Design and Implementation of Highly Scalable E-mail Systems

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Apologies

- Less “Implementation”
- More “Fundamentals & Architecture”
  - This stuff is hard
  - This stuff is surprisingly hard, even for experienced professionals

- Nick unable to attend

Outline

- Review of Major Publications
- Review of Typical POP3 Implementations
  – Enhancements
- Contrast with IMAP
  – Implications of protocol differences
- Functional Architecture
- Detailed Architecture

Information Sources

- Academia
  - Build vs. Buy
    - Frequently re-invent the wheel
  - Small Scale
  - Occasionally revolutionary

- Commercial
  - Buy vs. Build
    - Time-to-market crucial
  - Large Scale
  - Usually Evolutionary
  - Any revolutions are usually in the area of scaling

Publication Categories

	Small	Large
Lists		√
MTAs	√	√
POP3	√	√
IMAP	√	○
Distr.	√	

Publications Review

- Large Mailing Lists
  - Kolstad97
  - Chalup98
- MTAs
  - Knowles98
  - Christenson99
  - Venema98
  - Golanski2000
- POP3 Mail Systems
  - Grubb96
  - Christenson97
  - Horman99
- IMAP Mail Systems
  - Stevens97
  - Beattie99
- Distributed
  - Yasushi99

Publications Review

- POP3 Mail Systems
  - Grubb96
  - Christenson97
  - Horman99

Review: Grubb96

- Problem
  - NFS mail spool/hub configuration using 7th edition mailbox (mbox) format for ~5000 users could not scale to ~20,000 users

Review: Grubb96

- Solutions
  - Front-end MXes handle incoming communications
  - Back-end servers handle mailboxes
    - Front-ends “trickle” feed via smaller number of cached connections to back-end servers
  - Separate syslog data onto separate disk
  - Tweak kernel, NFS server, & NFS client settings
  - Change client config to use mailhub name based on userid via DNS CNAME records

Review: Grubb96

- Solutions, continued
  - Implement additional mailhubs to serve chunks of user community based on CNAMEs
  - Turn on POP3 & IMAP2bis w/ 7th edition mailbox (mbox) format on each new “post office” server
  - Provide users with POP3/IMAP clients
  - Turn off NFS
  - Convert POP3/IMAP2 mbox → POP3/IMAP4 Cyrus on each “post office” server

Review: Grubb96

- Applicability
  - Does cover entire mail system, not just MTA
  - Doesn’t really tell us anything about how POP3/IMAP system is managed
  - Doesn’t scale
    - Users have to know too much about post office configuration
    - Requires CNAME RR for each customer
  - Mixes inbound and outbound services on same machines

Review: Christenson97

- Problem
  - Existing information on architecture for robust large-scale mail systems is scarce, doesn’t address key issues, and doesn’t scale to required levels

Review: Christenson97

- Solutions
  - Front-end MXes handle external communications
    - Secondary MXes do not attempt delivery to back-end, in case there is a problem with deliveries
    - Front-end MXes do not authenticate recipient names
  - **<u>All</u>** machines are dataless
  - Modify LDA to handle authentication methods, mailbox formats and quotas

Review: Christenson97

- Solutions, continued
  - Back-end servers <u>**do**</u> accept outgoing SMTP mail
    - Do not do local delivery, pass to inbound MXes instead
    - POP3 code must also be modified to know about authentication methods and mailbox format
  - All data (mailboxes and *sendmail* `mqueues`) stored on NetApp NFS servers
  - Mail spool directories hashed and split across multiple NFS servers

Review: Christenson97

- Solutions, continued
  - Dynamically balance mailboxes or expand capacity
    - Both POP3 daemon and LDA know about “old” vs. “current” mailbox location
    - POP3 daemon moves mailbox if necessary
  - POP3 & LDA modified to use database for user authentication, avoiding use of `/etc/passwd`
  - Cluster & fail-over for user authentication database

Review: Christenson97

- Solutions, continued
  - NFS file locking doesn't work reliably
    - Replace w/ lockfiles on separate shared NFS server
      - Uses semantics of `open()` system call with exclusive write
  - Lock system needs to be replaced to scale further
    - Custom clustered servers w/ shared RAID & unbuffered writes
    - Query different lock servers for different ranges of mailbox names

Review: Christenson97

- Applicability
  - Does cover entire mail system in centralized fashion
  - NFS servers are SPOFs
  - UDP & RPC are major security hazards
  - Customized code is expensive to maintain
  - Specific to POP3, does not cover IMAP

Review: Horman99

- Goal
  - Define architecture to scale mail systems transparently to multiple servers

Review: Horman99

- Solutions
  - Multiplex SMTP
    - Single layer
      - If recipient not local, must forward to correct server
      - With growth, amount of forwarding approaches 100%
    - Dual layer
      - No local recipients on front-end servers
      - Must always forward to correct back-end server
    - Add layer 4 load-balancing switches to hide number of machines accepting SMTP connections

Review: Horman99

- Solutions, continued
  - Multiplex POP3 & IMAP
    - Single layer
      - Must handle local connections
      - Must also proxy for remote connections
    - Dual layer
      - Dedicated content-free proxies

Review: Horman99

- Solutions, continued
  - Mailbox migration
    - Calculate metric for each server over reasonable time
    - Migrate only if a server deviates significantly from avg.
    - Order users by decayed metric cost
      - How long are migrations remembered?
      - How long since this mailbox migrated?
    - Generate user list probabilistically

Review: Horman99

- Solutions, continued
  - Mailbox migration, continued
    - Move from most heavily loaded server to least heavily loaded server(s)
    - Move only if result would not push recipient over average
    - Continue with next most heavily loaded server until no more migrations are possible

Review: Horman99

- Applicability
  - Covers only POP3 and not IMAP
  - Proper load balancing requires programming for peaks, not long-term averages
  - Focuses exclusively on “free” or “cheap” solutions
  - Too much time/space spent on less important issues
  - Not enough detail provided where needed

Publications Review

- IMAP Mail Systems
  - Stevens97
  - Beattie99

Review: Stevens97

- Statistics
  - 60,000 accounts
  - 4,000 peak concurrent logins
  - 1.4 million logins per month
  - 500,000 messages/day
  - 1,083 peak messages/minute
    - 65,000 peak messages/hour

Review: Beattie99

- Goals
  - Implement and document replacement mail system for ~30,000 users
    - Reliable
    - Secure
    - IMAP & SMTP
    - Web interface available
    - Quotas

Review: Beattie99

- Solutions
  - Mix & match software on cluster of commodity computers running Unix-like OS
    - UW imapd
    - Exim
    - Apache/mod_perl
    - WING (Web IMAP/NNTP Gateway)
    - PostgreSQL
    - BIND
    - Custom account & cluster management tools

Review: Beattie99

- Solutions, continued
  - Two front-end servers are firewalls & nameservers
    - Configured for fail-over
  - IMAP servers hold all per-user filestore
    - IMAP, POP3, & SMTP (public)
    - NFS export to other nodes (private)
      - Vacation messages
      - Forward files
      - Personal home page links

Review: Beattie99

- Solutions, continued
  - WING servers hold only temporary data
    - HTTP (public)
    - IMAP & NFS to IMAP/NFS servers (private)
    - SQL to front-end/firewall servers (private)
  - Each user has DNS entry
    - `username.herald.ox.ac.uk`
    - CNAME alias to home IMAP node

Review: Beattie99

- Solutions, continued
  - Front-end machines are
    - Cluster nameservers
    - SMTP & HTTP login gateways
    - DBMS servers for all user config data
    - Generate mailer tables and push to other nodes

Review: Beattie99

- Solutions, continued
  - Security
    - Front-ends are firewalls
    - IMAP & WING servers trust front-ends 100%
    - IMAP servers export `~foo/wing` directory owned by `httpd` for each user *foo*
      - Automap games to handle mounts
    - Break-in on WING servers allows modification of forward files, vacation messages, & personal links but **NOT** mail

Review: Beattie99

- Solutions, continued
  - Failure analysis
    - IMAP
      - Mail stored on RAID5
        - » Immune to single disk failure
        - » If node dies, all users on that node lose access
    - WING
      - Current sessions die
      - 1/n login attempts fail until server manually removed from lists
    - Switch = SPOF

Review: Beattie99

- Solutions, continued
  - Failure analysis
    - Front-end
      - DNS continues
      - IP traffic dropped but can reconnect
      - SQL failover currently manual
        - » Lose config changes since last sync
  - Changes
    - Added outbound mail relay servers to speed up acceptance of mail from dumb clients

Review: Beattie99

- Statistics
  - Recent average week
      - 2 IMAP servers, 2 WING servers
    - 82,000 total connections to IMAP servers
    - 113,000 mail deliveries by IMAP servers
      - 95,000 local
      - 18,000 outgoing
    - 26,000 outgoing messages from WING
    - 66,000 IMAP sessions (including 38,000 WING)
    - 120,000 POP3 sessions

Review: Beattie99

- Applicability
  - Very small scale
    - We have ~7.5x their # of users
    - We do ~38x their number of inbound mail messages
    - We do ~35x their number of local mail deliveries
    - We do ~64x their number of outbound mail messages
    - We don’t know how many more POP3 sessions we do
      - Too expensive too track

Review: Beattie99

- Applicability
  - Not scalable, not enough functional decomposition of services
    - Front-end/firewall/nameserver/user meta-data server doing <u>**way**</u> too much
    - IMAP servers should not be used as outbound mail relays
    - IMAP servers should not be used as NFS servers

Publications Review

- Distributed
  - Yasushi99

Review: Yasushi99

- Goals
  - Build and describe distributed, replicated, clustered, automatically load-balanced, functionally homogenous mail system

Review: Yasushi99

- Solutions
  - Use commodity hardware and OS
  - Write all custom application code
  - Mailboxes fragmented at message level
    - Replicated across two servers
    - Distributed across as many as four servers
  - All servers run all protocols
    - SMTP in & out, POP3, IMAP, User metadata database

Review: Yasushi99

- Solutions, continued
  - Soft limit of four distributed servers can be exceeded if one or more nodes is down
  - Some affinity of distributed servers is maintained to reduce latency
  - Automatically discover new resources
  - Detect and route around failures automatically
  - Balance cluster automatically across all nodes

Review: Yasushi99

- Solutions, continued
  - Claims to be lock-free because POP3 and IMAP require only convergence to consistency over time
  - “Load” defined as boolean + integer
    - Disk full or not?
    - Total number of outstanding potential I/O requests
  - Node with full disk is always considered to be “very loaded”
    - Used only for reading and deleting mail

Review: Yasushi99

- Solutions, continued
  - Testing methodology
    - Avg. msg size 4.7KB w/ fat tail to 1MB
    - SMTP traffic = 90% of load
    - POP3 traffic = 10% of load
    - Compare against *sendmail* 8.9.3 + ids-popd-0.23
    - Custom load-generation programs
    - POP3 test program collects and deletes all mail for user
    - Linux async writes are used

Review: Yasushi99

- Solutions, continued
  - Testing results
    - One node w/ no replication and one IDE disk could handle ~23 msgs/sec.
    - Adding two SCSI disks to single node, it could handle ~105 msgs/sec.
    - Two nodes w/ one IDE and two SCSI disks each could handle ~38 msgs/sec. w/ replication, ~48 msgs/sec. w/ simulated NVRAM for coordinator log

Review: Yasushi99

- Solutions, continued
  - Testing implications
    - @ ~105 msgs/sec. per node, ~62 nodes could saturate 1Gbps network, w/ ~562 million msgs/day
      - ~6500 msgs/sec. aggregate
    - With replication, this drops to ~5200 msgs/sec. aggregate, and ~450 million msgs/day on ~108 NVRAM nodes or ~137 non-NVRAM nodes

Review: Yasushi99

- Applicability
  - Throws out all previous application work
    - 100% new, untrusted code
  - Can't list 100 IP addresses in DNS for POP services
    - Won't fit into 512 byte UDP packets
  - Can't list 100 IP addresses in DNS for MX services
  - Forced to use proxy front-ends or L4 load-balancing switches to hide the number of servers

Review: Yasushi99

- Applicability
  - Microsoft OSes only ever use the first IP address, then cache forever (until reboot)
  - Forced to use L4 load balancing switches
    - Must be set up in HA/failover mode
    - May have application proxies behind them
  - Some SMTP MTA or resolver implementations are equally dain-bramaged
    - L4 load-balancing switches in front of MXes

Review: Yasushi99

- Applicability
  - Can’t get around DNS UDP packet size restrictions with multiple IP addresses per name
    - If connection refused, skip to next name
    - Iff connection timed-out, go to next IP address for same name
  - At ~2 min. TCP timeout per IP address, 45 IP addresses = 90 minutes to timeout
    - If you have a queue runner fired off every 60 minutes, you ultimately wind up with all memory taken up and no mail flow

Review: Yasushi99

- Applicability
  - Did not use standard benchmarking tools
    - May or may not be valid to create own tools, but needs justification
  - Fundamentally, locking <u>**IS**</u> required
    - Users simply will not accept messages appearing and disappearing and reappearing again
    - Requires serialization which violates most basic principles espoused

Review: Yasushi99

- Applicability
  - Did not test suitable array of MTAs, POP3 daemons, message size and arrival distributions, mailbox sizes, etc…
    - Did not even prove special case, much less general case
    - Anybody can select bad special case and demonstrate superiority
    - To claim general superiority, you must test across a much broader array of variables

Review: Yasushi99

- Applicability
  - IMAP implementation is only a subset — does not include shared folders
    - Perhaps possible in small academic environment
    - Simply not acceptable in large commercial environment
  - SMTP server holds sender open while all writes are completed
    - Violation of RFC 1123, section 5.3.2?
    - All other MTAs accept first, then deliver in background

Review: Yasushi99

- Applicability
  - Each server must implement all protocols
    - Doesn't allow for scaling of each part independently
  - Load discovery protocol is broadcast-based
  - Uses Linux async writes
    - Violation of RFC 1123, section 5.3.3
    - Replication already used to address lower reliability of commodity hardware, OS, and custom application code

Review: Yasushi99

- Applicability
  - Peak sustained rates do not scale linearly
    - Msgs/sec. → msgs/min. → msgs/hr. → msgs/day
      - Msgs/hr. * 10 = ~ msgs/day

Review: Yasushi99

- Applicability
  - Good things
    - Splitting mailboxes at message level
    - Replicate messages to at least two servers
    - Distribute messages across up to four servers
    - Dynamically distribute messages to least loaded servers
    - Calculate “load” based primarily on current and potential disk I/O operations

Skynet Statistics

- POP3 Mail Server
  - 285,000 Accounts
  - 225,000 Mailbox files
  - 600,000 Aliases
  - 6800 Domains
  - 150 GB Total mailbox storage
    - 1 GB Overhead

Skynet Statistics

- POP3 Mailbox Sizes
  - 80,000 Empty
  - 690 KB Average
  - 9282 bytes Median (50th percentile)
  - 1.1 MB 90th percentile
  - 3.35 MB 95th percentile
  - 12 MB 99th percentile
  - 42.1 MB 99.9th percentile

Skynet Statistics

- POP3 Connections
  - 100 peak connections/attempts per second
  - 2300 peak connections/attempts per minute
  - 105,000 peak connections/attempts per hour
  - ??? peak connections per day?
  - 13.14 second typical daily average connection time
  - 300 Max total simultaneous connections allowed

Skynet Statistics

Millisecond response times (14 day sample)

Protocol	Min	Avg.	Max
SMTP	33	672	3600
POP3	28	185	949

Skynet Statistics

- Typical messages per day
  - 450,000 inbound SMTP
    - 450,000 POP3 mailbox deliveries
    - 200,000 webmail/freemail
    - 40,000 business SMTP
  - 400,000 outbound SMTP

Skynet Statistics

- Peak messages per hour
  - 48,000 inbound SMTP
  - 42,000 outbound SMTP

Skynet Statistics

- Typical message volume per day
  - 48 GB inbound
    - 25 GB POP3
    - 18 GB webmail
    - 4.5 GB business
  - 48 GB outbound

Skynet Statistics

- Average message sizes
  - 110 KB inbound
    - 60 KB POP3
    - 100 KB webmail
    - 120 KB business
  - 120 KB outbound

Protocol Implementation Analysis

- POP3
  - Typical implementation
  - Qpopper “Server Mode”
  - Indexed Mailbox
  - Login Frequency Limitation
  - Mailbox Directory
- IMAP Differences & Implications

Analysis: Typical POP3

- User login
- Lock mailbox
- Create temp file
- Copy mailbox to temp file
- Truncate mailbox
- Unlock mailbox
- Operate on temp file
  - New messages may come in to mailbox

Analysis: Typical POP3

- User logout
- If any messages are being retained
  - Re-lock mailbox
  - If mailbox not empty
    - Append new messages to temp file
    - Truncate mailbox
  - Merge retained temp file contents onto mailbox
  - Unlock mailbox
- Delete temp file

Analysis: Qpopper "Server Mode"

- User login
- Lock mailbox
- Operate on mailbox
  - New mail messages wait to be added to mailbox
- User logout

Analysis: Qpopper "Server Mode"

- Are messages being retained?
  - Yes
    - Create temp file
    - Merge retained contents of mailbox onto temp file
    - Move temp file to mailbox
  - No
    - Truncate mailbox
- Unlock mailbox

Analysis: Qpopper “Server Mode”

- Improvements
  - Big “win” if no mail is left on server
    - Virtually all synchronous meta-data operations eliminated
  - No “loss” if mail is left on server
- Issues
  - Still have to scan entire mailbox every time user logs in, even if only to tell them they don’t have any new messages

Analysis: Indexed Mailbox

- User login
- Lock index
- Stat index & mailbox
- If index newer, all questions can be answered from index
  - Only need to lock mailbox if messages are deleted

Analysis: Indexed Mailbox

- If mailbox newer
  - Lock mailbox
  - `lseek()` to last position specified by index, then scan and update index
- Otherwise, like Qpopper "Server Mode"

Analysis: Indexed Mailbox

- Improvements
  - Each message read from mailbox is handled by `lseek()` and large-size `read()`
  - Greatly increases use of read-ahead cache
  - Assumes that LDA appends only
  - Assumes that LDA & POP3 server are only methods of reading or writing mailboxes

Analysis: Indexed Mailbox

- Problem
  - Still have to update mailbox if messages are retained and message status changes
- Solution
  - In index, separately store header and body start+offset info
  - Store message status in index
  - Generate message status header info on-the-fly

Analysis: Indexed Mailbox + status

- Results
  - Twice as many read operations
  - Fewer write operations
  - More complex POP3 server
    - Probably a big win for leave-on-server

Analysis: Limiting User Login

- Problem
  - Some clients still login too frequently to check their mail
- Solution
  - Require that at least *X* minutes elapse before you allow updating of index
  - Tune *X* for pain threshold of your users

Analysis: Mailbox Directory

- Some POP3 implementations create a directory that comprises the mailbox, and store one message per file
  - Trades smaller number of larger I/O operations for much larger number of smaller I/O operations
  - Avoids mailbox locking issues
  - Creates message locking issues

Analysis: Mailbox Directory

- Problems
  - The I/O operations it creates in trade are all synchronous meta-data operations
    - The most expensive kind
    - The type we most want to eliminate, reduce, or optimize
  - May need to implement directory hashing within mailbox to avoid excessively large directories

Analysis: Mailbox Directory

- Problems
  - Typically has to scan entire directory tree to build mailbox status
    - Must know size of each message
      - Must `stat()` each file or have file size encoded in file name
    - Must know UIDL value for each message
      - Must open and read each file
  - Can solve these problems by using index
    - Still doesn't eliminate sync. meta-data updates

Analysis: Mailbox Directory

- Claim
  - More NFS-friendly
  - Avoids mailbox locking
  - Mechanism for creating filenames sufficiently unique to virtually eliminate collisions on files
    - Uses “create w/ exclusive ownership” semantics to detect

Analysis: Mailbox Directory

- Reality
  - Christenson97 shows that 7th edition mailbox (mbox) format can also be made NFS-friendly, using same trick
  - Still have issues with sync. meta-data updates
    - Now problem for NFS server vendor?
  - Does not solve locking problems with message changes, moves, or deletions
  - Mailbox locking not really a problem

Implications

- POP3
  - Only one reader process at a time
    - Can safely lock entire mailbox
  - Only one writer process at a time
    - Can safely lock entire mailbox
  - Long-term mail storage is local to user
  - Large sites may not allow "leave on server"
    - Otherwise mitigated by quota or expiration mechanisms

Implications

- IMAP
  - There **<u>will</u>** be more than one simultaneous reader and/or writer process
    - Cannot lock entire mailbox
    - Must lock at message level or below
  - Long-term mail storage is centralized
    - Only cached locally

Implications

- Solutions
  - Easiest way to deal with message locking is to avoid 7th edition mailbox (mbox) format
  - Use mailbox directory instead, but can use folders
    - One message per file
    - Some typical POP3 enhancements not applicable
  - However, so long as lock mechanism is shared by LDA & IMAP server, can avoid file locking and use database instead

Scaling Growth

- Problem
  - Number of users is increasing
  - Number of messages sent/received per user is increasing
  - Average size of messages is increasing
  - Length of retention of messages increasing
    - Due to centralized storage of mailboxes

Scaling Growth

- Result
  - Disk storage requirements increasing exponentially
  - Number of I/O operations increasing exponentially

Scaling Growth

- Mitigating Factors
  - Disk storage space increasing exponentially
- Complications
  - Disk rotational speed increasing
    - But not increasing very fast
  - Track-to-track latencies improving
    - But not improving very quickly

Scaling Growth

- Result
  - Disk storage requirements still increasing
    - Not quite as bad
  - Number of I/O operations increasing exponentially
    - Our main killer before
    - Will become bigger and bigger bottleneck

Scaling: Future Improvements

- Single Instance Message Store
  - If storing message per file, store message only once per machine and hard link other recipients to same file
    - Reduces I/O bandwidth requirements
    - Doesn’t reduce sync. meta-data updates since linking to an existing inode requires just as much directory update work as creating new file

Scaling: Future Improvements

- Multi-session Single Instance Message Store
  - Generate MD5 or SHA-1 hash of message
  - Already in system?
    - Yes
      - Compare binary files, store if different, link otherwise
    - No
      - Store
  - Further reduces disk storage capacity issues
  - **Increases** synchronous meta-data I/O

Scaling: Future Improvements

- Multi-session Single Instance in Bodypart Store
  - Recursively parse MIME message structure, store bodypart-per-file
    - For attachments, insensitive to trivial changes in body
    - Allows you to replace base64 or quoted-printable with binary
    - Allows you to “invisibly” compress data
    - Further reduces disk storage requirements
    - Still doesn’t address issues of sync. meta-data updates

Scaling: Future Improvements

- Use Database for Everything
  - Eliminates sync. meta-data I/O problems
- Problem
  - No database handles BLOBs properly
  - Large scale database reliability problems?

Scaling: Future Improvements

- Use Message "heap"
  - Use INN timecaf/timehash-style files instead of message-per-file
    - New message comes in
      - Append to one of small number of large files
      - Update database index
    - Message is deleted
      - Mark space as available
      - Reclaim empty space at time of reduced load

Scaling: Future Improvements

- Message “heap”, continued
  - Virtually eliminates all sync. meta-data updates
  - Could potentially be combined with previous single-instance-store ideas
    - Probably not worth it
  - Does increase maintenance overhead

Scaling: Future Improvements

- From Yasushi99
  - Break mailboxes into component messages
    - Replicate messages to at least two servers
    - Distribute messages across four or fewer servers
  - Doesn’t help address either disk storage or sync. meta-data issues
  - Does address issues of reliability, load-balancing, speed, and perceived quality of service

Scaling: Future Improvements

- Yasushi99, continued
  - Could be combined with INN timecaf/timehash-like message "heap"
  - Could calculate "load" for re-balancing of messages on different criteria
    - Old messages could be migrated to specialized servers with more disk space, perhaps less disk I/O capacity

Best Current Practice

- Per message store server
  - Single instance message store
    - Hard links for multiple recipients of same message
  - Hashed mailbox directories
    - Two base-32 chars per subdir = 1024 max per dir
      - Minimizes path length
  - Message locks in fast and reliable database
    - Berkeley db, not SQL

Best Current Practice

- Per message store server, continued
  - Most important headers and MIME structure in database
    - Most meta-data queries answerable from database
  - User mailbox on single server (cluster)
  - Archive all messages at appl. level, if req'd
  - Clustered servers for HA

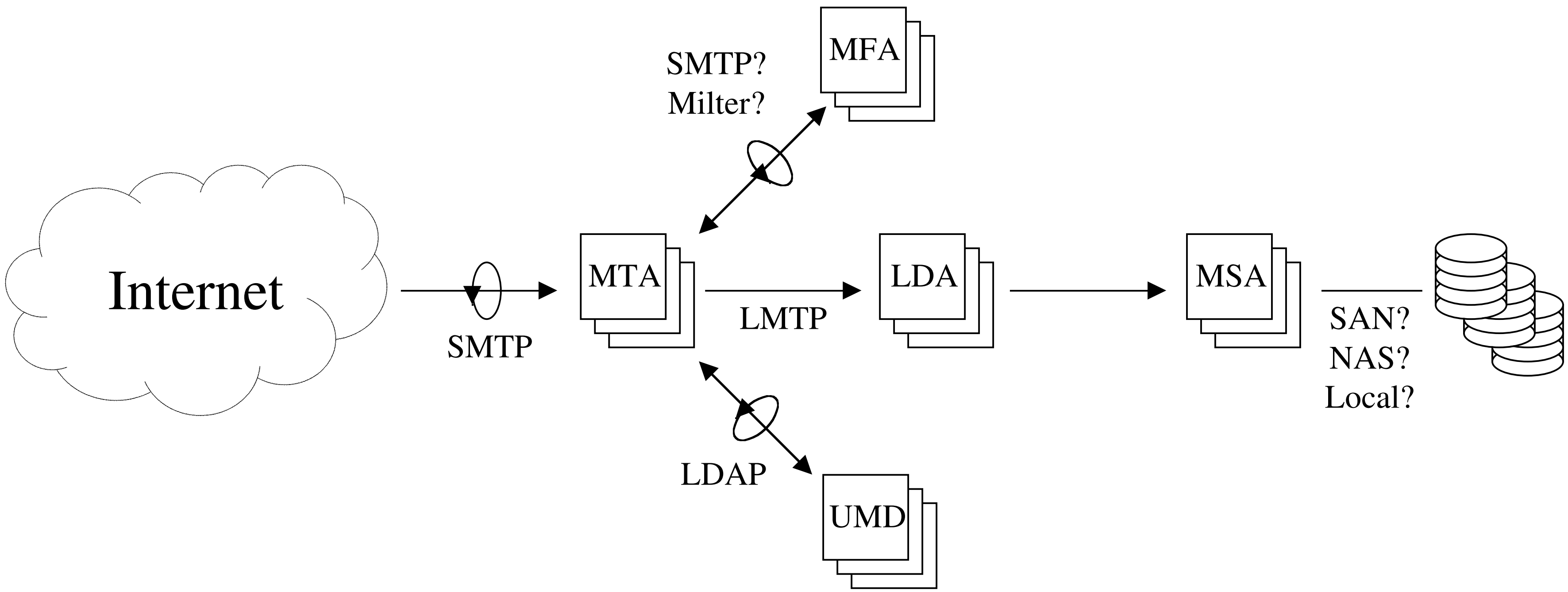
Best Current Practice

- User meta-data database kept outside of message store servers
- Minimize interface protocols
- Use application proxies to distribute traffic across *n* number of message store servers
- Use Layer 4 load-balancing switches in HA mode to hide number of application proxies

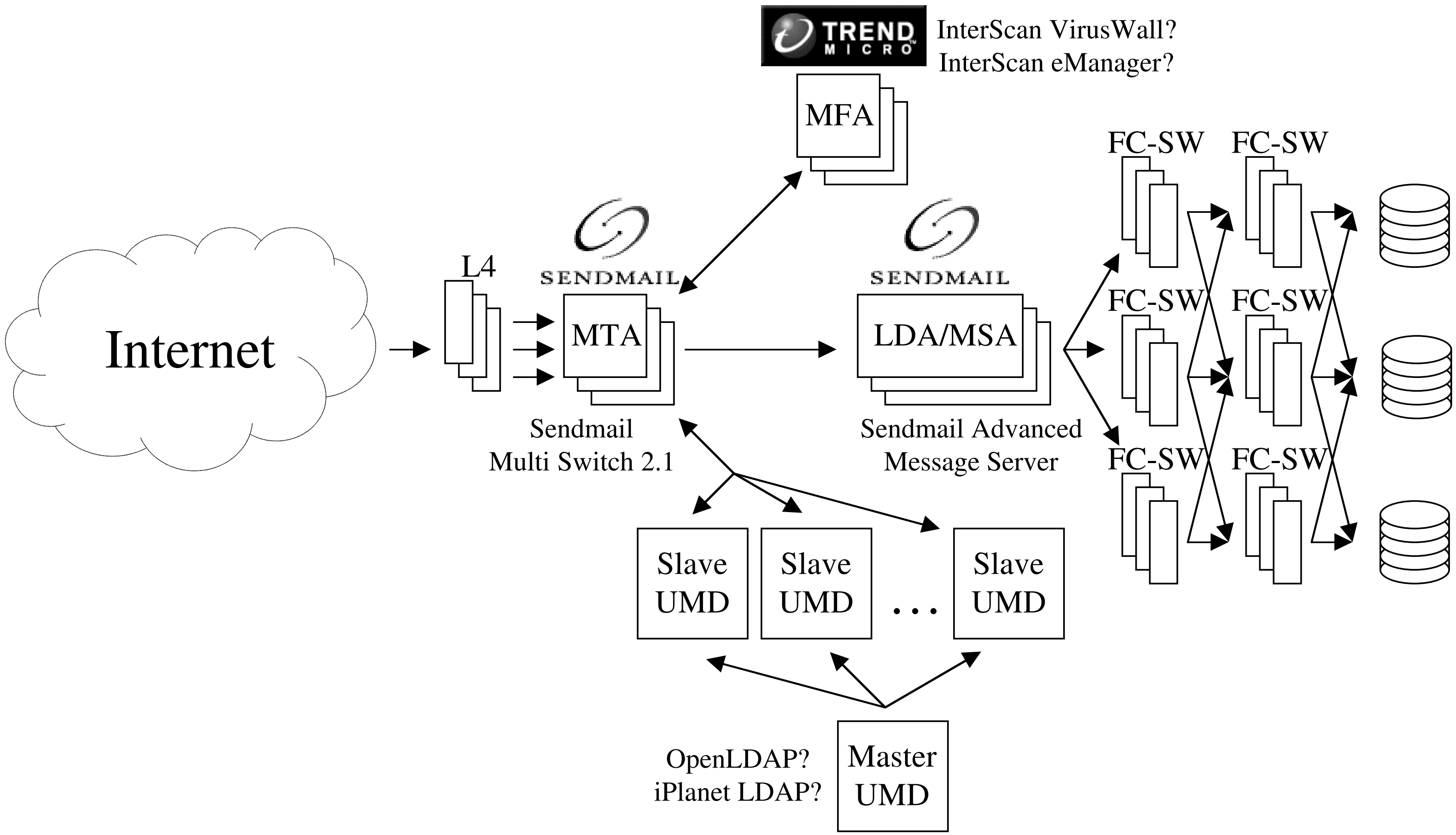
Best Current Practice

- Everything becomes LEGO™ building blocks
- However, scaling is still not quite linear
  - 1 million users = one servers
  - 10 million users ?= ten servers
  - 100 million users != hundred servers

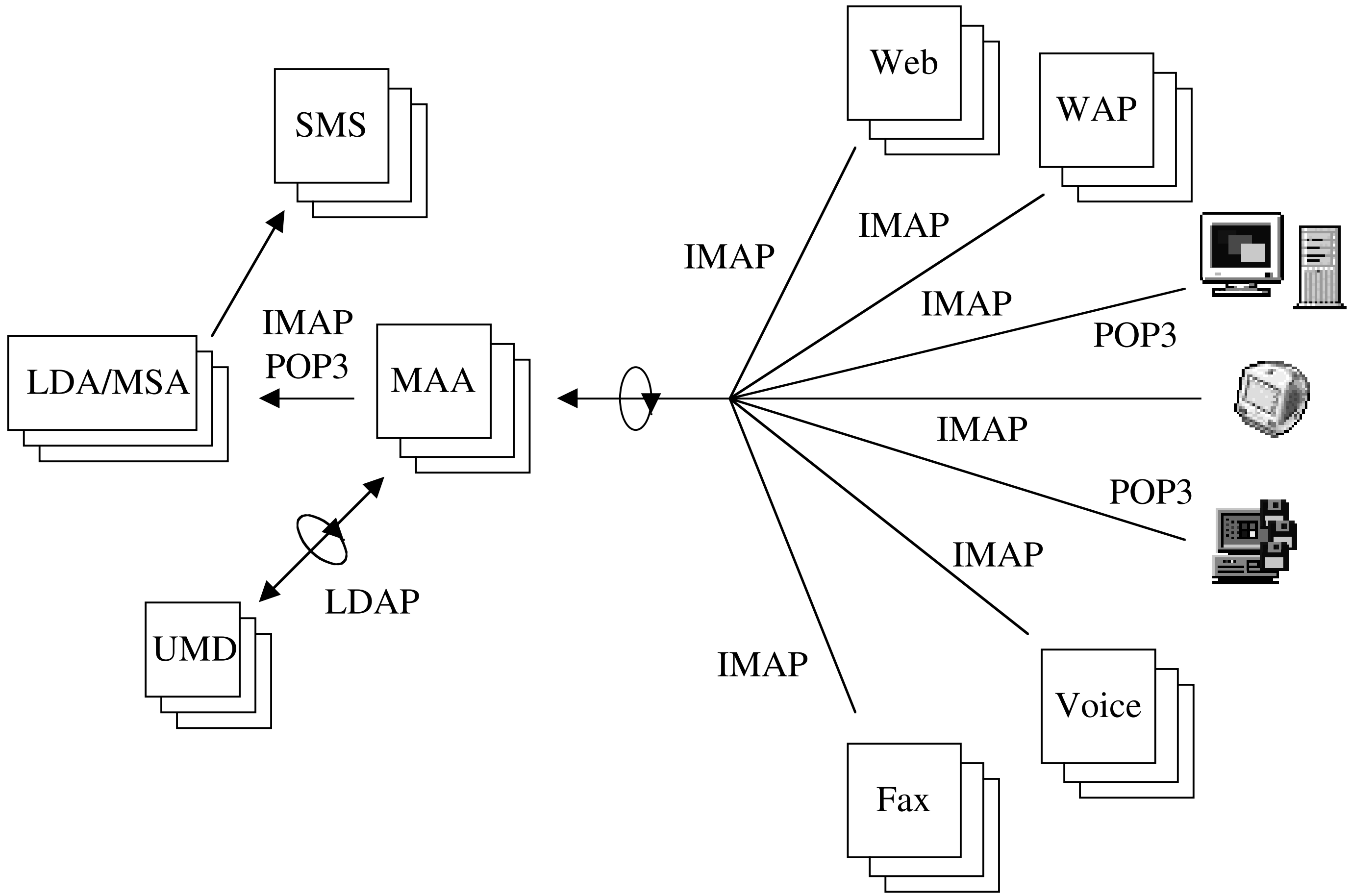
Functional Architecture: Storage



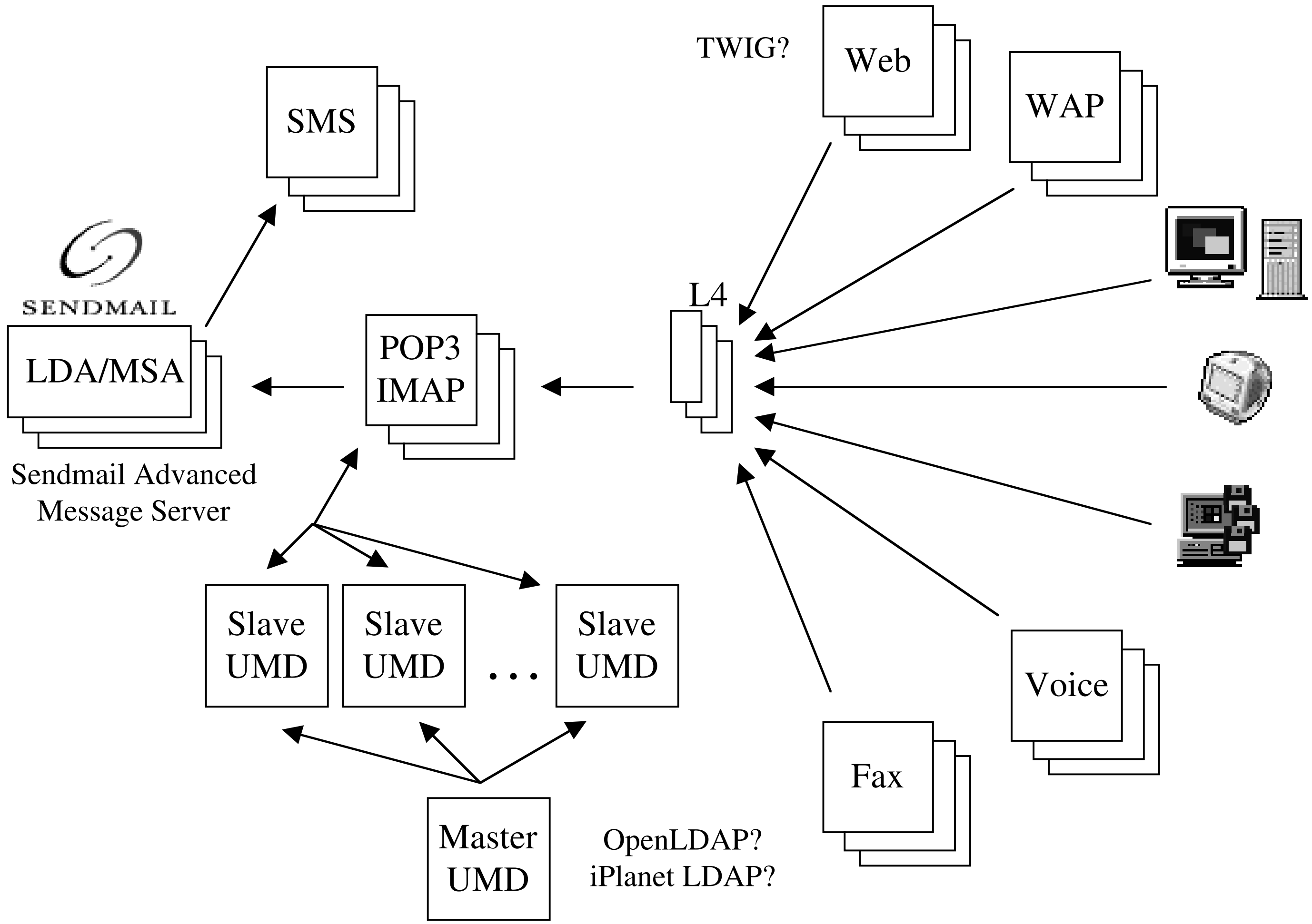
Detailed Architecture: Storage



Functional Architecture: Retrieval



Detailed Architecture: Retrieval



SMTP/POP3 Benchmarking

- Standard Performance Evaluation Committee
  - SPECmail2001
    `<http://www.spec.org/osg/mail2001/>`
- Russell Coker
  - postal
    `<http://www.coker.com.au/postal/>`
- Dan Christian, Mozilla Organization
  - mstone
    `<http://www.mozilla.org/projects/mstone/>`

SMTP/POP3 Benchmarking

- Wietse Venema
  - smtpsink & smtpstone
    `<http://www.postfix.org/>`
- Yasushi Saito
  - porctest
    `<http://porcupine.cs.washington.edu/porc1/distribution.html>`
- Stalker Software
  - SMTPTest & POP3Test
    `<http://www.stalker.com/MailTests/>`

SMTP/POP3 Benchmarking

- dREI C Systems
  - DeJam Analyzing Suite (Java)
    `<http://www.dejam.de/>`
- Quest Software
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    `<http://www.benchmarkfactory.com/benchmark_factory/>`
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Questions?

- Slides **<u>will</u>** be made available
  - Via USENIX/SAGE web site
  - Or via my “papers” sub-page

    `<http://www.shub-internet.org/brad/papers/>`
  - At very least, will be linked from my “papers” sub-page