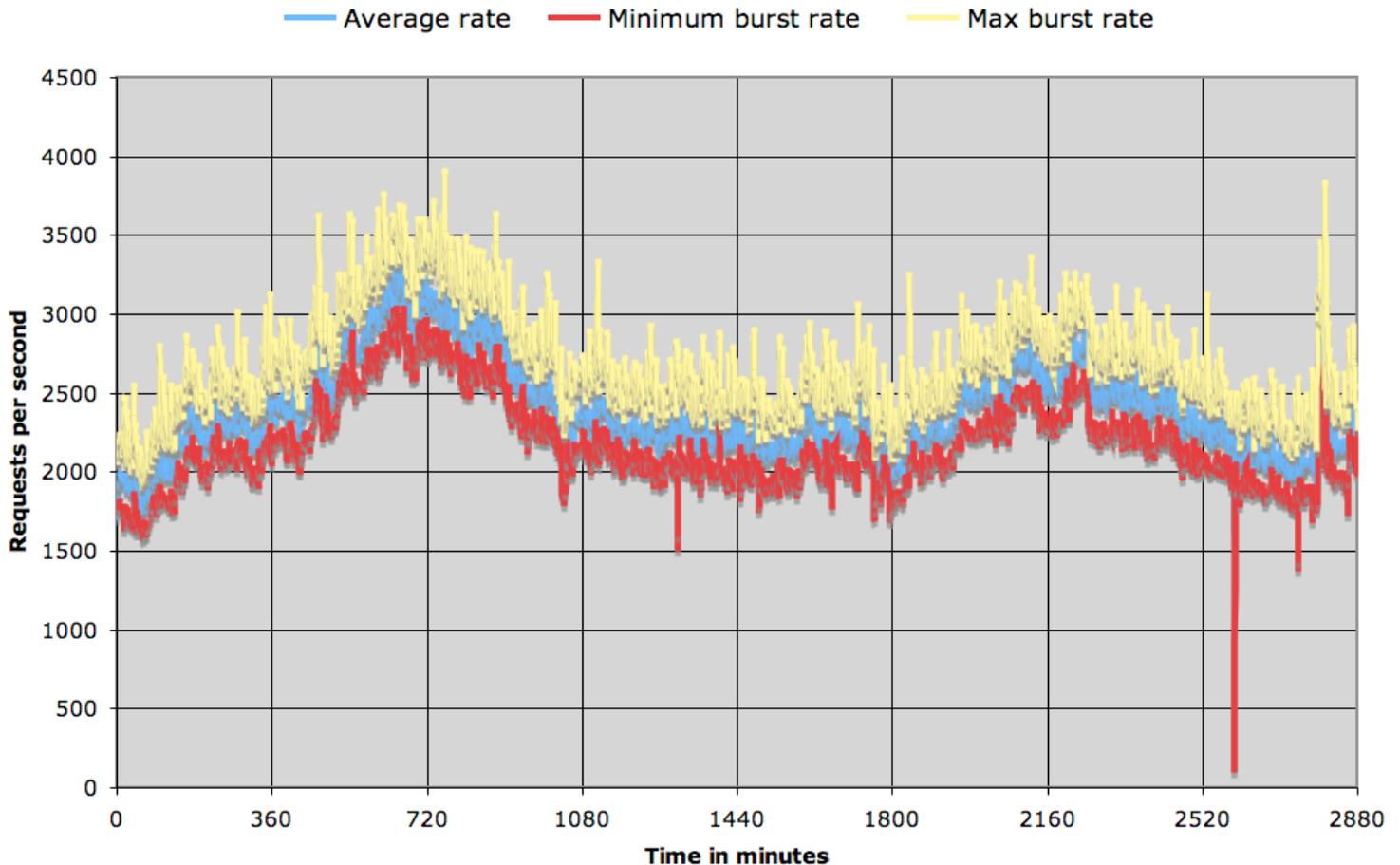
4451 failed (13.0%)

Return codes (percentages are of total query count):

159636174	38.5%	NXDomain
529285	0.1%	FormErr
504175	0.1%	update
79421	0.0%	echo
24769	0.0%	Refused
22763	0.0%	NotImp
2825	0.0%	notify
1788	0.0%	stat
178	0.0%	ServFail
43	0.0%	server,
32	0.0%	zoneInit
21	0.0%	updateA
8	0.0%	updateDA
8	0.0%	zoneRef
7	0.0%	inv_q
7	0.0%	op6
6	0.0%	op3
5	0.0%	updateM
1	0.0%	op7
1	0.0%	updateD
1	0.0%	updateMA

5.2. Plot of baseline stream against time

ISC baseline DNS test data set (15-17 November 2006)



6. DNS Protocol performance measurements

In earlier phases of this project we measured raw performance of proposed hardware platforms, and application performance of hardware/OS combinations. We used these measurements to select a test server system and we built a testbed using the selected systems as building blocks.

The ultimate purpose of all of this work is to measure the performance of the DNS protocols with the BIND software running on inexpensive commodity hardware. We spent time optimizing the speed of the server platform in order to ensure that we were getting the best possible results in our DNS protocol measurements.

In this section we describe the DNS protocol tests that we performed using our testbed and the results that we measured.

6.1. Test data

The test stream used is detailed in Section 5 of this report ("Test data stream"). The authoritative name servers were loaded with the COM zone as distributed by Verisign for 5 October 2007. Licensing restrictions prevent us from making that zone file public, but we can provide any suitably licensed research group with a copy of that file if Verisign no longer has a copy.

We wrote a program named "updgen", an update generator, which reads a zone file and produces from it an input file for the "nsupdate" program. Such input files must be created in the context of the zone file to which they are an update, in order to know the names of zones to be deleted and to make sure that added zones are not already there. During the testing various update streams were generated from various subsets of the COM zone. A tar file of the updgen program that generated them is at ftp://ftp.isc.org/isc/dns_perf/updgen.tar

6.2. Test conditions

6.2.1. Test systems used

The physical configuration of our testbed is described in [ISC Technote ISC-TN-2006-2](#). There are additional test conditions that we have imposed in order to make the tests as realistic as possible. The logical and network configuration is described at the beginning of the ["Operating system evaluations"](#) section.

A production name server would never be run with a physical RAM size that would cause it to swap. It would be purchased with enough memory for the entire application to be resident. Budgetary constraints limited our servers to 16GB of RAM. For some tests that required us to divide the test zone into slices, each of which can fit into physical memory. The slicing technique is widely used by search engines for the same reason; swapping introduces unacceptable performance delays.

All computers in the testbed were loaded with identical copies of FreeBSD 7.0-RELEASE, and name server computers were running BIND 9.4.2. Test data was transmitted using the version of queryperf that was bundled in the BIND 9.4.2 release (see below under "Sending test data").

6.2.2. Test data used

For queries-per-second measurements and DDNS update measurements we found that the COM zone could be divided into 2 pieces that did not cause swapping. For full-scale queries-while-updating measurements we found that the COM zone needed to be divided into 3 pieces.

The COM zone file that we used for these tests is 5.8 GBytes, unsigned. A signed version of that file is 15GBytes. Each unsigned half of the zone file is 2.9GBytes but causes BIND 9.4.2 to occupy 12.2GBytes of memory before answering any queries.

Query test streams were partitioned to match the slices of the zone file, using a simple awk command analogous to this one, which builds the subset of the queryperf file that corresponds to the 2nd slice of a 3-slice partition:

```
cat com.queryperf | awk '
{
    NAME=$1
    QTYPE=$2
    N=split(NAME,BurstNAME,"\\.")
```

```

Part2=tolower(BurstNAME[N-1])
if ((Part2 <= "f") || (Part2 > "n")) {
    next;
} else {
    print;
}
}
' > com.3part.g-n.queryperf

```

6.2.3. Sending test data

Server performance tests were executed by using the queryperf program (part of the BIND 9 distribution) on a machine dedicated to sending test data. We determined that a single queryperf process on this hardware base can send 46,000 queries per second under FreeBSD 7.0-RELEASE, and that if there are two queryperf processes running (either on one sender computer or two) that they can, combined, send 60,000 queries per second. Further addition of additional queryperf processes did not increase the test rate beyond 60,000 queries per second emitted from that server. In other words, a single load generator in our testbed cannot test at a rate faster than 60K queries per second in our configuration. We have two load generator computers and can if necessary use the "DNS Tender" as an additional source of load.

Note that in our testbed the load-sending computers have 4 CPU cores. When one queryperf process is sending at its maximum speed of 46,000 queries per second, the "top" system command indicates 5% idle time and a weighted CPU usage (WCPU) of 86%. With two queryperf processes running, idle time on the 4-processor system drops to 0.2% idle and the weighted CPU usage is 91%. Adding additional queryperf processes beyond these do not change the numbers from the 2-process measurements. This causes us to believe that this is an OS limit, but we did not investigate the reason for that limit.

6.2.4. Note

Performance of zone signing and re-signing is not part of this study. Current trends (2008) are towards hardware accelerator cards and incremental re-signing. We measured neither, except incidentally, during which we noted that our hardware platform was able to sign the entire COM zone (the edition that we are using) in a bit more than 2 hours, and that the signed zone files are about 2.6 times bigger than the unsigned files.

6.3. Test results

6.3.1. Simple queries of the COM zone

To fit into the physical memory available on our test servers, the COM zone was divided into two slices, each containing half of the zone. We ran the tests using BIND 9.4.1-P1 on several different OS configurations, all using the same hardware with the same BIOS settings. Numbers are the number of queries per second that each server computer was able to process at maximum load, averaged over 5 runs with the same data.

Average queries per second answered by 1 server at maximum load, unsigned zones

	COM 1st half	COM 2nd half
Linux-Fedora	80872	76531
FreeBSD-7-RC1	75362	74993
Linux-Gentoo	68881	71565
Solaris-10 edition of 8/07	64994	62915
Solaris-10 edition of 5/07	62248	59807
FreeBSD-6.2-Stable	56461	55271
FreeBSD-6.2-Release	53555	52700
NetBSD-4-current	31670	32589

Since these measurements are per-server reply rates, the overall testbed is capable of

responding to 1 million queries per second using our hardware and software configuration. At that rate it will consume about 4 Gbits/second of outbound network bandwidth, which means that the network speed would be the limiting factor of pure query speed for a production system built using this design.

6.3.2. Updates of the master server

The next measurement was to feed 10,000 DDNS update requests to the master server as fast as it would process them, measuring how long that took. We ran these tests using BIND 9.4.1-P1 on several different OS configurations, all using the same hardware with the same BIOS settings.

Rate at which BIND 9.4.1-P1 can handle DDNS updates to unsigned zone files, updates/second

	COM 1st half	COM 2nd half
FreeBSD-7-RC2	93.46	82.85
FreeBSD-6.2-Stable	89.52	77.34
FreeBSD-6.2-Release	471.70	446.23
NetBSD-4-Current	80.32	81.77
Solaris-10 edition of 5/07	87.80	83.54
Solaris-10 eidtion of 8/07	63.21	64.10
Linux-Gentoo	42.07	42.76
Linux-Fedora	22.29	15.07

The anomalous behavior of FreeBSD-6.2-Release is, we believe, an error in the FreeBSD autoconfiguration mechanism that caused BIND to be compiled without the file-system commits (fsync) that are required by [RFC2136](#). DNS updates are required to be committed to nonvolatile storage before the response is returned (RFC2136 section 3.5). The underlying hardware is not capable of that many committed file system writes per second, so the FreeBSD-6.2-Release tests could not have been committed to nonvolatile storage. We have no explanation for the anomalously slow performance under Linux-Fedora.

6.3.3. Queries of authoritative servers while they are being updated

The final test was to combine the previous two, and measure the rate at which an authoritative server can respond to queries while simultaneously being updated via IXFR from a master host which is itself under continuous update at a controlled rate. As noted above under "Test conditions", these tests were made with the COM zone divided into thirds.

We found that the test version of BIND that we were using (9.4.2) periodically paused to write safety copies of the updated zone information to stable storage. In our configuration that is not necessary because the production servers do not have the master copy of the zone information. We made a minor modification to BIND 9.4.2 so that it did not perform such writes, and with that modification in place, it ran nearly as fast when serving queries from a zone under constant update as it did when serving queries from a static zone. The modifications are available as a patch from ISC (contact info@isc.org) and will probably be included in a future version of BIND.

Query answer rate maxima while simultaneously processing DDNS updates

	DNSSEC disabled	DNSSEC enabled
No updating	69,400	61,200
Under update at 4 updates/sec	67,600	60,100
Under update at 8 updates/sec	68,100	58,500

Under update at 10 updates/sec	67,400	58,000
Under update at 32 updates/sec	60,900	54,900

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7. Conclusions

These results are encouraging, because they show that open-source software and commodity hardware are up to the task of providing full-scale production name service on the largest zones in existence. There are several obvious conclusions that can be drawn from them.

- Commodity hardware with BIND 9 software is fast enough *by a wide margin* to run large production name service, provided that it has enough physical memory to hold the zone data.
- The rate at which the COM zone experienced changes during 2006-2008 (typically 2-4 updates per second) is inconsequentially small in terms of the amount of processing power needed to handle those updates with RFC2136-compliant protocols such as those implemented by BIND 9.
- With minor changes to BIND 9 software, it can serve queries from a zone under update as rapidly as it can serve queries from a static zone.
- The query processing rate for signed zones is essentially the same as the query processing rate for unsigned zones, but it requires more physical memory to serve queries from a signed zone because they are larger.

Our testbed is available to qualified DNS and protocol researchers who wish to repeat our experiments or run other experiments; contact info@isc.org to make arrangements.

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Appendix A. Software availability

Very little custom software was necessary for this project. There are two packages developed for it:

- A rate-limited version of the Unix "cat" program that is used to control the rate at which updates are fed to name servers. It has been tested and found to be quite accurate over an extremely wide range of speeds, from one update per hour to tens of thousands of updates per second. It is in ftp://ftp.isc.org/isc/dns_perf/rlcat.tar
- A simple script to generate name-server update test streams from zone files. In order to have repeatable tests, we need to have update test streams. Updates include both adds and drops; a record needs to be in the zone before it can be dropped, and it ought not be in the zone if it is to be added as part of the test. For this reason, the test stream must be generated by processing of the zone that will be updated. The simple scripts that we used to do this are in ftp://ftp.isc.org/isc/dns_perf/updgen.tar

Our compilation and coding work was done on a FreeBSD 6.2 system, and these two packages are known to compile on FreeBSD 6 and 7 systems.

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