Modeling and Simulation of Tape Libraries for Hierarchical Storage Management Systems

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Universität Hamburg
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Overview

Motivation

Long-term storage and upcoming challenges for exascale supercomputers.

Why long-term storage?

- Preservation of human knowledge
- Preservation of cultural goods (arts, literature, music, movies, etc.)
- Archival of organizational data (e.g., raw movie footage)
- Preservation of personal documents and photos
- Compliance with legal requirements

Challenges for scientific users (e.g., DKRZ, CERN):

- Supercomputers highly parallel
- Produce data faster than can be stored persistently
- Producing insight was expensive and results should be preserved
- Deep storage hierarchies to balance cost and performance
- Scientific users already approaching exascale storage systems
- Innovation mostly dependent on vendors

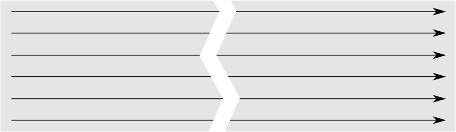
History of Magnetic Tape Storage

1890s	Valdemar Poulsen invents **Magnetic Wire Recording**. Only limited use through the 1920s and 1930s, but popular from 1946 to 1954. One hour of audio recording required about 2200m of thin wire (0.10 to 0.15 mm).
1928	Fritz Pfleumer uses ferric oxide ($Fe_2 O_3$) as a recording medium. The approach is improved by AEG and reel-to-reel tape recorder for tapes produced by BASF is released. The method was kept secret during World War II.
1947	John Bardeen, Walter Brattain and William Schockley invent the **Transistor**
1950	Reel-to-Reel recording and playback devices become affordable enabled by transistors.
1951	Data storage UNIVAC I (UNIVersal Automatic Computer I) 128 chars per inch, written on 8 tracks
1952	IBM introduces the first magnetic data storage devices often referred to as *7 Track*.
1962	Phillips invents **Compact Cassete** for audio recordings, though it was also sometimes used for data storage.
(1956)	*Focus on tape from here on, as other media such as floppies and diskettes are beyond the scope of the section.*
1959	Toshiba introduces helical scan as tape draw speed determines the maximum recordable frequency. The signal may not get imprinted which was a problem for video recording. Sony later pushed this technology further forward.
1980s	Introduction of **automated robotic tape libraries** by Sun with the Brand StorageTek. Tape is suddenly accessible within tens of seconds instead of hours or days. The term *nearline storage* gains traction to describe such systems.
1990s	Linear Tape Open (LTO) Consortium is founded. LTO is todays most wide-spread format.

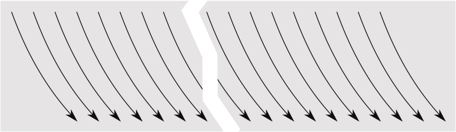
Competing On-Tape Data Layouts

Linear-serpentine provides high data densities and scaleable throughput.

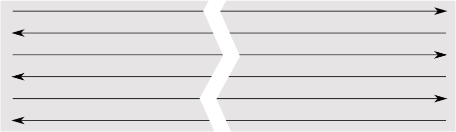
linear



helical-scan

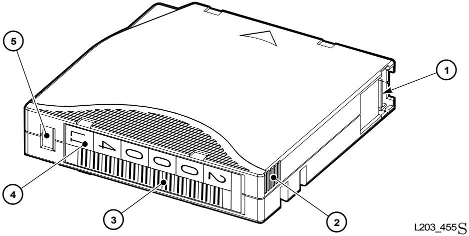


linear-serpentine



LTO Tape Format

Linear Tape Open - Standards are beneficial for customers and vendors.



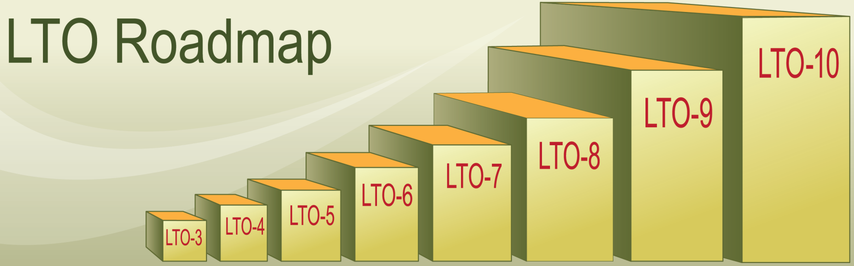
Sun (2006)

Gen	Thickness (μm)	Length (m)	Tracks	Bit Density	EEPROM
1	8.9	609	384	4880	4 kb
2	8.9	609	512	7398	4 kb
3	8.0	680	704	9638	4 kb
4	6.6	820	896	13250	8 kb
5	6.4	846	1280	15142	8 kb
6	6.1	846	2176	15143	16 kb
7	5.6	960	3584	NA	16 kb

- LTO-6: 0.011 USD/GB native, 0.005 USD/GB compressed, (2.5 to 6 TB)
- LTO-7: 0.028 USD/GB native, 0.012 USD/GB compressed, (6 to 15 TB)

Linear Tape Open (2)

LTO release strategy: Backwards-compatibility; New generation every 2-3 years.

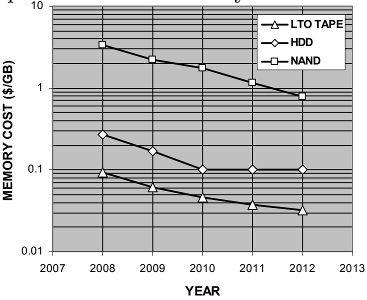


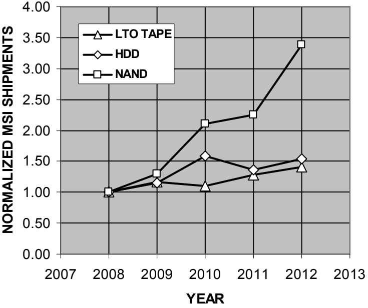
	LTO-3	LTO-4	LTO-5	LTO-6	LTO-7	LTO-8	LTO-9	LTO-10
Shipment Year	2005	2007	2010	2013	2015	TBD	TBD	TBD
Native Capacity	400GB	800GB	1.5TB	2.5TB	6.0TB	Up to 12.8TB	Up to 25TB	Up to 50TB
Compressed Capacity	800GB	1.6TB	3.0TB	6.25TB	15TB	Up to 32TB	Up to 62.5TB	Up to 125TB
Native Transfer Rate	80 MB/s	120 MB/s	140 MB/s	160 MB/s	300 MB/s	Up to 472 MB/s	Up to 708 MB/s	Up to 1100 MB/s
Compressed Transfer Rate	160 MB/s	240 MB/s	280 MB/s	400 MB/s	750 MB/s	Up to 1180 MB/s	Up to 1770 MB/s	Up to 2750 MB/s

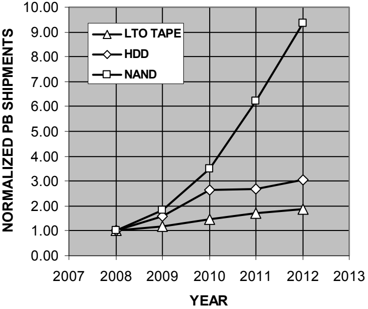
(Spectralogic, 2016a)

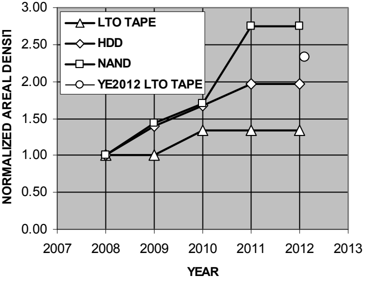
Future of Tape

Is tape obsolete? Probably not for another decade or two. (Fontana et al., 2013)





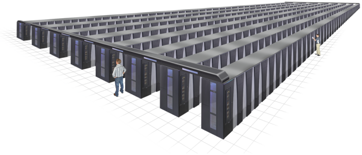




Automated Tape Libraries

Archives; Data reduction and compression; Encryption; Self-describing tape formats;

IBM TS3500 Library Complex (IBM, 2011b)



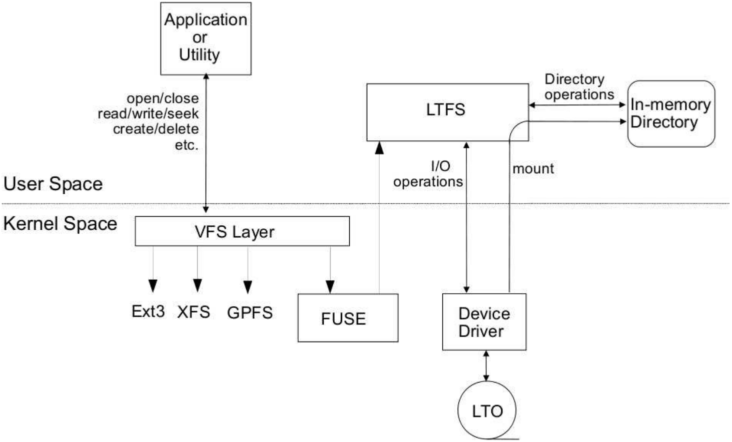
TFinity Library Complex (Spectralogic, 2016b)

StorageTek SL8500 Library Complex (Oracle, 2015)

Scalar i6000 Library Complex (Quantum, 2015)

LTFS

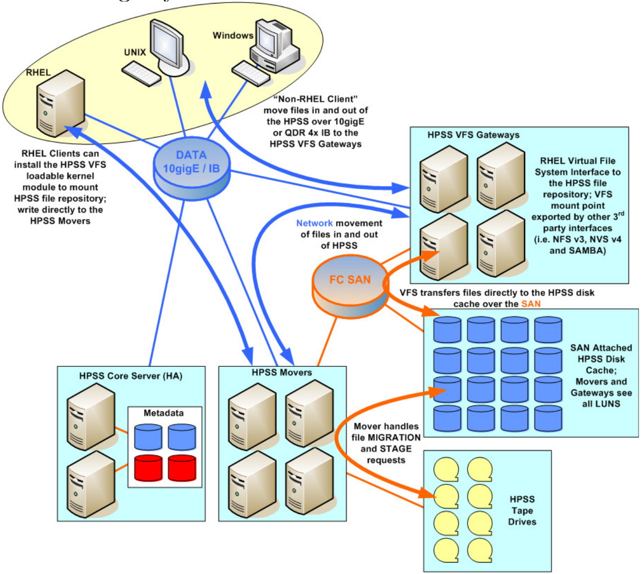
Linear Tape File System - Portable and self-describing cartridges



(Pease et al., 2010)

HPSS

High Performance Storage Systems



(IBM, 2011a)

Goals of the Thesis

A framework to simulate automated tape library systems.

1. Development of **models** to describe key aspects of tape systems
2. Simulation of tape systems using **discrete event simulation**
3. Virtual monitoring system for simulation to **collect key metrics**.
4. Reporting and data analysis workflows for hierarchical storage types
5. Tooling to gain insight on the benefits of different configurations for HSM

More informed answers to questions like:

- How to deploy a cost-efficient system from a data center perspective?
- What are the minimal requirements to meet a specification or QoS?
- Which features do we need for the next generation of systems?

1. Motivation and Background

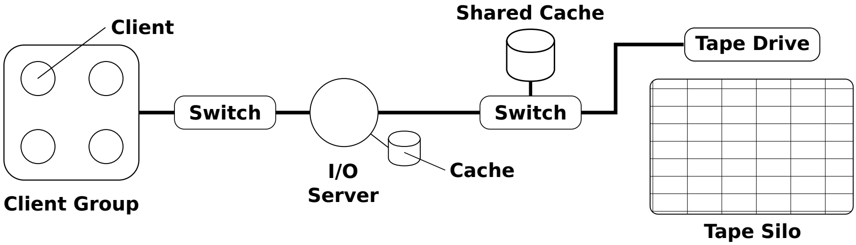
2. Modeling and Simulation Tape Storage Systems

3. Evaluation

4. Conclusion / Discussion

A simple model to get started

Introduction of the most important components.

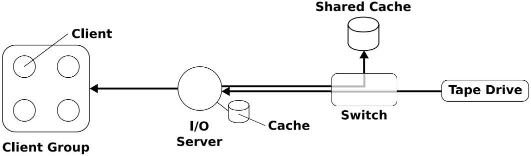


1. Multiple *clients* which may issue requests to `read` and `write` data
2. An *I/O Server* to receive and handle the requests
3. Different *cache levels*, to speed up access for recently touched files
4. Automated *tape silos* and *tape drives* to access the archive

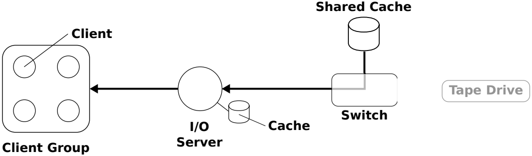
Handling READ Requests

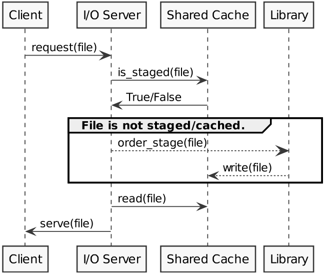
Staging of recently accessed files for reads.

READ (not in cache)



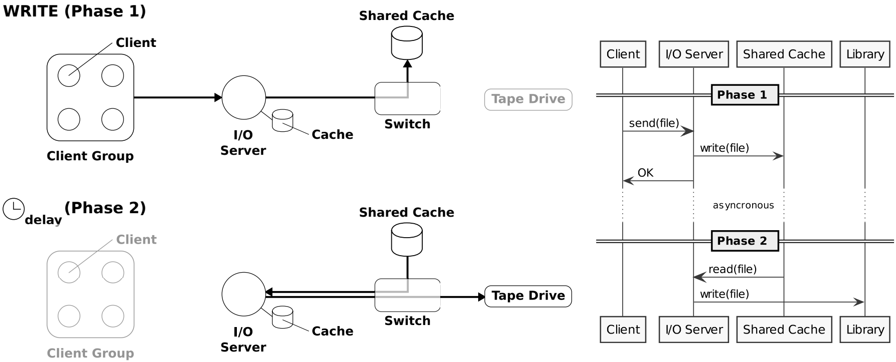
READ (cached)





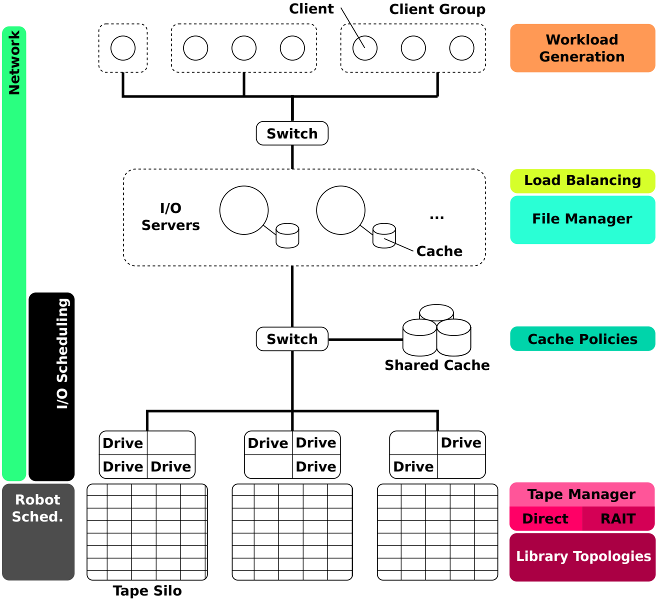
Handling `WRITE` Requests

Two-Phase write with delayed persistence on tape.



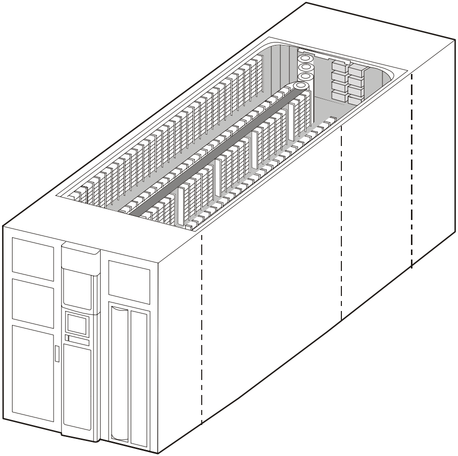
Model Overview

Hardware and software components in a combined overview.



Library Topology

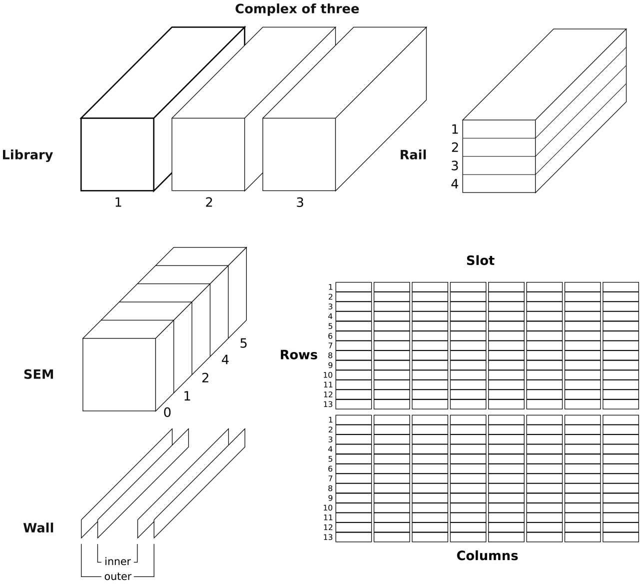
Invent models to estimate time panelties for certain actions.



(Sun, 2006)

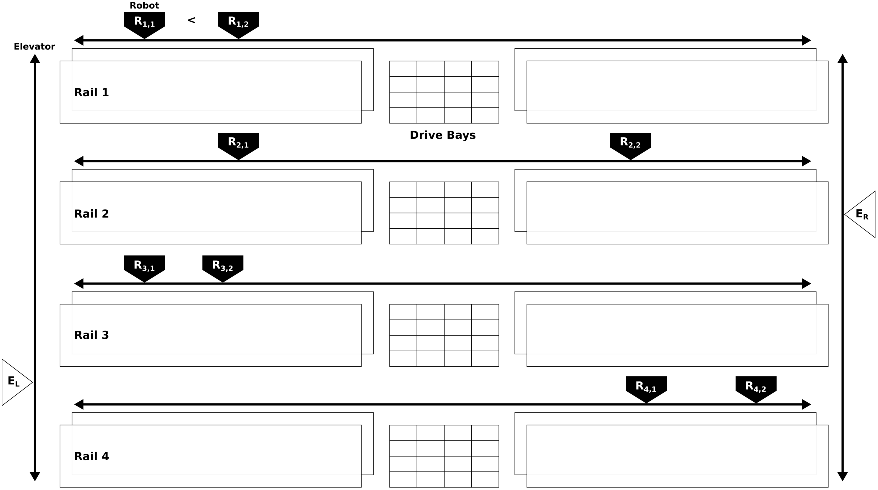
Library Topology

Buying a system vs. running a system.



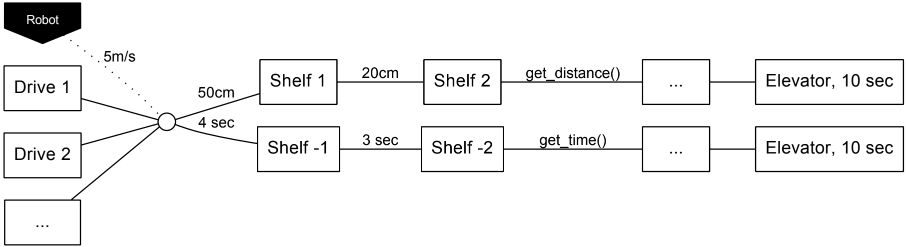
Robot Scheduling

Example: How a single SL8500 library maybe seen by a scheduling component.



Graph-Based Topology Model

Component connecticity graphs with distance or time panalties.

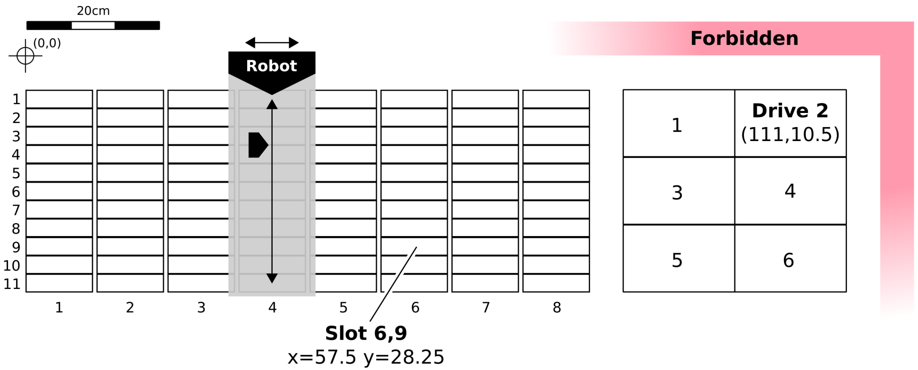


$$\text{get\_time}(e_{v_i,v_j} \text{ or } v) := \begin{cases} t & \text{if } e_{v_i,v_j} \text{ or } v \text{ have time } t \text{ set} \\ \frac{\text{get\_distance}(v_i,v_j)}{v_{robot}} & \text{if } e \text{ but no time is set} \\ 0 & \text{otherwise} \end{cases}$$

$$T_G(v_i, v_j) = \sum_{v_i,v_j}^{\text{shortest\_path}(v_0,v_1)} \text{get\_time}(v_i) + \text{get\_time}(e_{v_i,v_j})$$

2D Topology Model

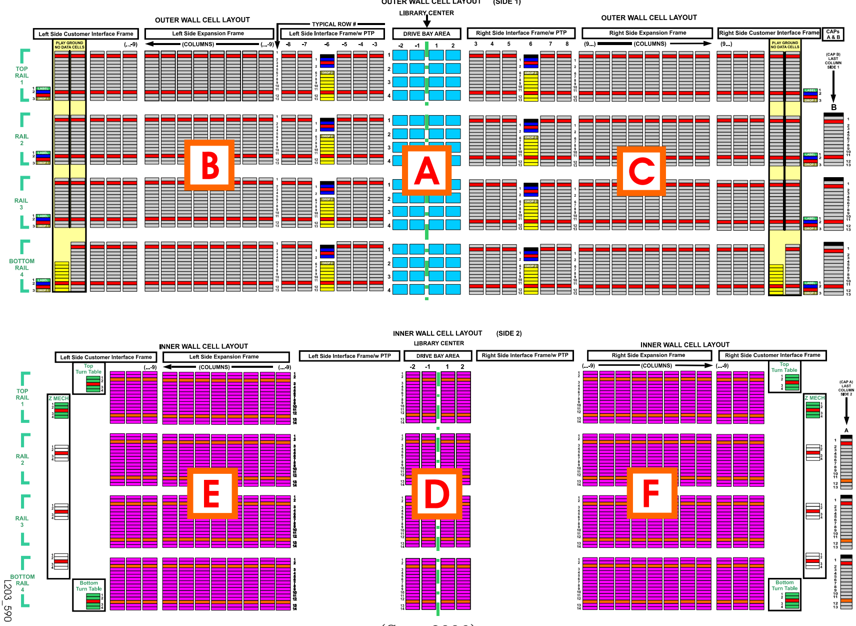
Flat library projections and tape receive times. Optional with easing.



$$T_{2D}(p_j, p_i) = max\left(\frac{|p_{ix} - p_{jx}|}{v_x}, \frac{|p_{iy} - p_{jy}|}{v_y}\right)$$

$$T_{2D}(path) = \sum_{p_i, p_j}^{path} T_{2D}(p_i, p_j) + T_{wait/work}$$

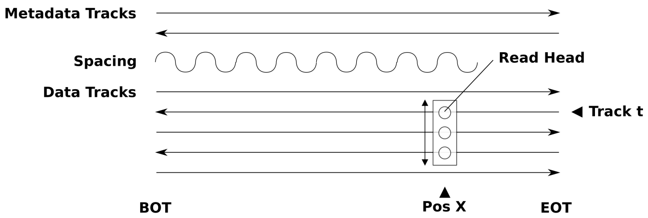
Outer and Inner Wall Cell Layout Map



(Sun, 2006)

Serpentine Tape Model

Estimating spool and seek times for tape access.



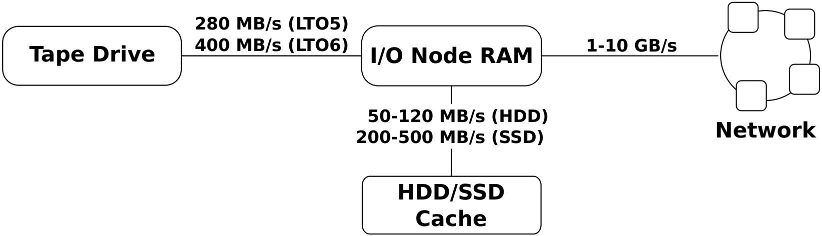
$$T_{seek}(pos_j, pos_i) = max\left(\frac{|pos_{ix} - pos_{jx}|}{v_{spool}}, \frac{|pos_{it} - pos_{jt}|}{v_{head}}\right)$$

$$T_{read/write}(bytes) = \frac{bytes}{v_{read/write}}$$

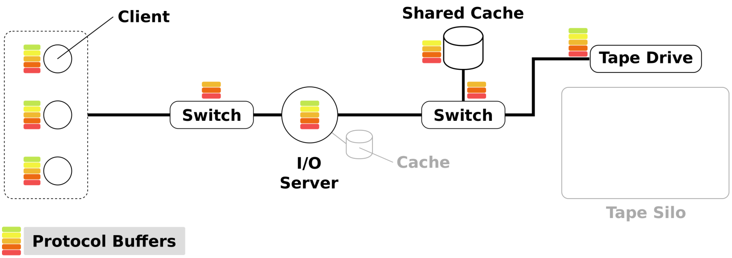
$$T_{busy} = T_{mount} + \left(\sum_{pos_i, pos_{i+1}}^{BOT,\ldots,BOT} T_{seek}(pos_i, pos_j) + T_{read/write}(bytes_i)\right) + T_{unmount}$$

Network Model Granularity

Tape Drive and HDD/SSD throughput are limiting factors.



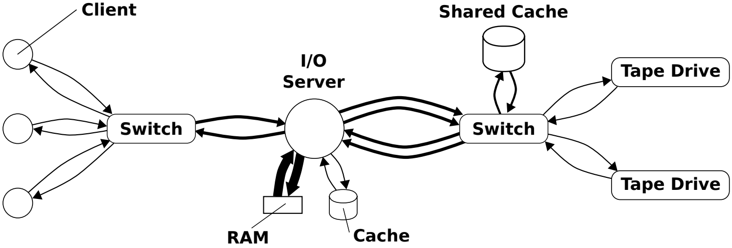
PDU/Package-based Network Model



	Layer	Protocol data unit	Function / Example
Host layers	7 Application	Data	CSS, HTML, Javascript
	6 Presentation		
	5 Session		FTP, NFS, HTTP, HTTPS, RPC, SMTP
	4 Transport	Segment (TCP) / Datagram (UDP)	TCP, UDP, SSH, NetBIOS
Media layers	3 Network	Packet	IPv4, IPv6, ICMP
	2 Data link	Frame	IEEE 802.2, L2TP, MAC, PPP
	1 Physical	Bit	Ethernet, SCSI, USB, ISDN, DSL

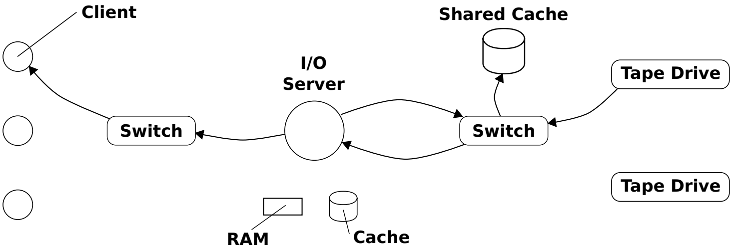
Graph-based Network Model

Required in any case: Network component connection graph.



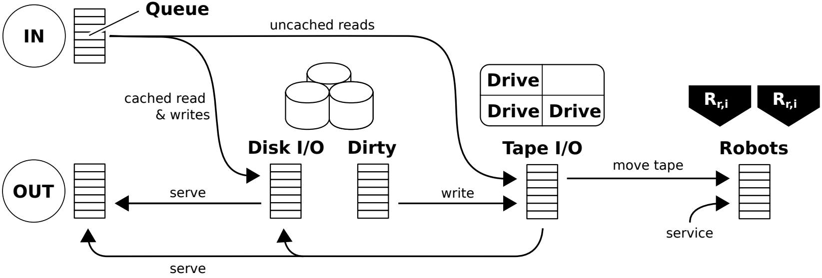
Graph-based Network Model

Combined maximum-flows when considering I/O servers, clients and caches.



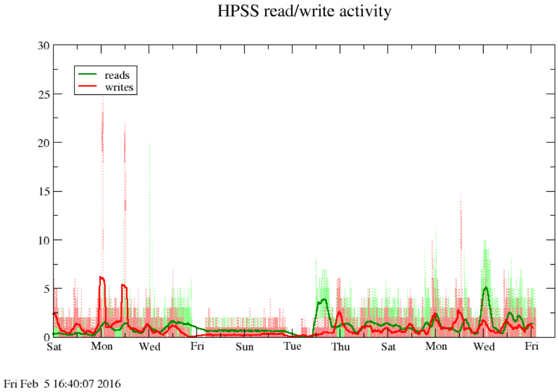
Scheduling and Request Queues

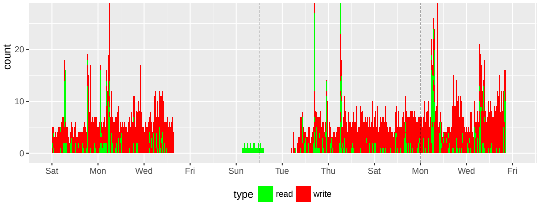
Chaining specialized request queues makes resource allocation manageable.



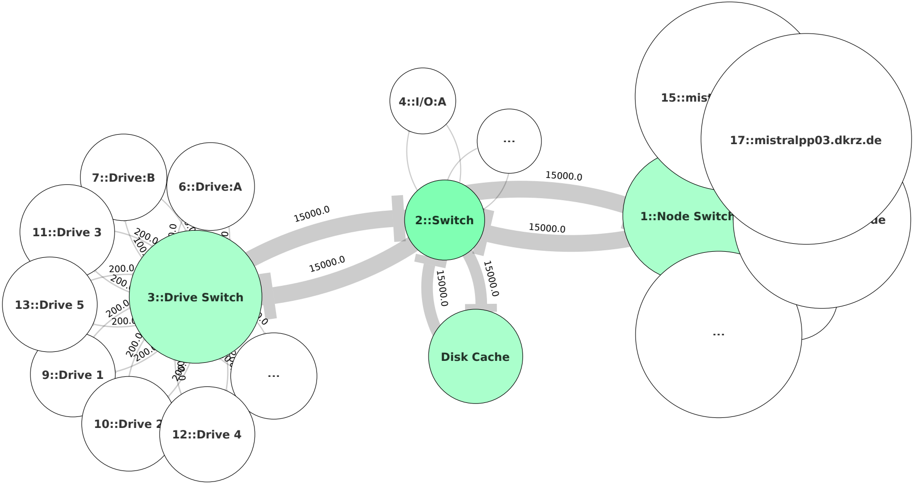
- Request data
  - `requests.csv` summaries (e.g. throughput, duration, size, status)
  - `stages.csv`
  - `wait-times.csv`
  - Detailed request histories including bandwidth changes (optional)
- Simulation process log when enabled (Default: `stdout`)
- Simulation state in limited detail
  - Filesystem state
  - Tape system state (Tapes and Slots)
  - Global cache state
- HSM/Tape System Configuration
  - Network Topology as XML
  - Library Topology (pickle/XML)

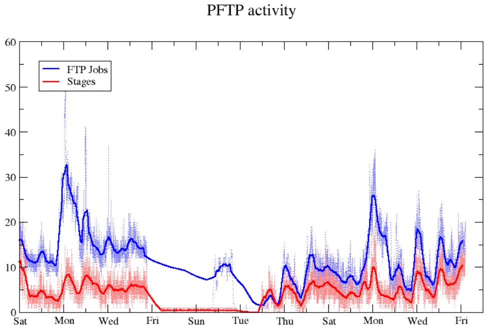
Workload Trace





Network Topology used for Evaluation





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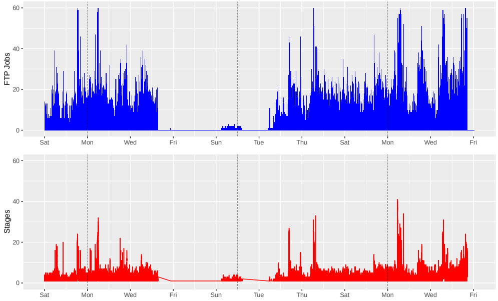
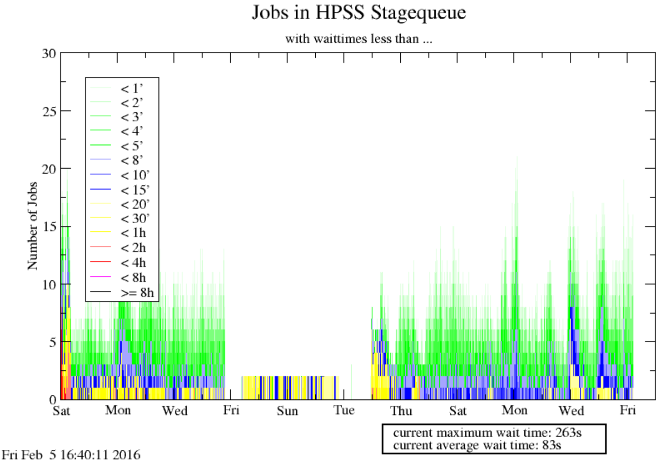
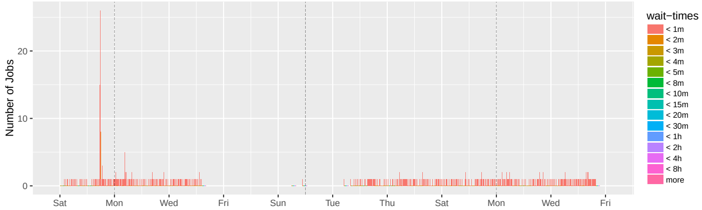



Jobs in HPSS Stagequeue
with waittimes less than ...
Number of Jobs
< 1'
< 2'
< 3'
< 4'
< 5'
< 8'
< 10'
< 15'
< 20'
< 30'
< 1h
< 2h
< 4h
< 8h
>= 8h
Sat
Mon
Wed
Fri
Sun
Tue
Thu
Sat
Mon
Wed
Fri
current maximum wait time: 263s
current average wait time: 83s
Fri Feb 5 16:40:11 2016


Number of Jobs
wait−times
< 1m
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< 3m
< 4m
< 5m
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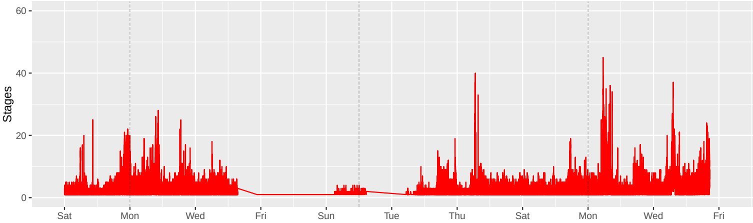
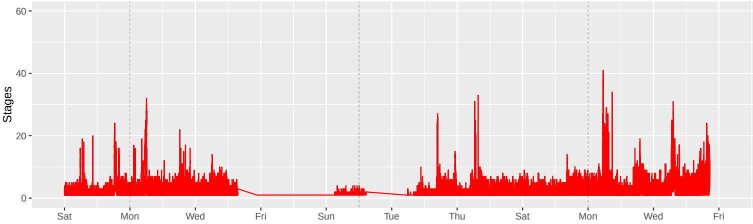
< 10m
< 15m
< 20m
< 30m
< 1h
< 2h
< 4h
< 8h
more
Sat
Mon
Wed
Fri
Sun
Tue
Thu
Sat
Mon
Wed
Fri

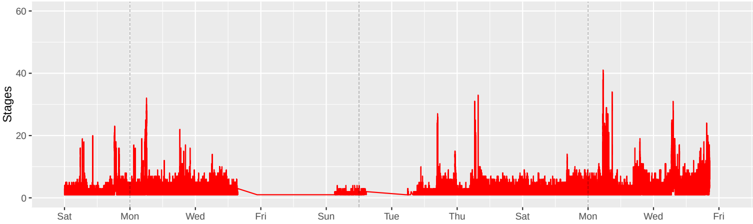
30 drives



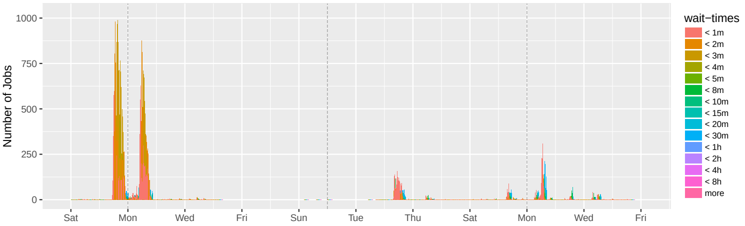
45 drives



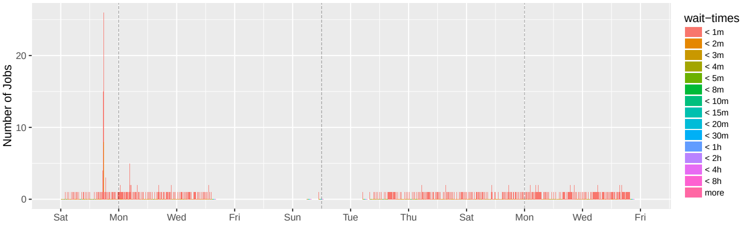
75 drives



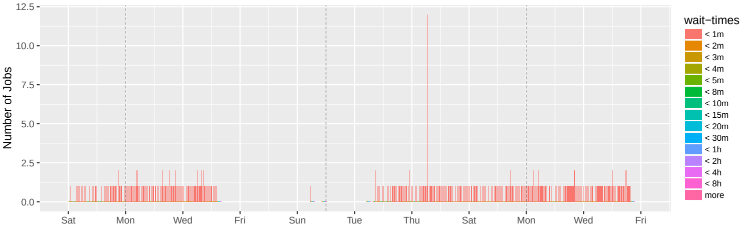
30 drives



45 drives



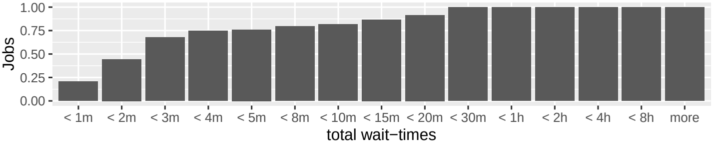
75 drives



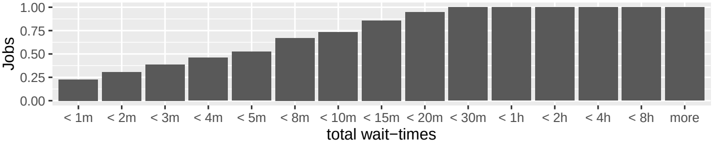
Example: Easy to determine QoS for Total-Waittime

E.g.: How many drives to serve x % of requests in under y minutes.

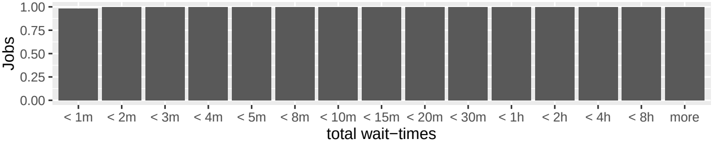
30 drives



45 drives



60 drives



Conclusion and Discussion

Summary

- Tape to remain relevant if cost advantage is maintained
- Better models now available to be used by schedulers
- Simulation resembles behavior of a real system
- Automatic exploration of configurations is feasible

Future Work

- Improve configuration process, consider GUI
- Mature existing architecture to manage physical tape libraries
- Port core APIs to more efficient programming languages
- Conduct experiments and prepare workflows for common cost minimization/performance maximization problems

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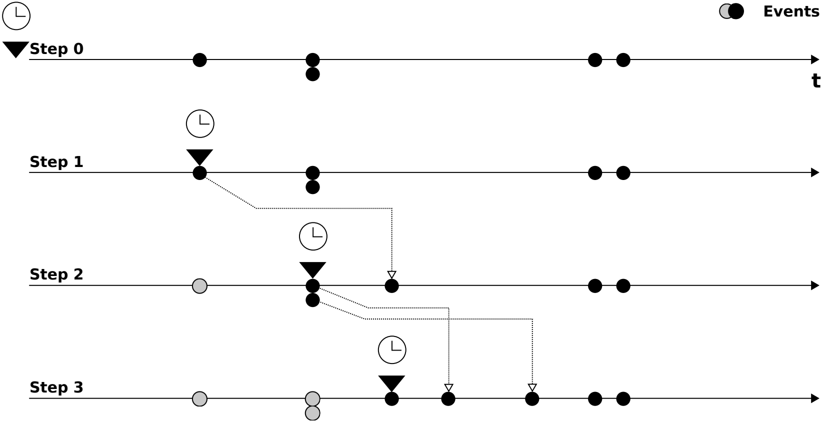
Appendix

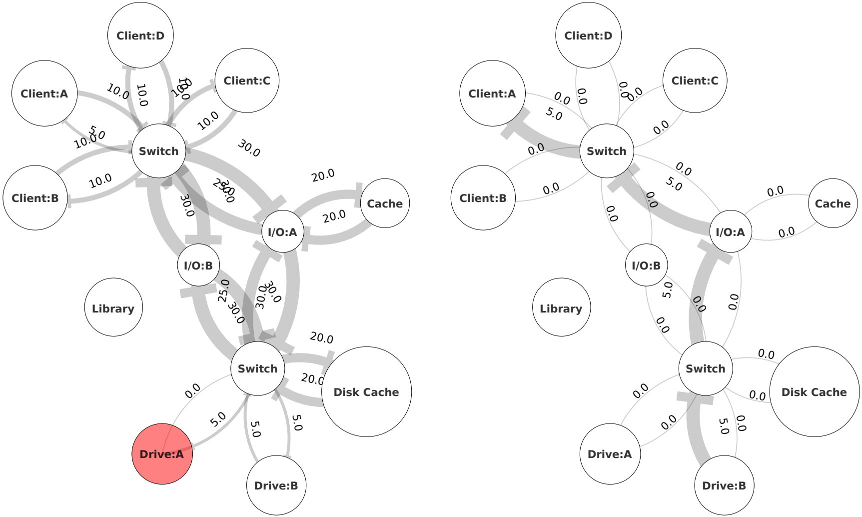
Discrete Event Simulation

Only require calculations when the state of the system changes.



Network Model (Implementation)

Example: The network with one busy drive. Max-flow used to estimate throughput.

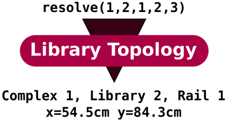


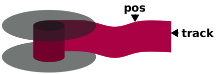
Library Organisation and Management

File and tape management.

File	Size	Position	Tape
file1	3134	pos,track	012345L1
file2	6483	45,447	LTO834L5
file3	39485	1623,187	274344L4
file4	38474	2245,184	274344L4
file5	345	3749, 47	LTO834L5

Tape	Slot
012345L1	1,1,1,18, 9
264653L4	3,1,3, 7, 5
274344L4	1,4,2,-6,12
267753L4	2,2,4, 3, 5
LTO834L5	1,3,3, 7, 1
CLN004CU	2,3,1,-7, 8
CLN031CU	1,2,1, 2, 3





Concurrency

I/O scheduling and strong vs. weak ordering semantics

Incoming requests in order:

write(**file1**)	write(**file5**)	write(**file3**)	write(**file2**)	write(**file1**)	write(**file4**)	write(**file6**)	...

time

Bundled requests:

a	**b**	**c**	**...**
~~file1~~	file3	file5	:
file1	file2	file4	
file6	:	:	
:			

Reordered requests:

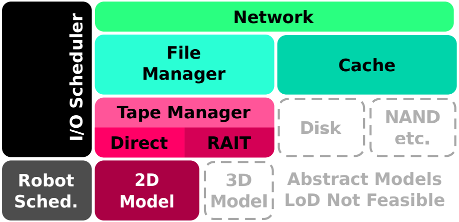
a	**b**	**c**	**...**
file6	file2	file4	:
file1	file3	file5	

File	Tape	Pos
file1	a	3
file2	b	4
file3	b	2
file4	c	3
file5	c	5
file6	a	1

1. $O_i = read(D)$, $O_j = read(D)$. Maybe handled concurrently.
2. $O_i = read(D)$, $O_j = write(D)$. Can not be handled concurrently.
3. $O_i = write(D)$, $O_j = read(D)$. Can not be handled concurrently.
4. $O_i = write(D)$, $O_j = write(D)$. Can not be handled concurrently.

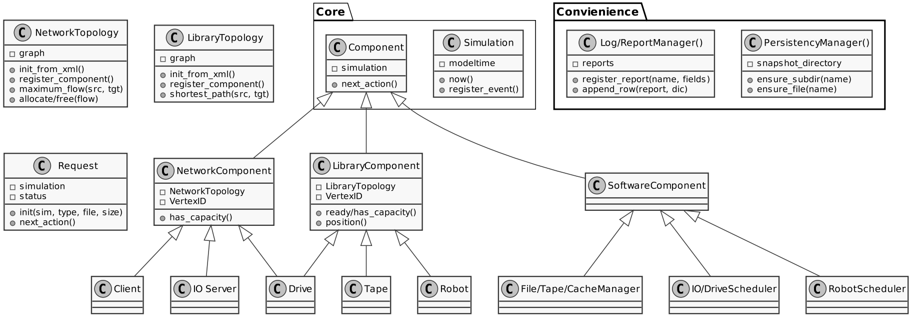
Tape System Software Stack

A similar stack should also allow to run a real tape system.



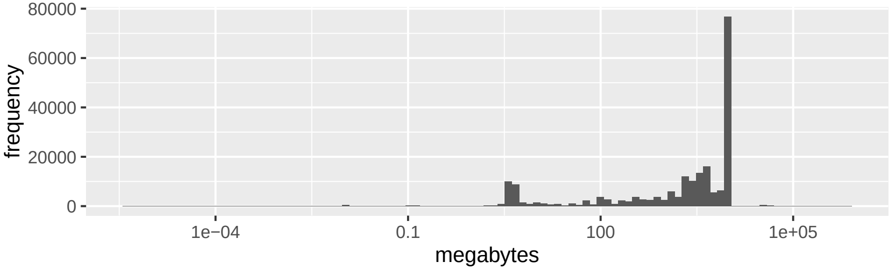
Components and Classes

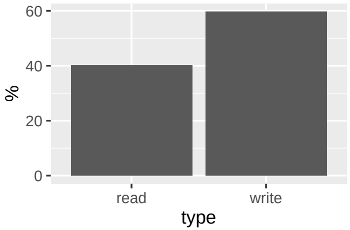
UML Class Diagram



Workload Trace (2)

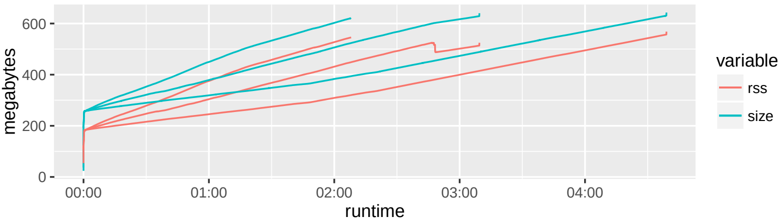
Request size and request type distributions





Runtime and Memory Consumption

Only request data is immediately written to disk. Some other data accumulates.



5. Library Management

6. Concurrency

7. Runtime and Memory Requirements

8. Misc