TECHNISCHE UNIVERSITÄT DRESDEN

ComNets
Deutsche Telekom Chair of Communication Networks

Deutsche Telekom Chair of Communication Networks
Technische Universität Dresden

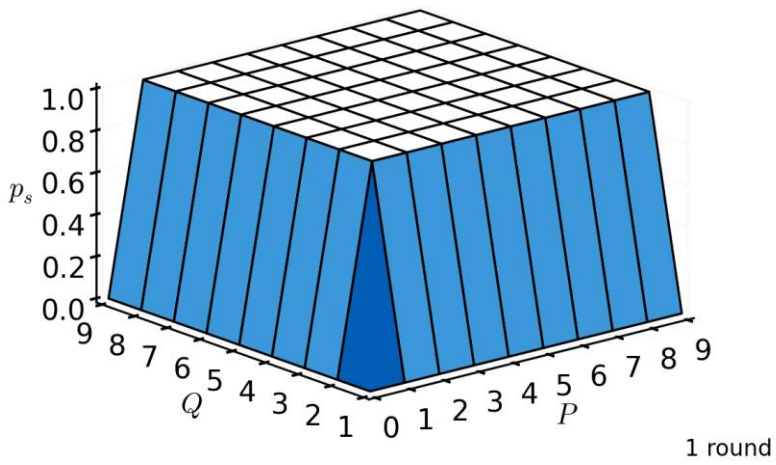
Practical Implementations of Network Coding

Frank Fitzek // Summer Semester 2019

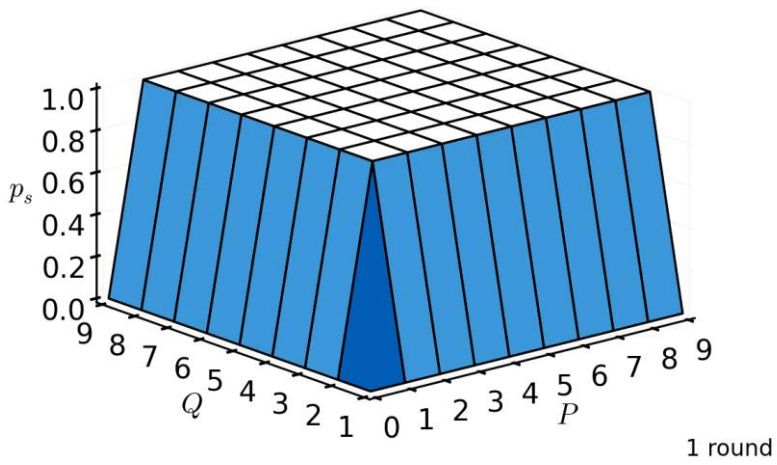
Network Coding for Storage

Comparison

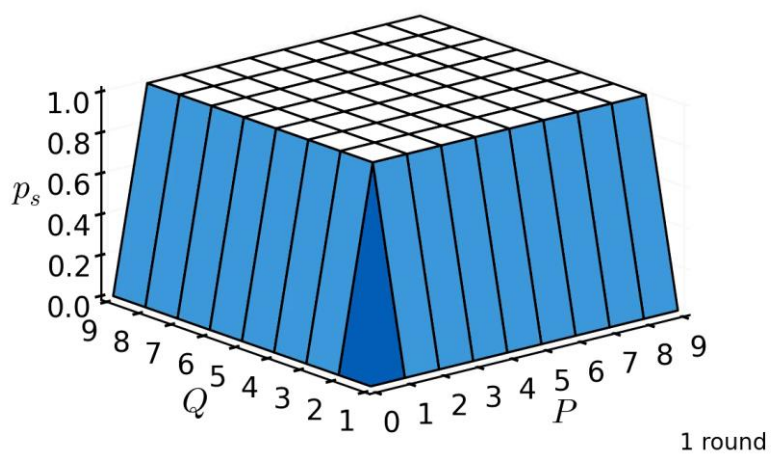
Uncoded



RS coded



Recoding



see lecture on storage

Network Coded Storage

Introduction and Motivation

Cloud storage

- Fast growth in the past years (both enterprise and home users)
- Free storage space: Dropbox, Google Drive, SkyDrive, Box, iCloud, and countless more
- Public APIs, usually REST-based

Issues:

- Reliability issues
- Privacy and security issues
- Limited free storage space

Distributed storage on clouds – in use today on the provider side

Our approach:

- Distribute data to multiple cloud providers on the user side
- Use network coding to create a robust, fast and secure distributed storage solution

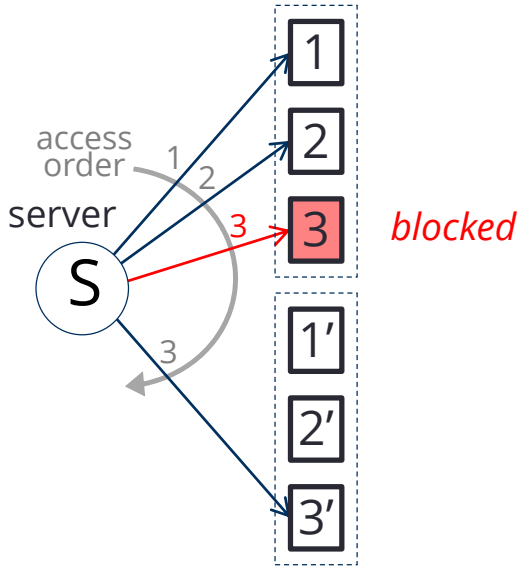
Distributed Storage

Data Centre 1G

User Cloud Storage 2G/3G

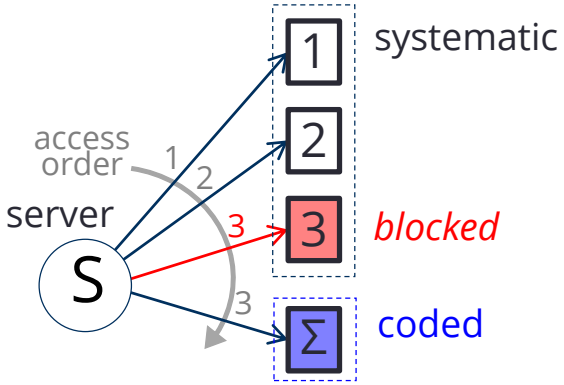
Distributed Storage

Conventional SAN



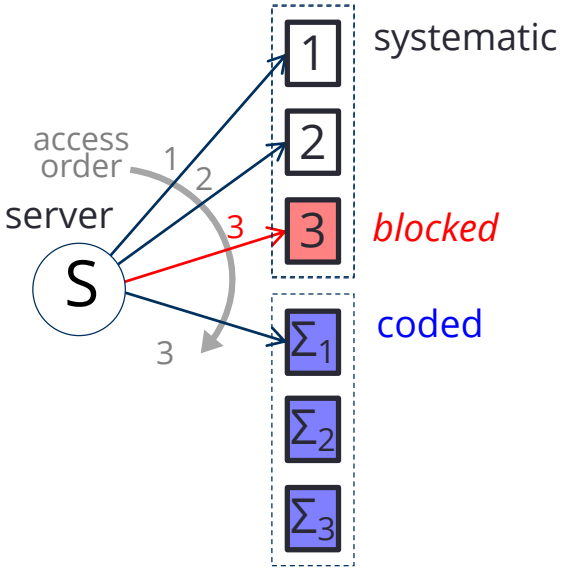
- 2 file copies
- 3 file chunks
- One chunk per drive
- Round-robin server access
- Chunk “3” blocked

RLNC-encoded SAN (two options)

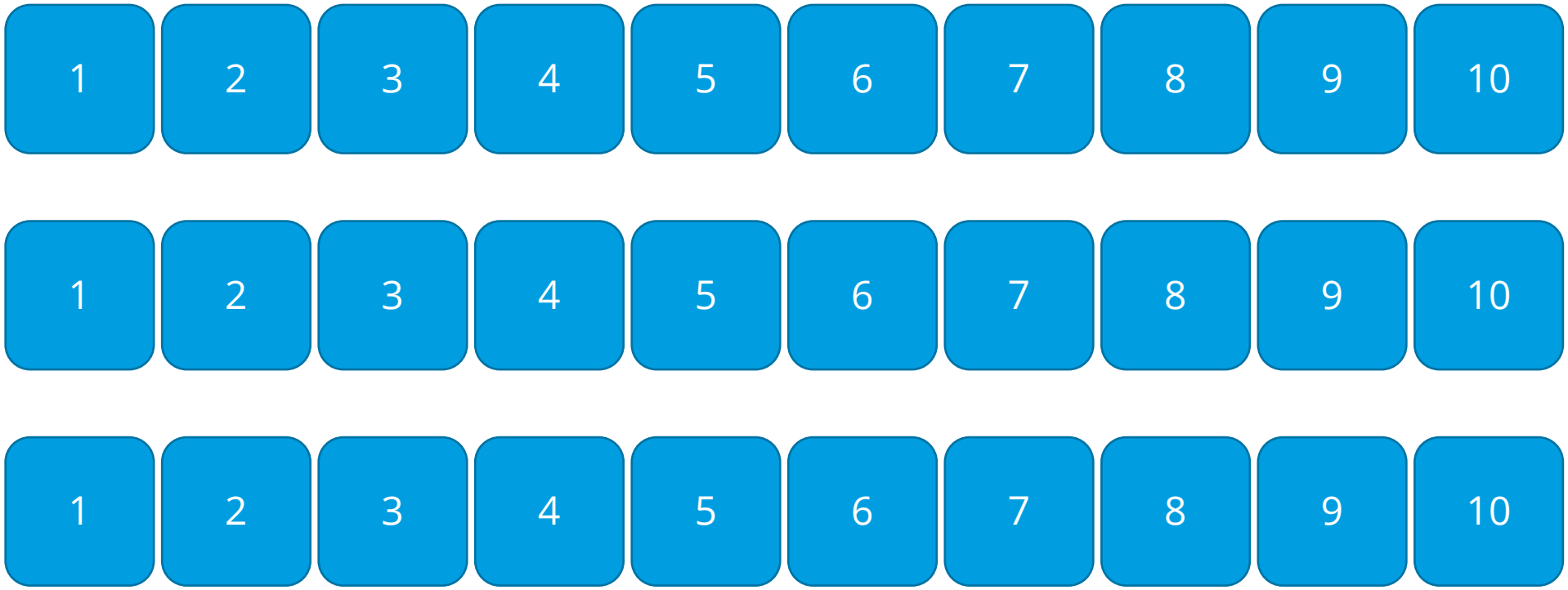


Decoding

$3 = \Sigma - 1 - 2$

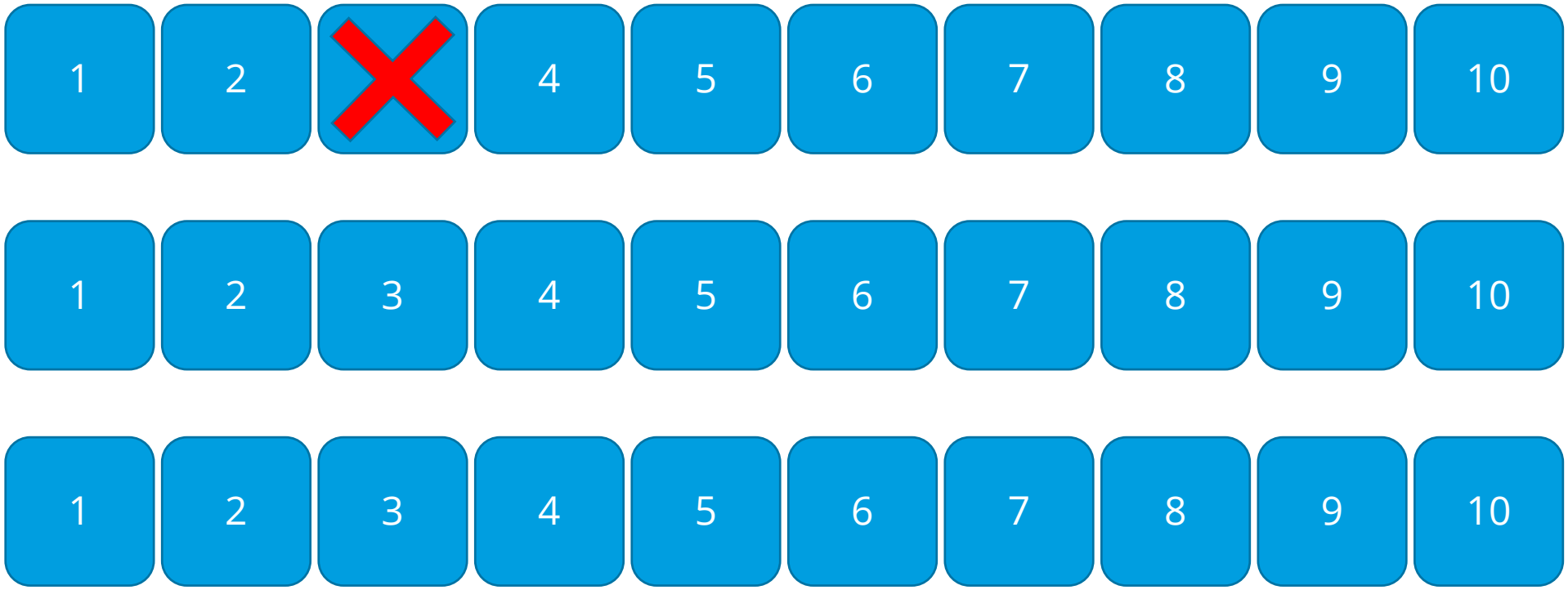


State of the Art



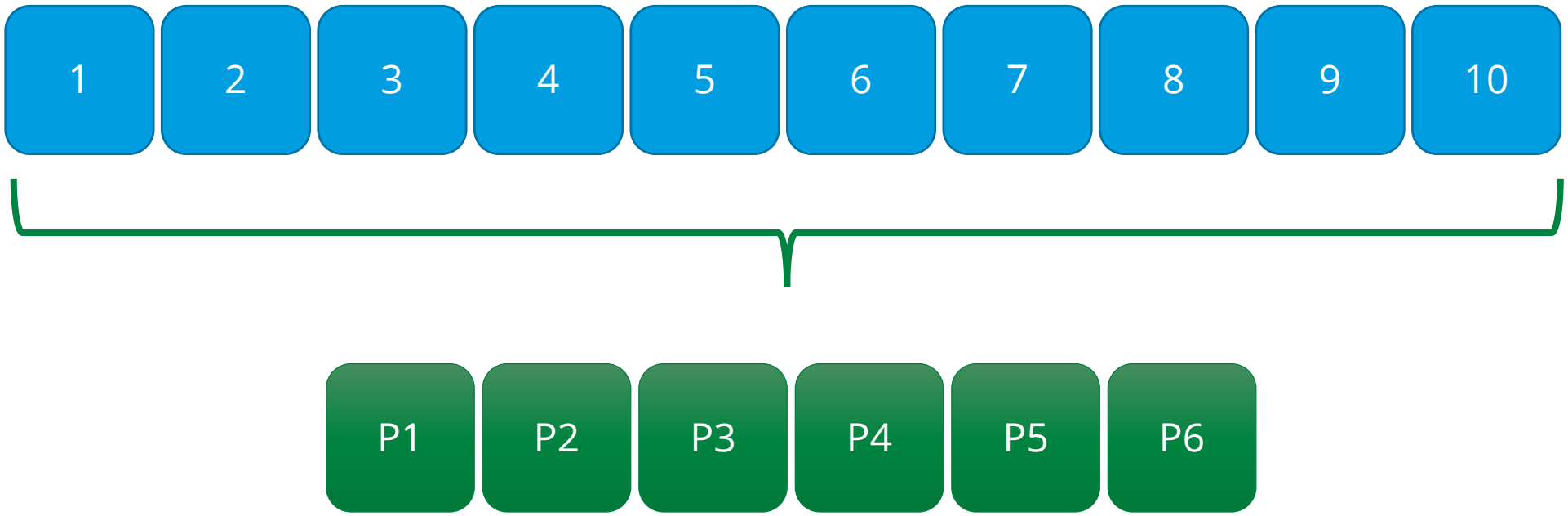
Overhead: 200%

State of the Art



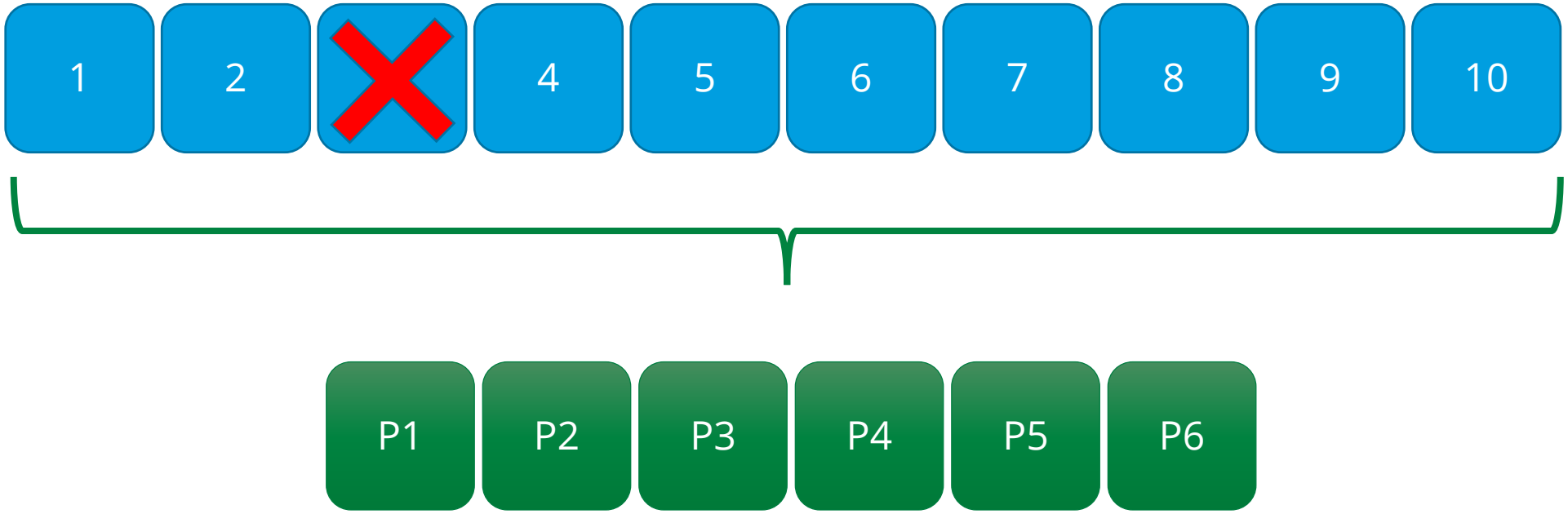
One failure results in one traffic unit

10:6 Code (Facebook)



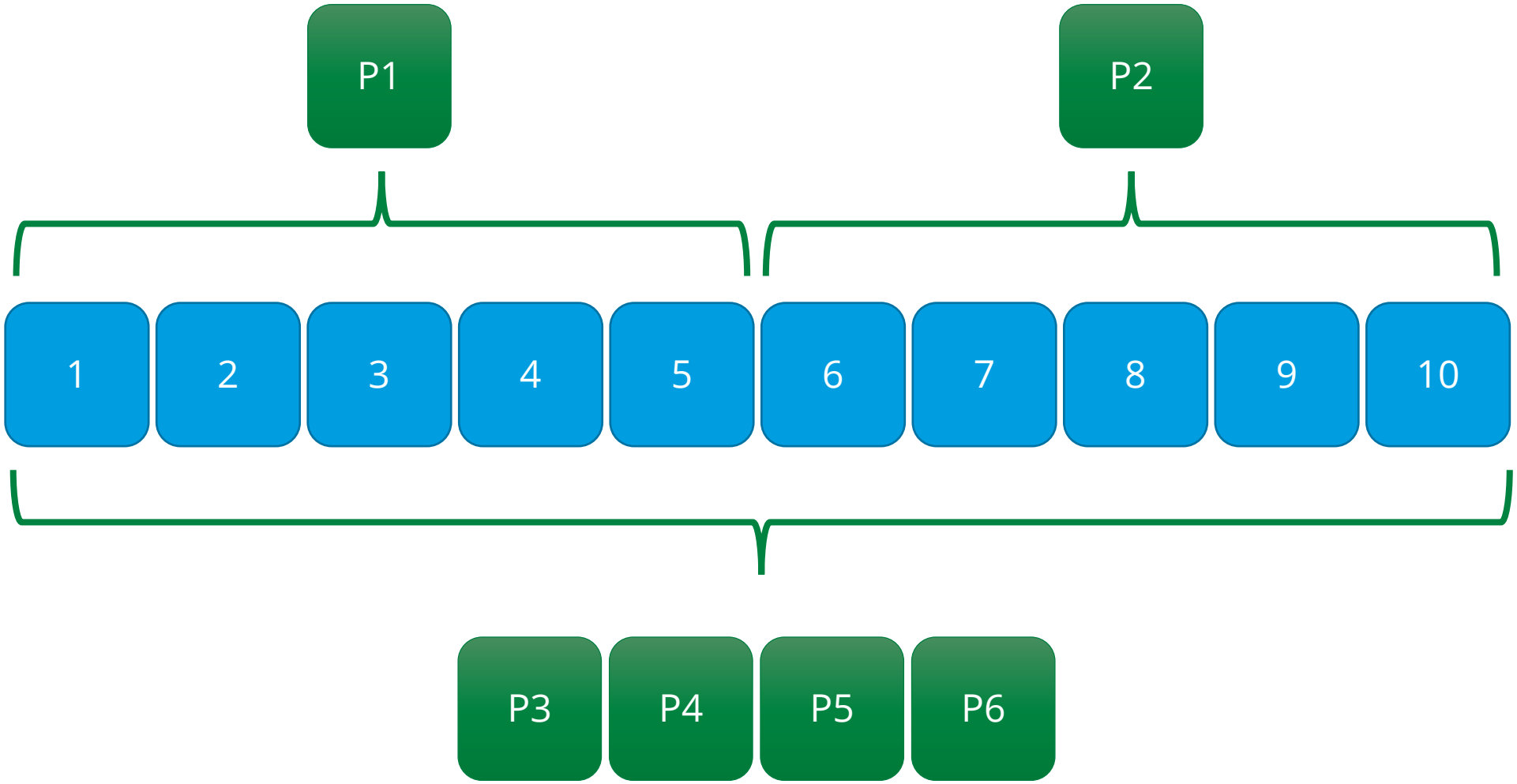
Overhead: 60%

10:6 Code (Facebook)

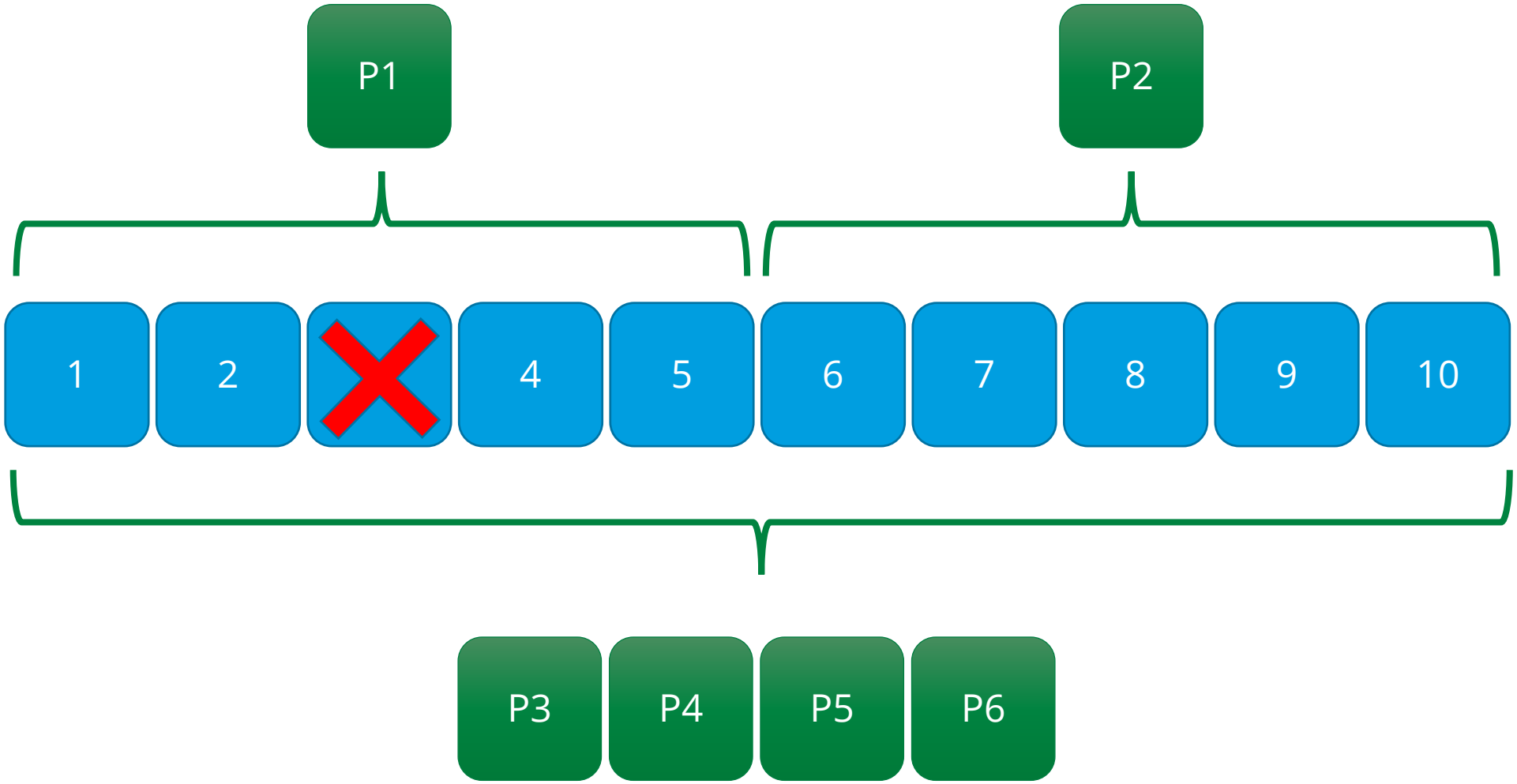


One failure results in 10 traffic units

Xorbas



Xorbas



One failure results in 5 traffic units

Sounds familiar?

Redundant Array of Independent Disks (RAID)

Goal

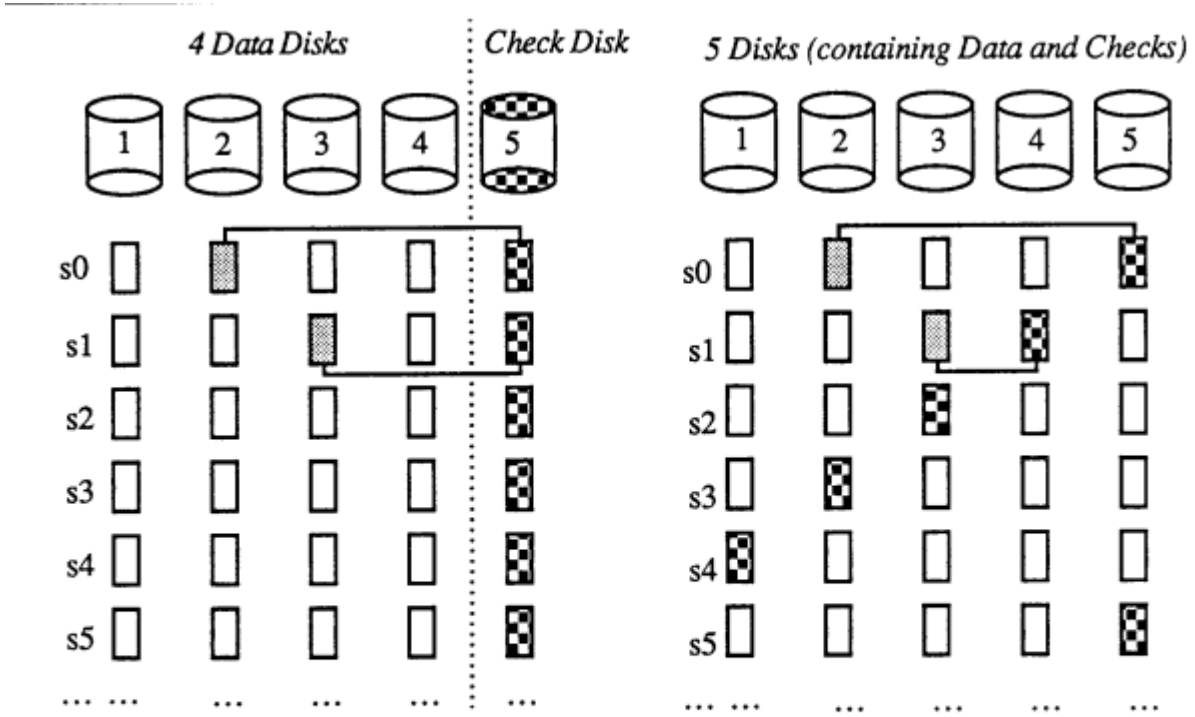
- Redundancy in storage
- Faster information transfer
- Reduce cost

RAID 0,1,(2),(3),4,5, ...

XOR

RAID 4/5

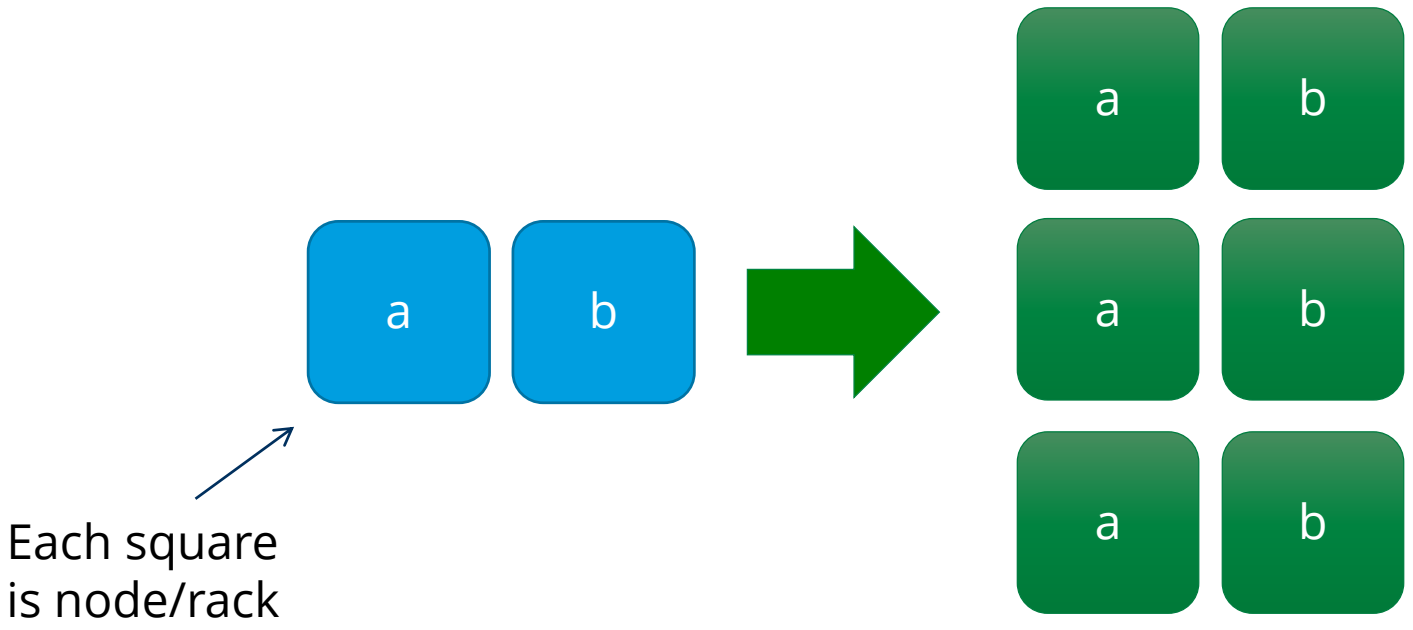
A case for redundant arrays of inexpensive disks (RAID), D. A. Patterson, G. Gibson und R. H. Katz, 1988



(a) Check information for Level 4 RAID for G=4 and C=1. The sectors are shown below the disks. (The checked areas indicate the check information.) Writes to s0 of disk 2 and s1 of disk 3 imply writes to s0 and s1 of disk 5. The check disk (5) becomes the write bottleneck.

(b) Check information for Level 5 RAID for G=4 and C=1. The sectors are shown below the disks, with the check information and data spread evenly through all the disks. Writes to s0 of disk 2 and s1 of disk 3 still imply 2 writes, but they can be split across 2 disks: to s0 of disk 5 and to s1 of disk 4.

State of the Art: Replication



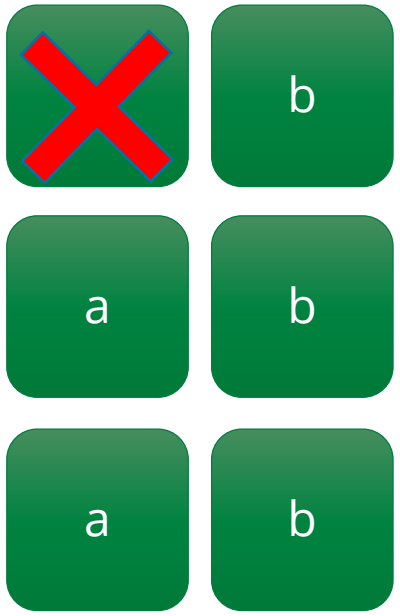
Overhead: 200%

State of the Art: Replication

Overhead: 200%
- High storage cost

Traffic to repair loss:
- 1 unit

Protection:
- 4 losses (best case)
- 2 losses (worst case)



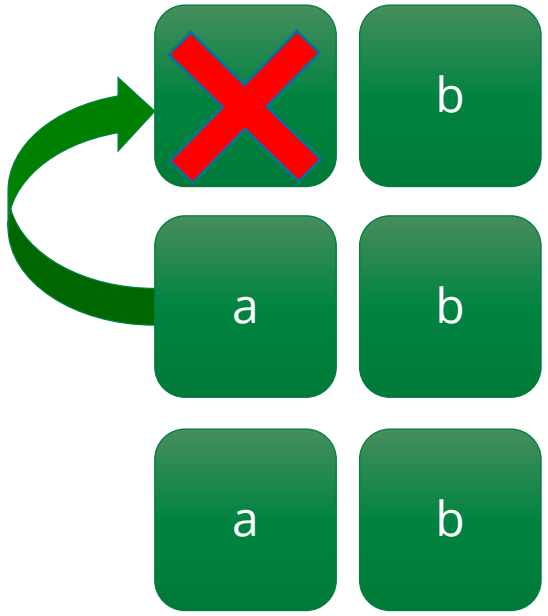
Overhead: 200%

State of the Art: Replication

Overhead: 200%
- High storage cost

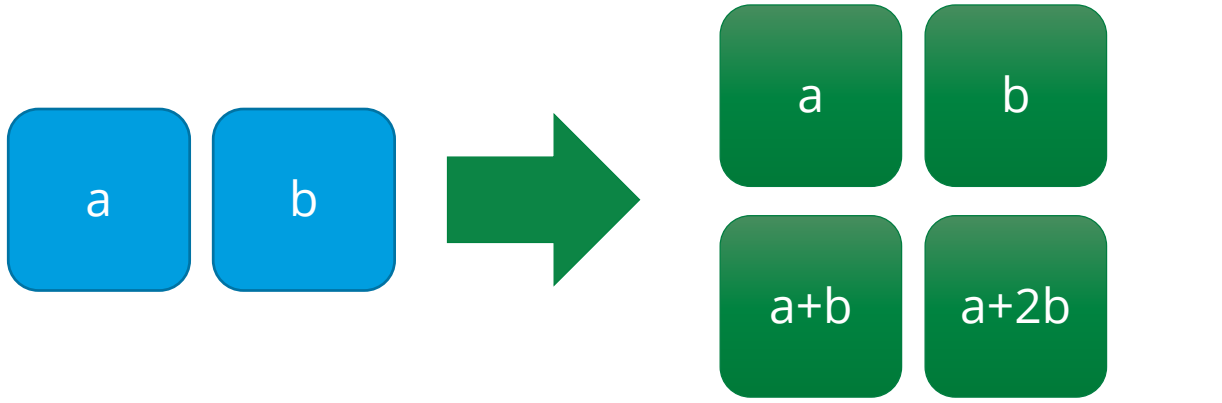
Traffic to repair loss:
- 1 unit

Protection:
- 4 losses (best case)
- 2 losses (worst case)



Overhead: 200%

State of the Art: RAID6



e.g. Reed-Solomon code

Overhead: 100%

State of the Art: RAID6

Overhead: 100%

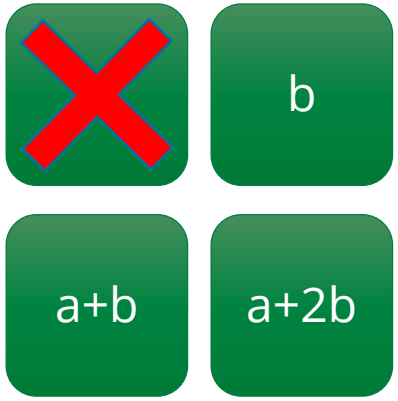
- Medium storage cost

Traffic to repair loss:

- 2 units

Protection:

- 2 losses (any case)



e.g. Reed-Solomon code

Overhead: 100%

State of the Art: RAID6

Overhead: 100%

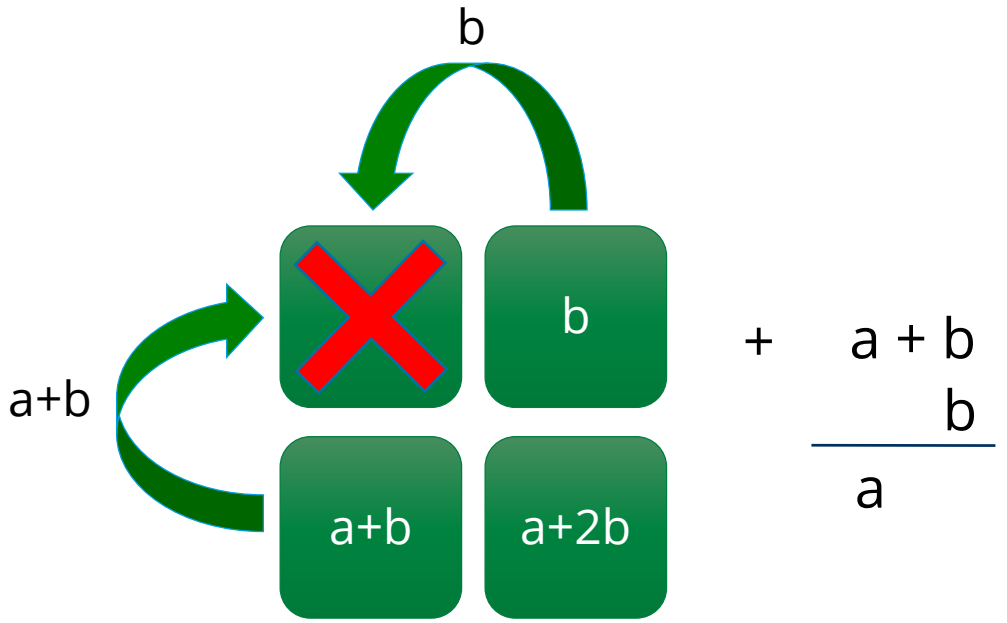
- Medium storage cost

Traffic to repair loss:

- 2 units

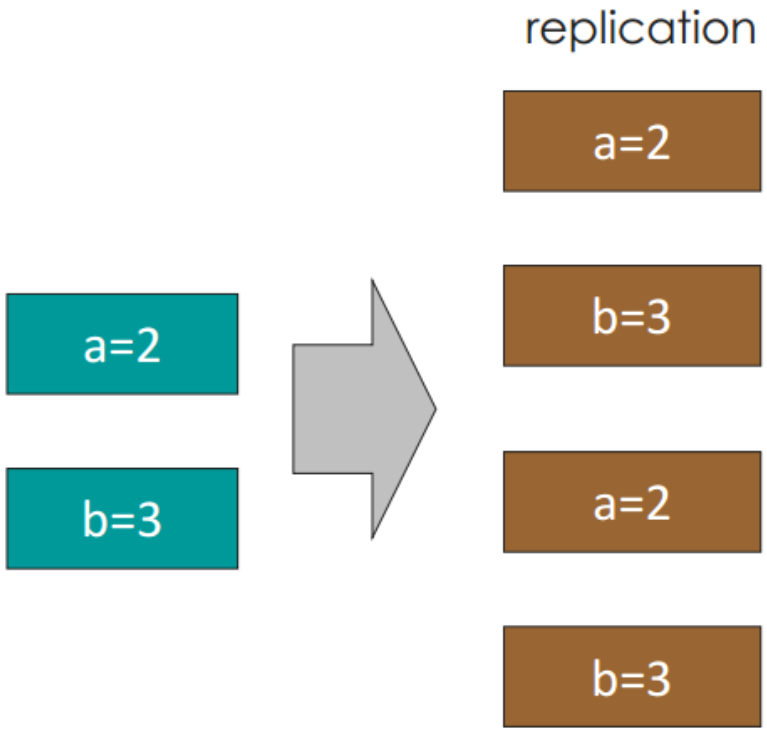
Protection:

- 2 losses (any case)



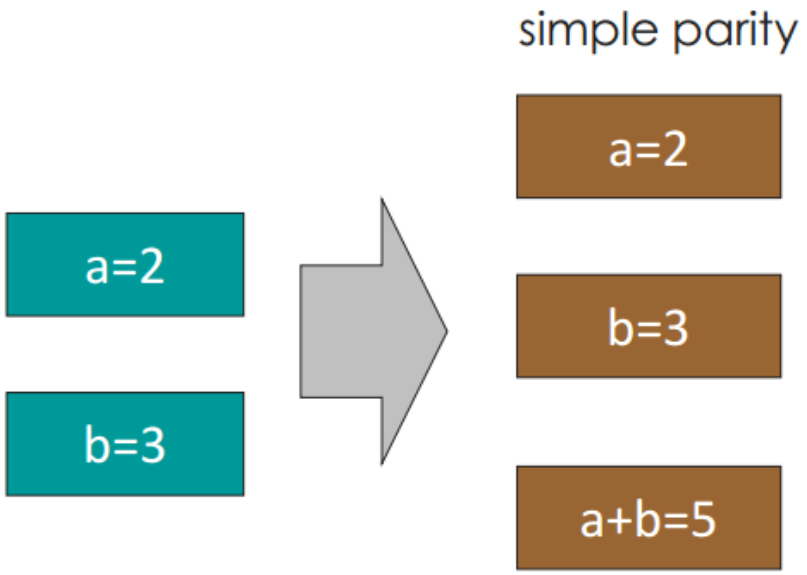
e.g. Reed-Solomon code

Simple Erasure Coding – Replication



- # of data units k = 2
- # of code units n = 4
- # of tolerable unit losses
  - worst case $r_w = 1$
  - best case $r_b = 2$
- overhead: n/k = 2x

Trivial Erasure Coding – Simple Parity



- # of data units k = 2
- # of code units n = 3
- # of tolerable unit losses
  - worst case $r_w = 1$
  - best case $r_b = 1$
- overhead: n/k = 1.5x

MDS Codes and Systematic Codes

MDS codes

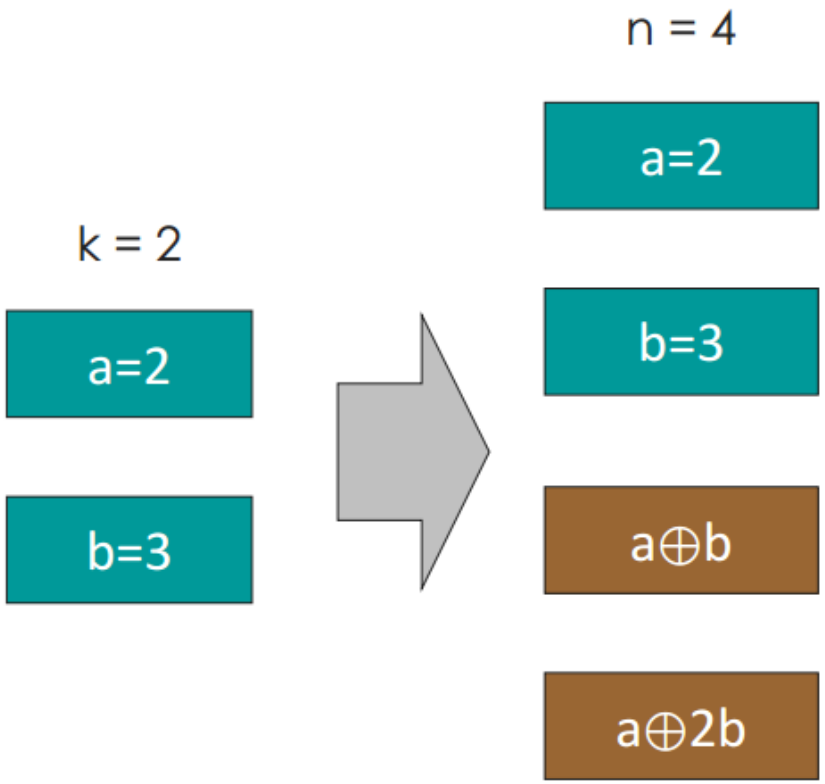
- Same number of tolerable losses (best vs. worst)
- Optimal overhead
- Extra computational complexity to perform coding

Systematic codes

- Direct access to the content without the need for coding if no losses
- Coded information only needed with losses and then also increased traffic

Reed-Solomon Example

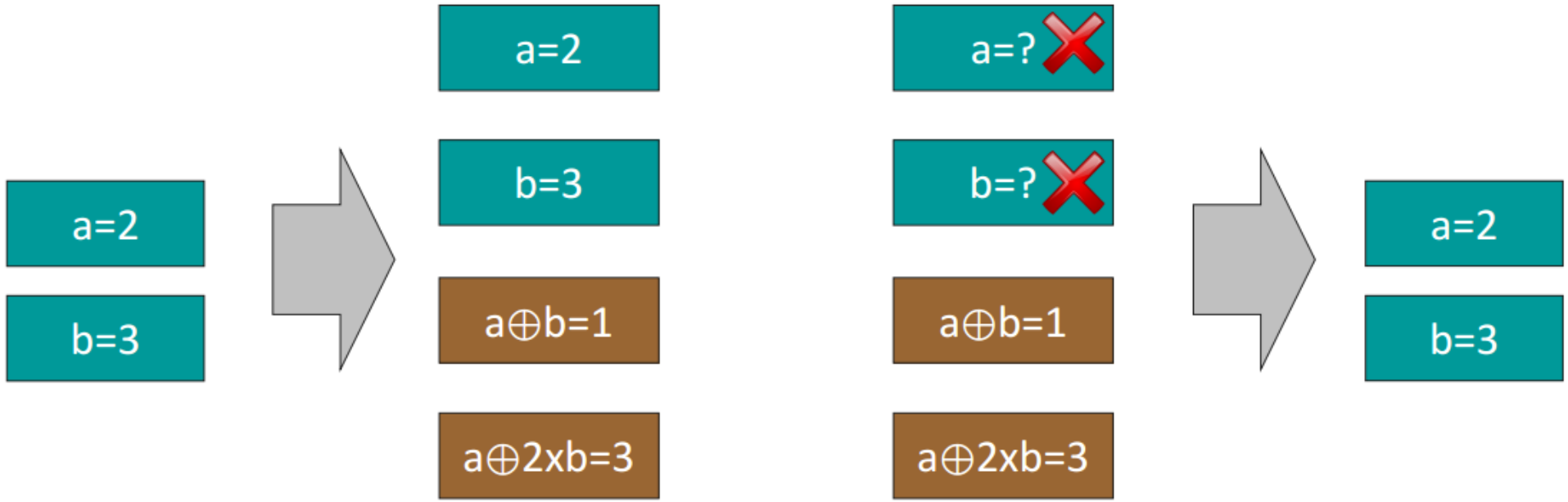
- The most important class of MDS and systematic codes
- Example



Reed-Solomon Example: Operations in FF

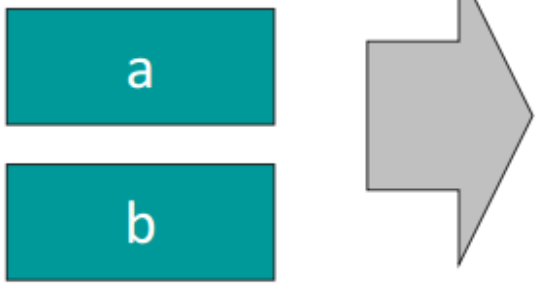
⊕	0	1	2	3
0	0	1	2	3
1	1	0	3	2
2	2	3	0	1
3	3	2	1	0

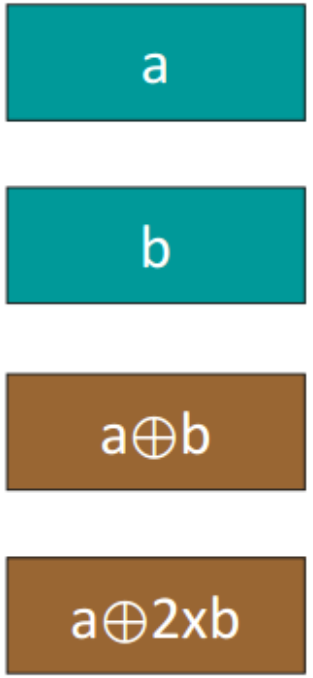
X	0	1	2	3
0	0	0	0	0
1	0	1	2	3
2	0	2	3	1
3	0	3	1	2



TECHNISCHE UNIVERSITÄT DRESDEN

Reed-Solomon Example: Operations in FF





- a & b can be of any size
  - Network packet (1KB)
  - Storage disk (1TB)
- ⊕ is very fast on CPU
- What about multiplication?

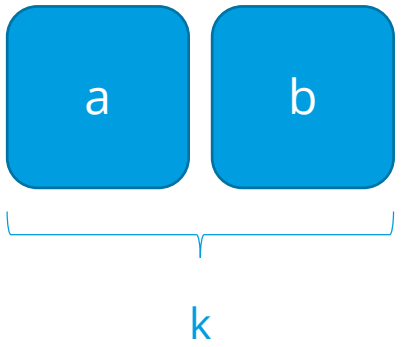
Repair Problem

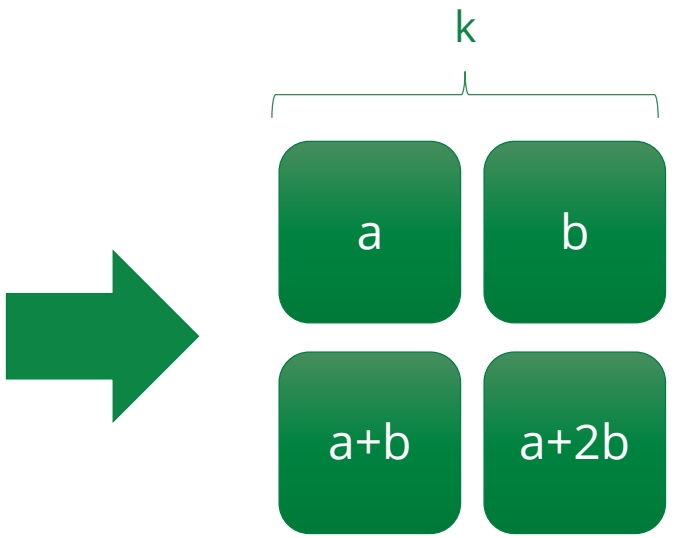
More General Reed-Solomon

Can split data into k fragments and generate n fragments

Any k fragments would be enough to recover

Overhead:	(n-k)/k
Traffic for repair:	k
Protection:	can recover from n – k losses





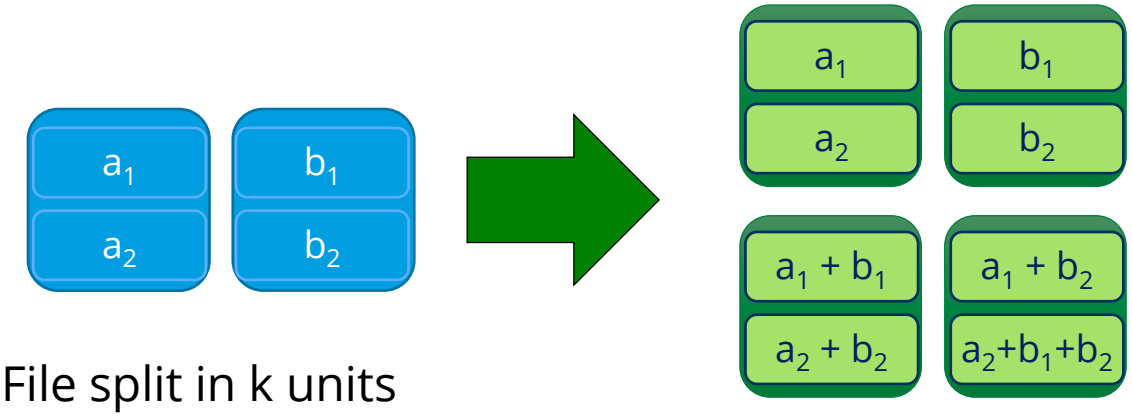
e.g. Reed-Solomon code

Regenerating Codes

Goal: Minimize repair traffic with same fault tolerance as Reed-Solomon

- Faster repair
- Inherent trade-off of storage and traffic cost
- Network coding is key: recoding needed at the nodes/racks before sending

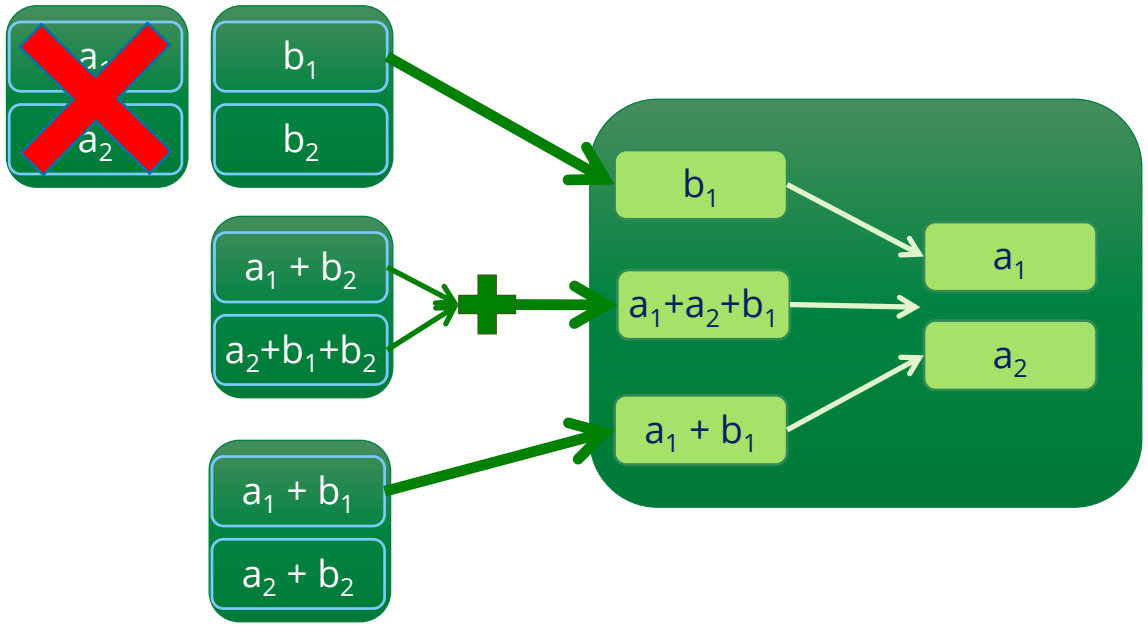
Regenerating Codes



File split in k units

Regenerating Codes

Overhead:	100%
Protection:	2 losses of nodes/racks
Repair traffic:	1.5 units → ¾ of file size



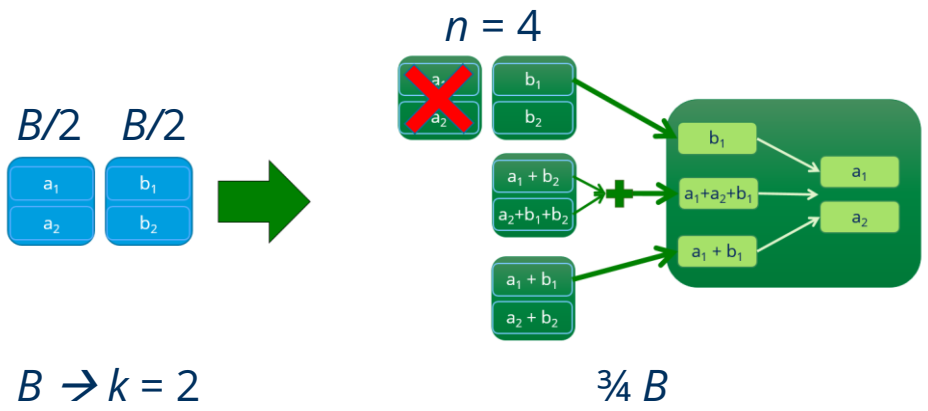
Regenerating Codes

For a file of size *B* bits, split into *k* pieces and encoded into *n* pieces
Each piece is stored in a disk with *B/k* bits per disk
Theorem: it is possible to **functionally** repair a code by communicating:

$$\frac{n-1}{n-k}\frac{B}{k} \text{ Bits}$$

As opposed to transmitting *B* bits (naive cost)

Previous Example: For *n* = 4, *k* = 2, then at least ¾ *B* bits (B=2k → 6/4 k = 1.5 k) are needed (and we used exactly that)



New Challenges in Storing

So far the structure has been static

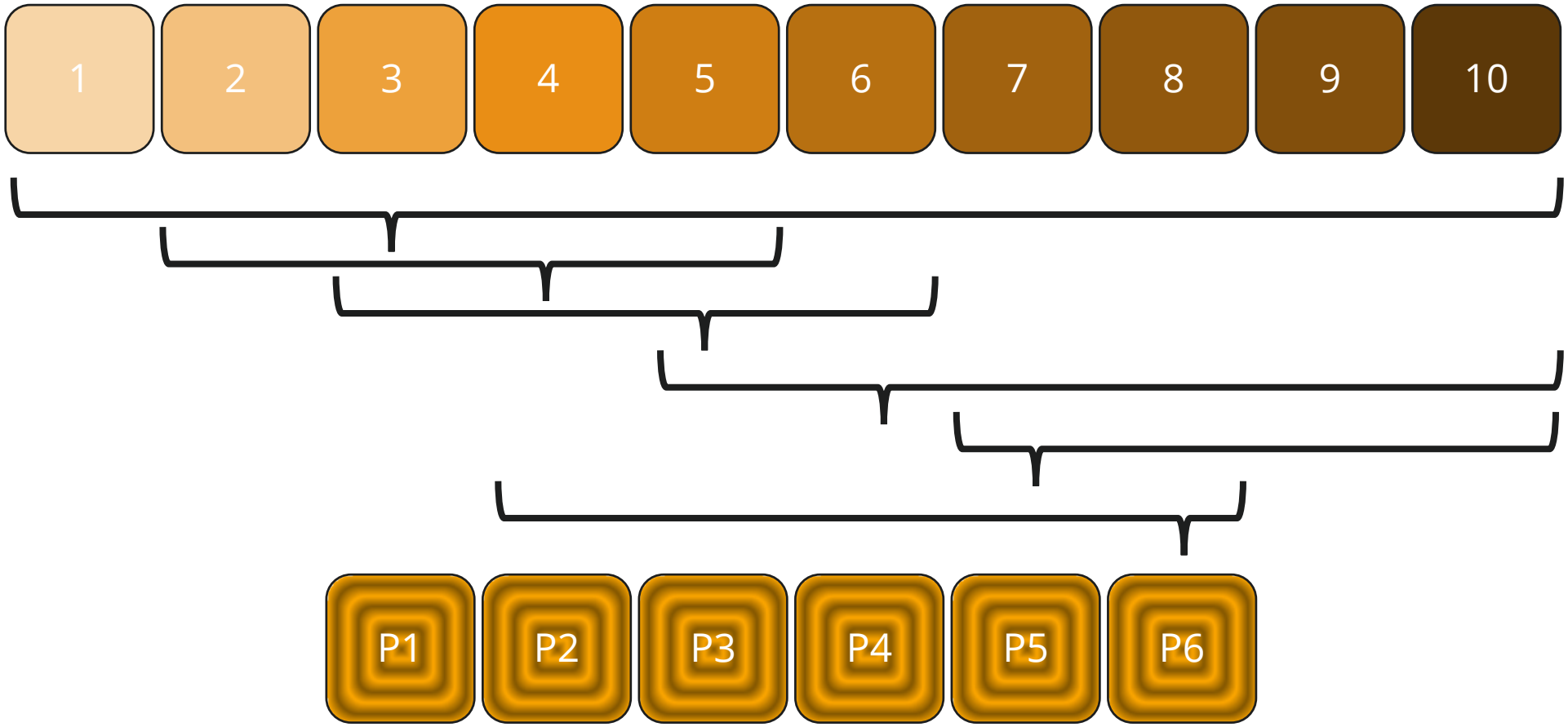
But new use cases require dynamic / versatile codes

- Edge caching
- Storage in mobile nodes

What RLNC can do

- New cloud storages can be filled with available information
- Some information might become lost or not available
- Filling storage on arrival without storing data in memory before decoding

RLNC



Overhead: scalable

What we looked at

- Reliability
- Privacy and security
- Storage space
- Costs
- Download speed
- Amount of transferred data
- Computational overhead of network coding

Reliability

Failures are not uncommon in the world of cloud computing:

- Google (partial): 16th of August 2013 , 18th-19th of March 2013, 11th of August 2008
- Microsoft Azure: 22nd of February 2013, 13th of March 2009
- Amazon S3: 31st of January 2013, 20th of July 2008
- Dropbox: 10 th of January 2013

Permanent data loss is possible too:

- Microsoft & T-Mobile Sidekick: 11th of October 2009

However, the chance that more than one provider is down at a given time is very low

Solution: distribute the data to multiple providers with some added redundancy

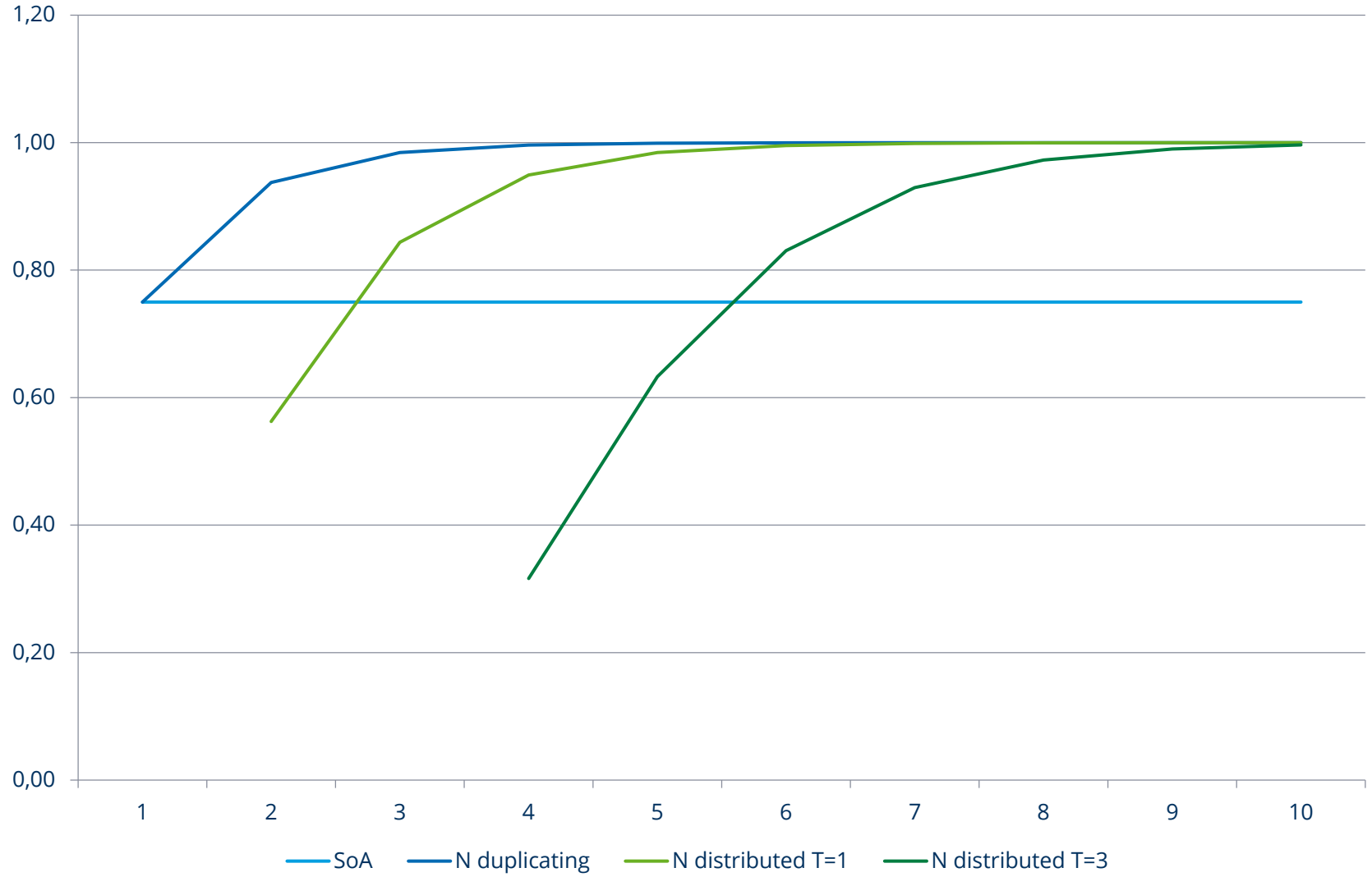
Reliability

It is relatively simple to calculate the probability that the data is not available at a given time:

$$\mathcal{P}(T, N, p) = 1 - \sum_{t=0}^{t=T} \binom{N}{t} \cdot (1-p)^{N-t} \cdot p^t$$

- N – number of clouds
- T – number of simultaneous cloud failure to be able to sustain
- p – the probability that a provider is unavailable

Reliability



Privacy and Security

One of the biggest hurdles holding back cloud computing is lack of trust in the providers

Security breaches:

- Sony PlayStation Network: 17th and 19th of April 2011 – 77 million accounts stolen
- Smaller breaches have occurred with most cloud computing providers

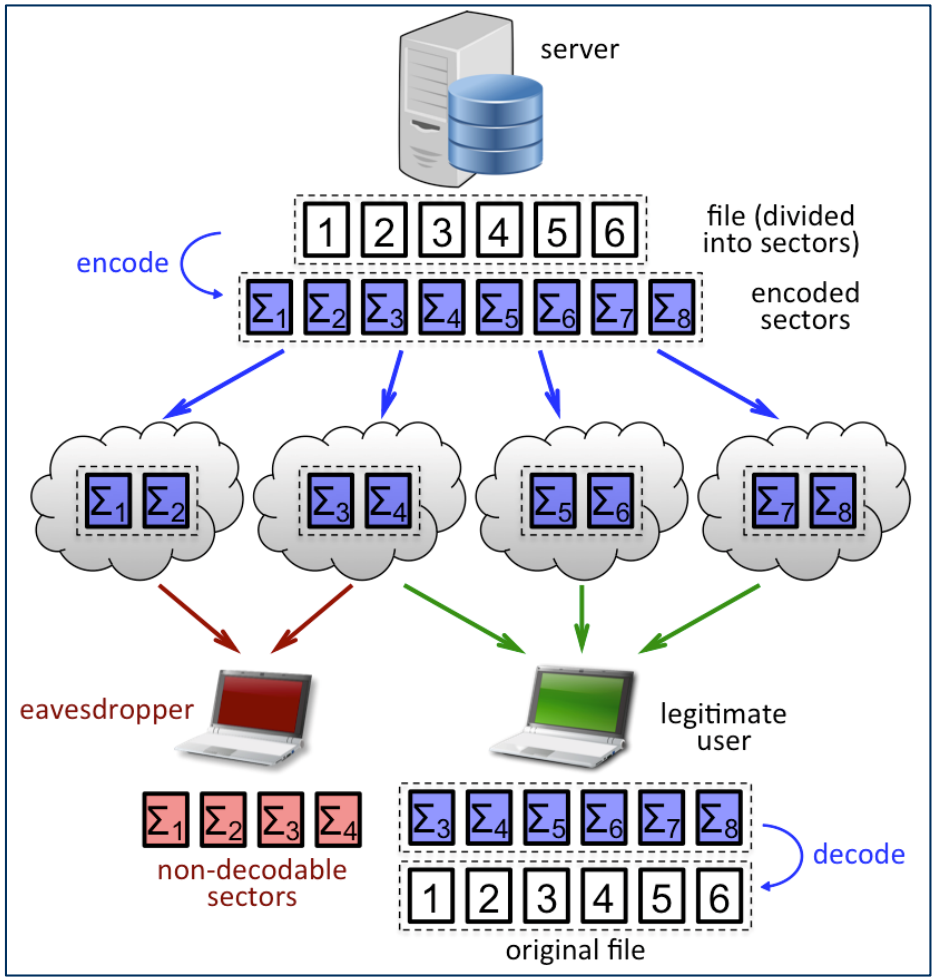
Government agencies have access to data stored by cloud services in some countries:

- PRISM

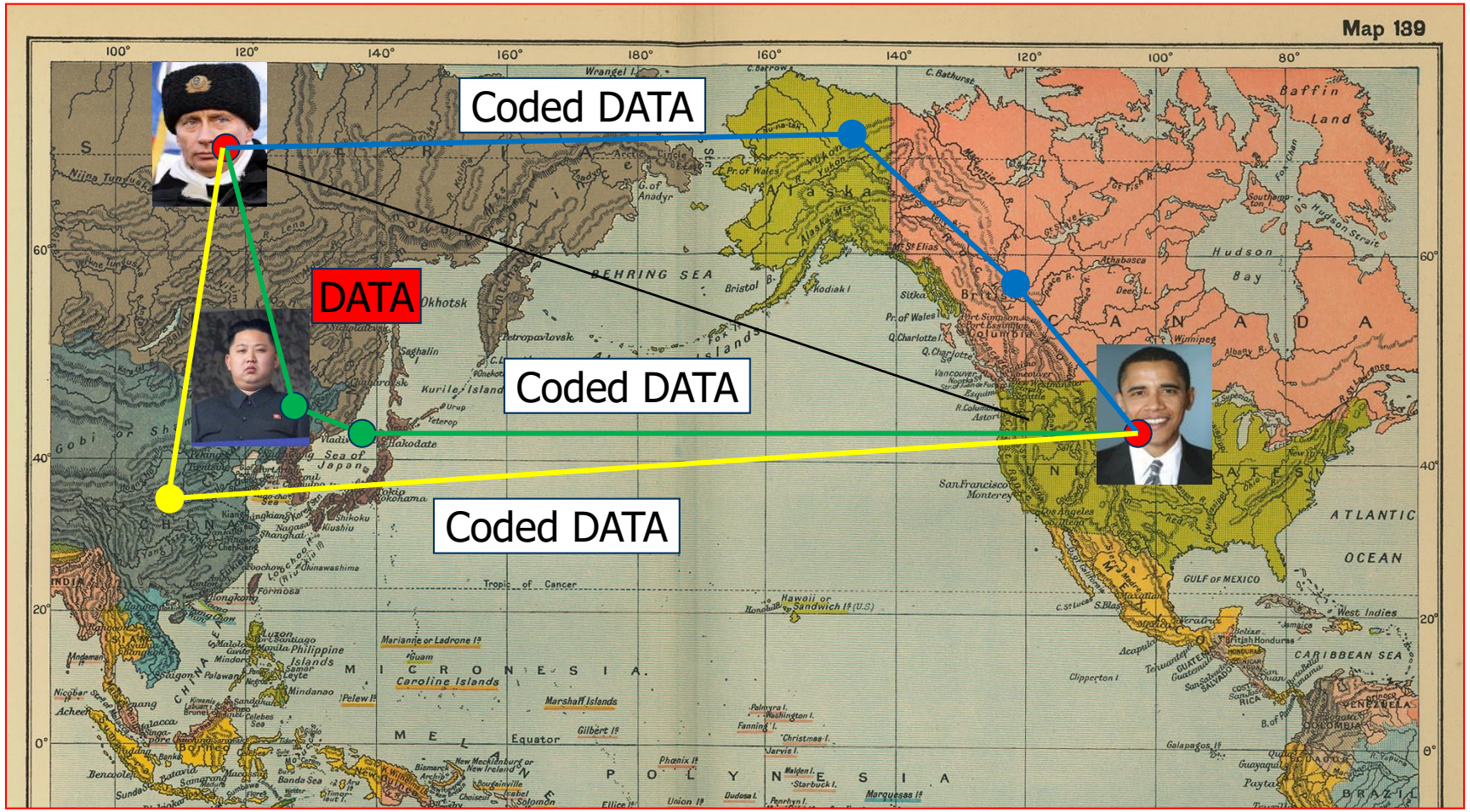
By using network coding, it is possible to force the attacker to need to compromise several of the providers to access any of the data

- The number of providers that need to be hacked can be set arbitrarily.

Coding as a Measure Content of Protection



Some insights for security



Erik Kline, USC ISI, kline@isi.edu

Storage costs

Each provider grants some free storage space. With our approach you can add up the capacities

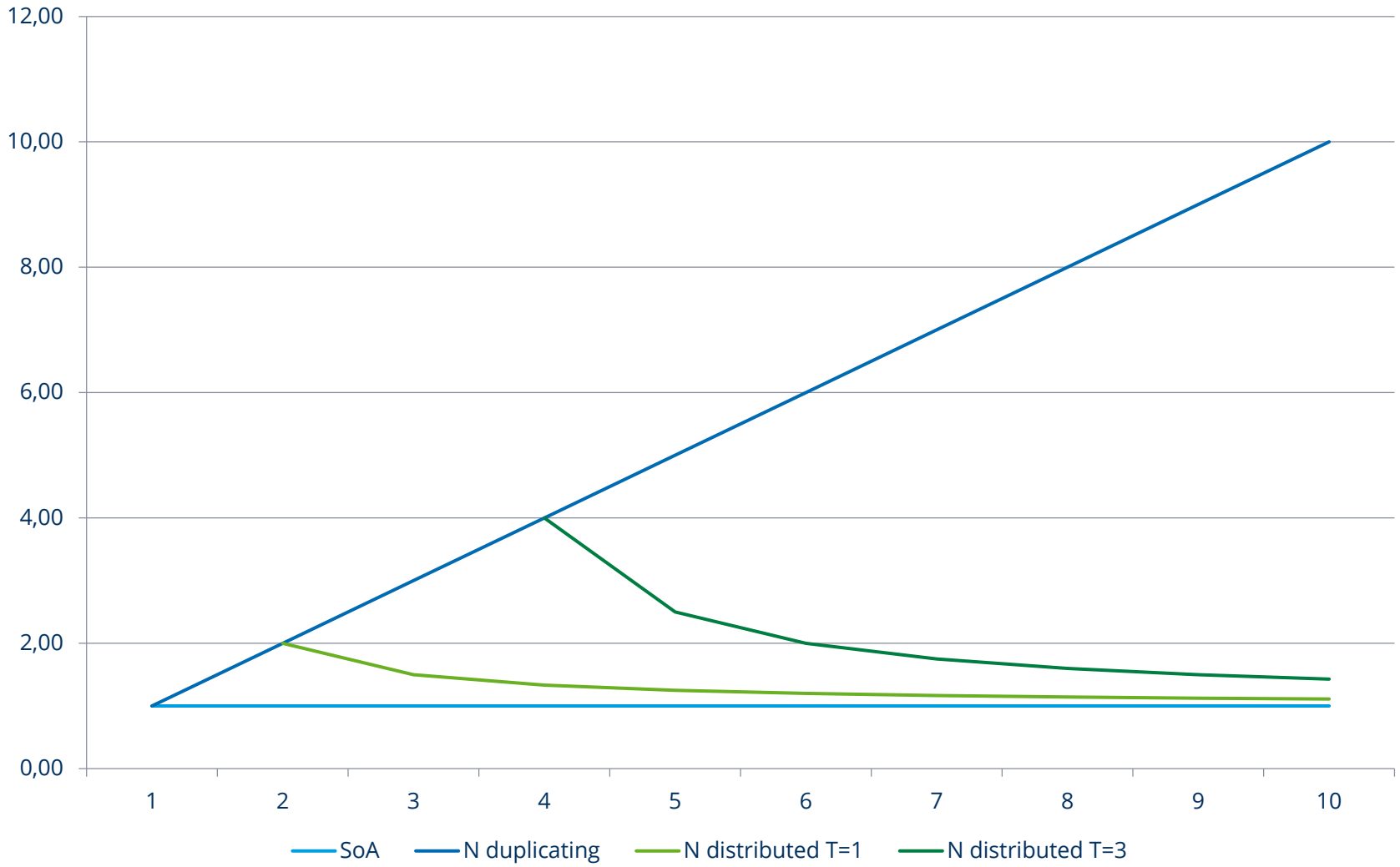
Reliability can be easily quantified in terms of costs. The required storage space is:

$$H(N,T,F,P) = \frac{N}{N-T} \cdot F = F + F \cdot \frac{T}{N-T}$$

- *F* – file size in bytes

Clearly if *N* >> *T*, the storage cost becomes negligible

Storage/Cost



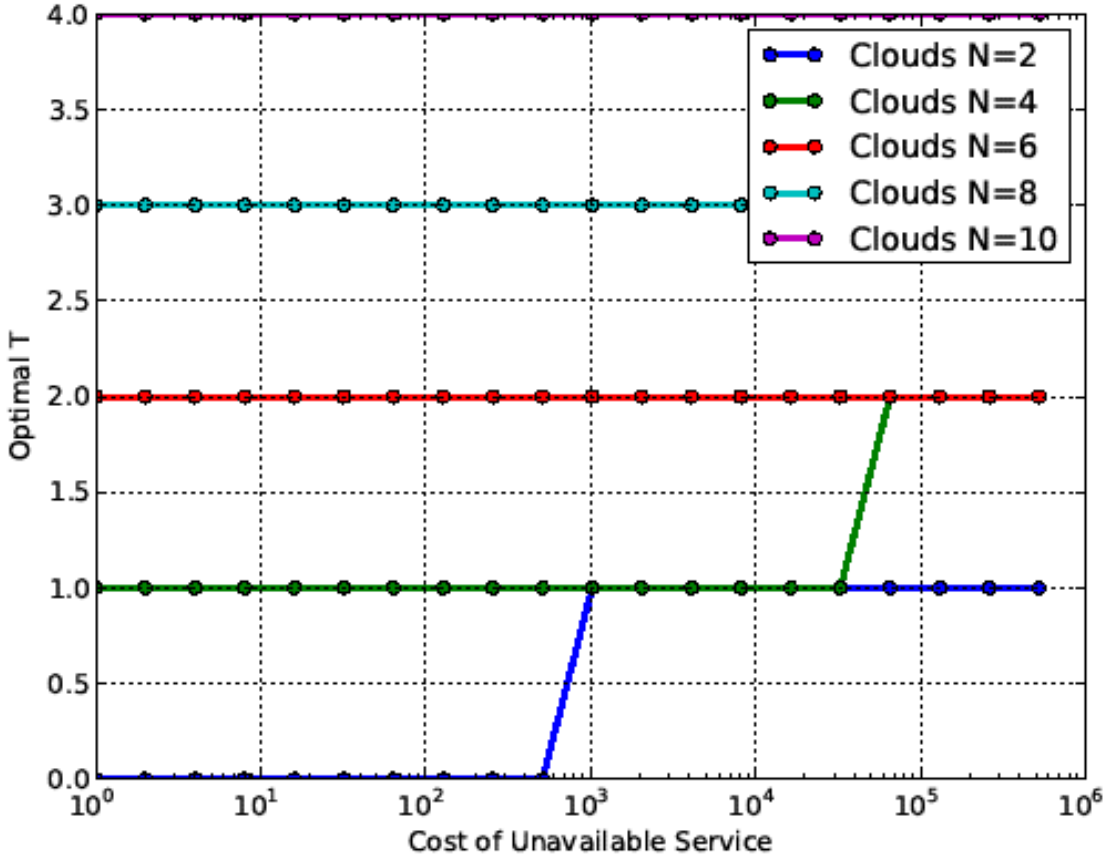
Total costs

The goal is to find the number of redundant clouds (T) for which the total cost is minimal:

$$\min_{T} H(N,T,F,P) + U_c \cdot \mathcal{P}\left(T,N,\{p_i\}\right)$$

- Uc – cost of data being unavailable
- H(N,T,F,P) –storage costs

Finding the optimal T



Download speed

Considering clouds with various download rates (R), the fraction of file requested from cloud c_i is:

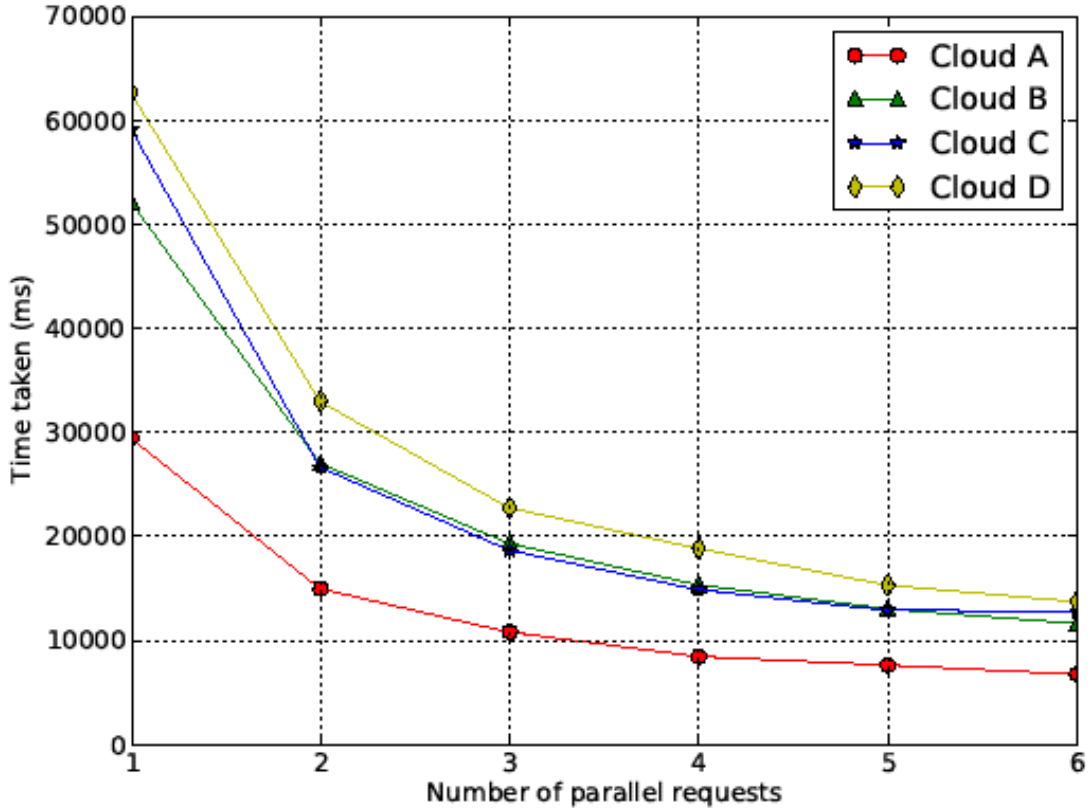
$$\alpha_i = \frac{R_{(c_i,u)}}{\sum_{i=1}^{N} R_{(c_i,u)}}$$

$$P_i = \max\left(\frac{1}{N-T}, \alpha_i\right) = \max\left(\frac{1}{N-T}, \frac{R_{(c_i,u)}}{\sum_{i=1}^{N} R_{(c_i,u)}}\right)$$

If we chose to optimize for download speed whilst still ensure a give level of reliability, the fraction of data stored in cloud should c_i be at least:

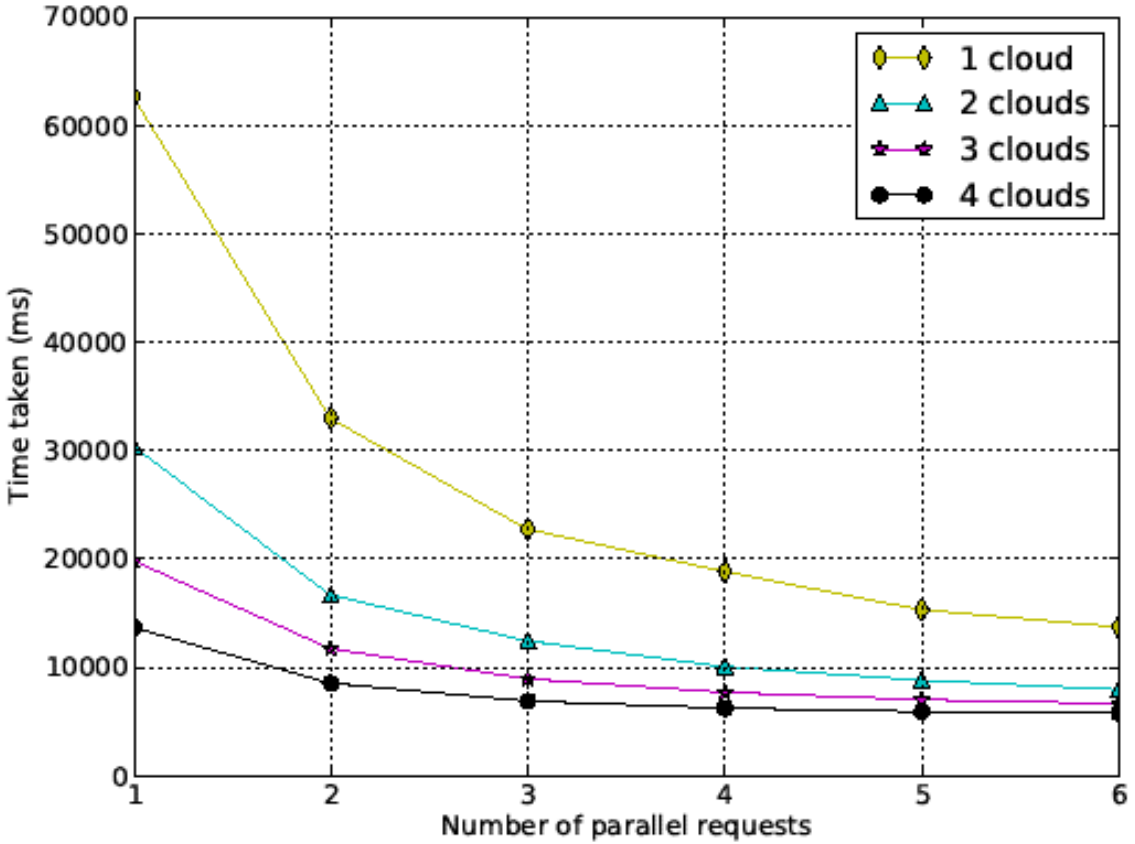
Download speed – individual clouds

We looked at how each cloud performs on its own. 16 MB file, packets of 512k



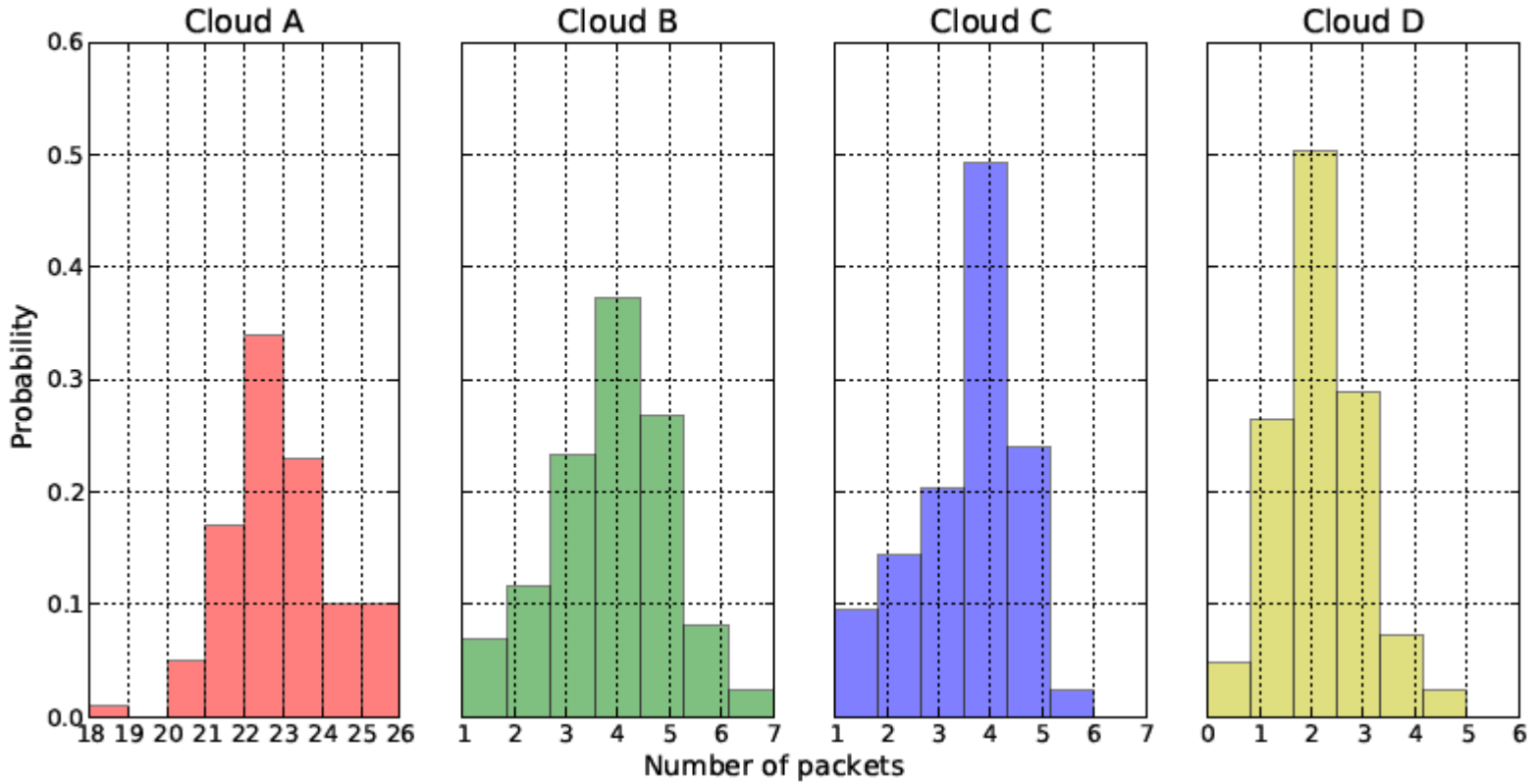
Why use multiple clouds?

Collaboration



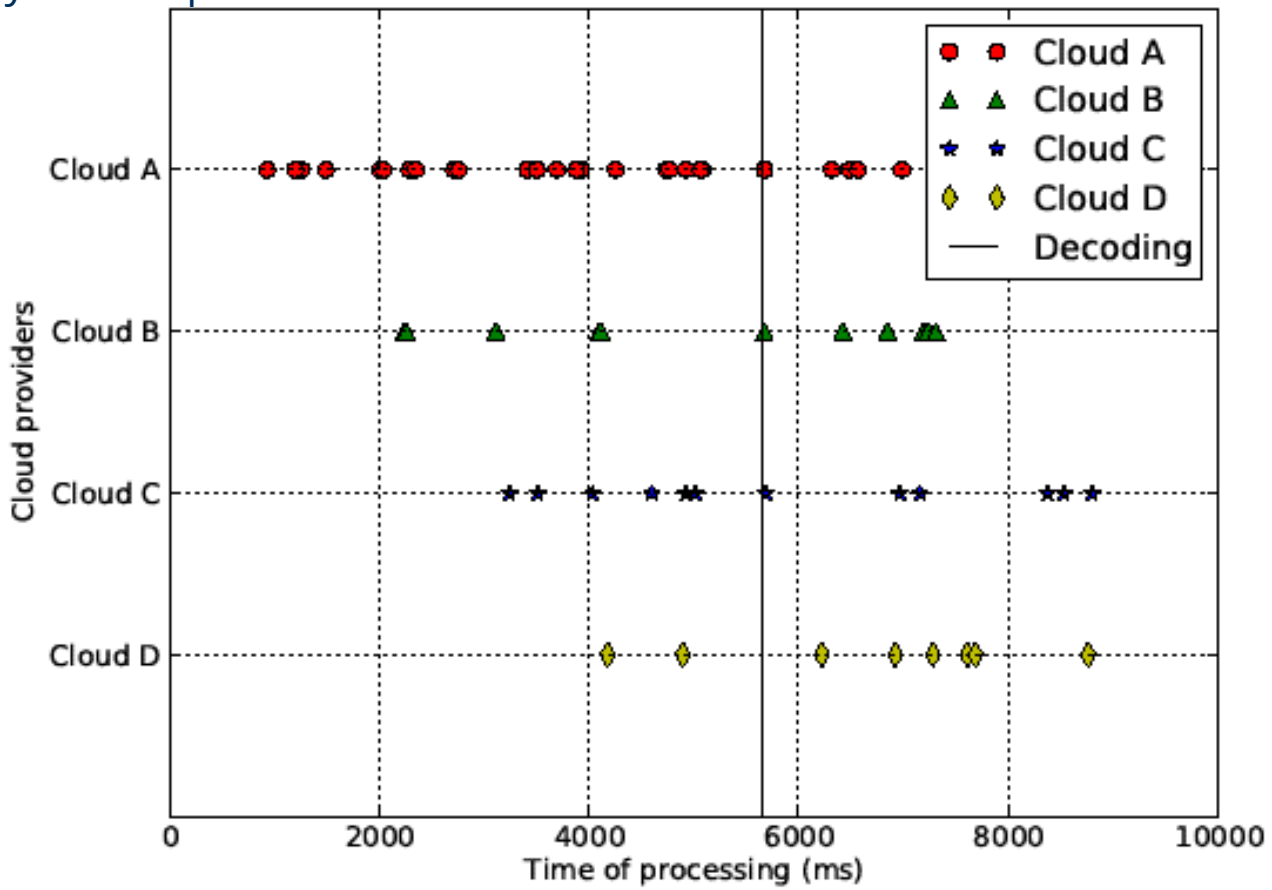
Why use network coding?

Conditions change.

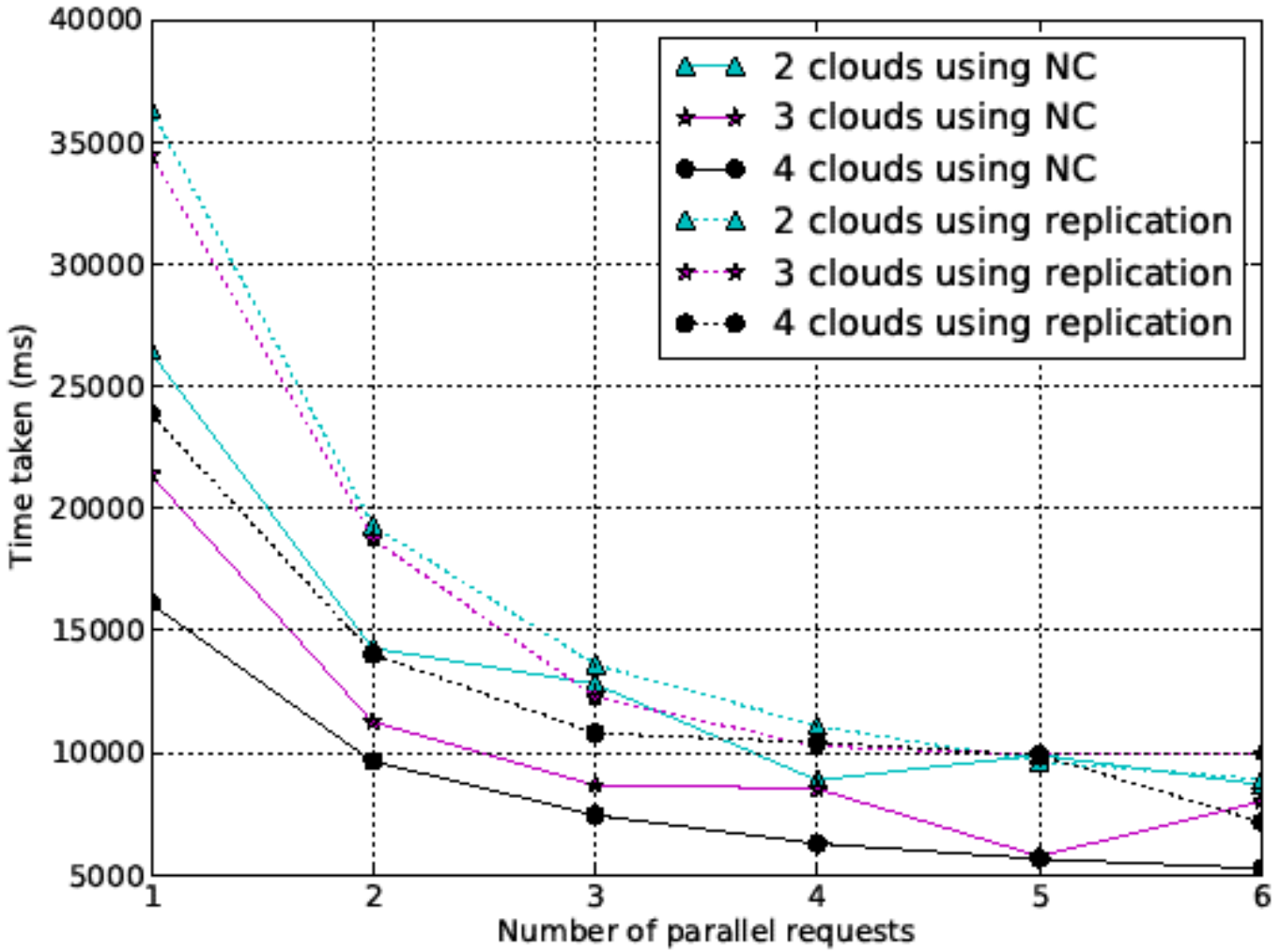


Why use network coding?

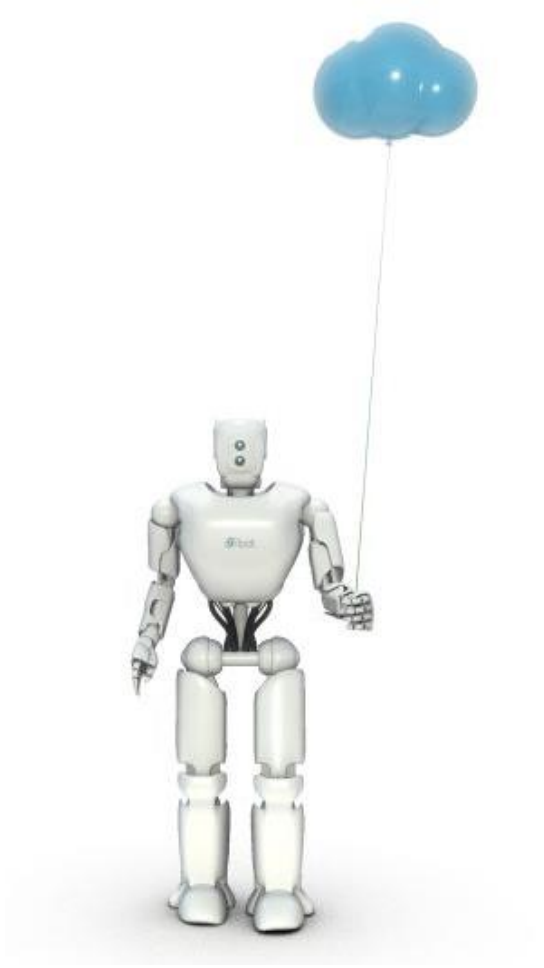
Collaboration is usually not simple



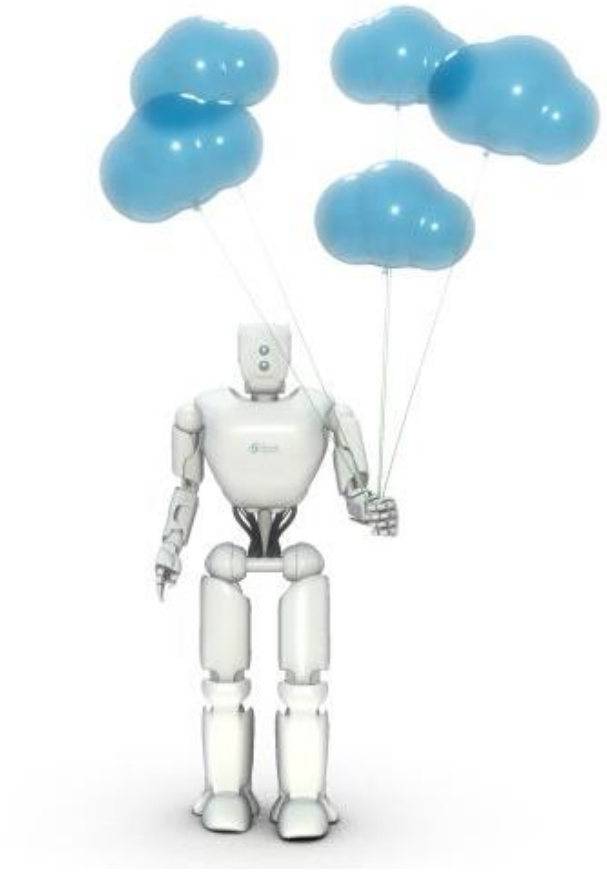
Comparing NC to replication redundancy



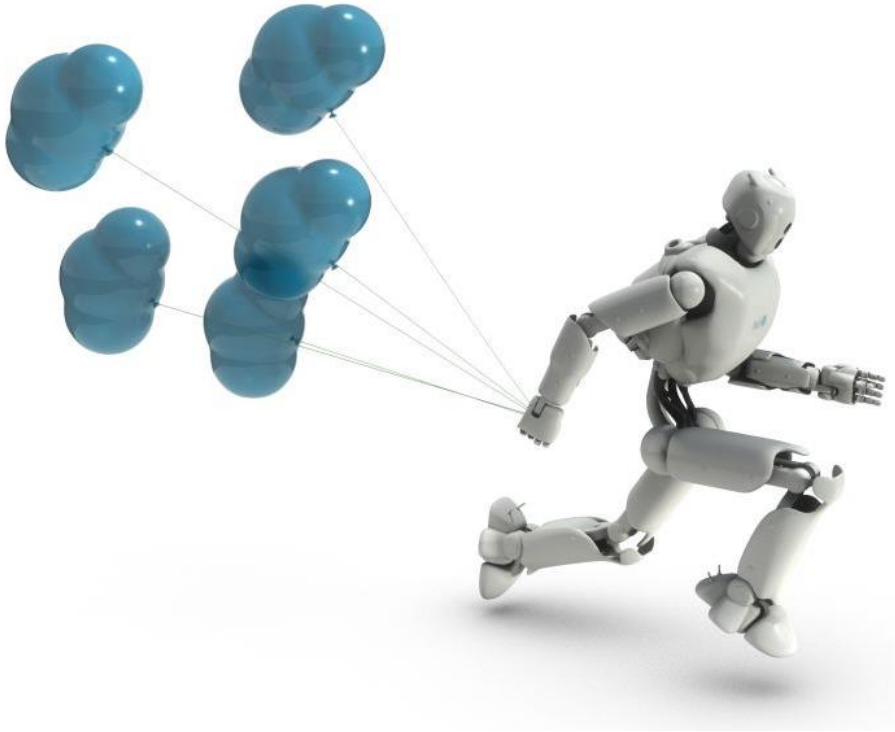
Cloud Evolution



Single/Static



Distributed/Static



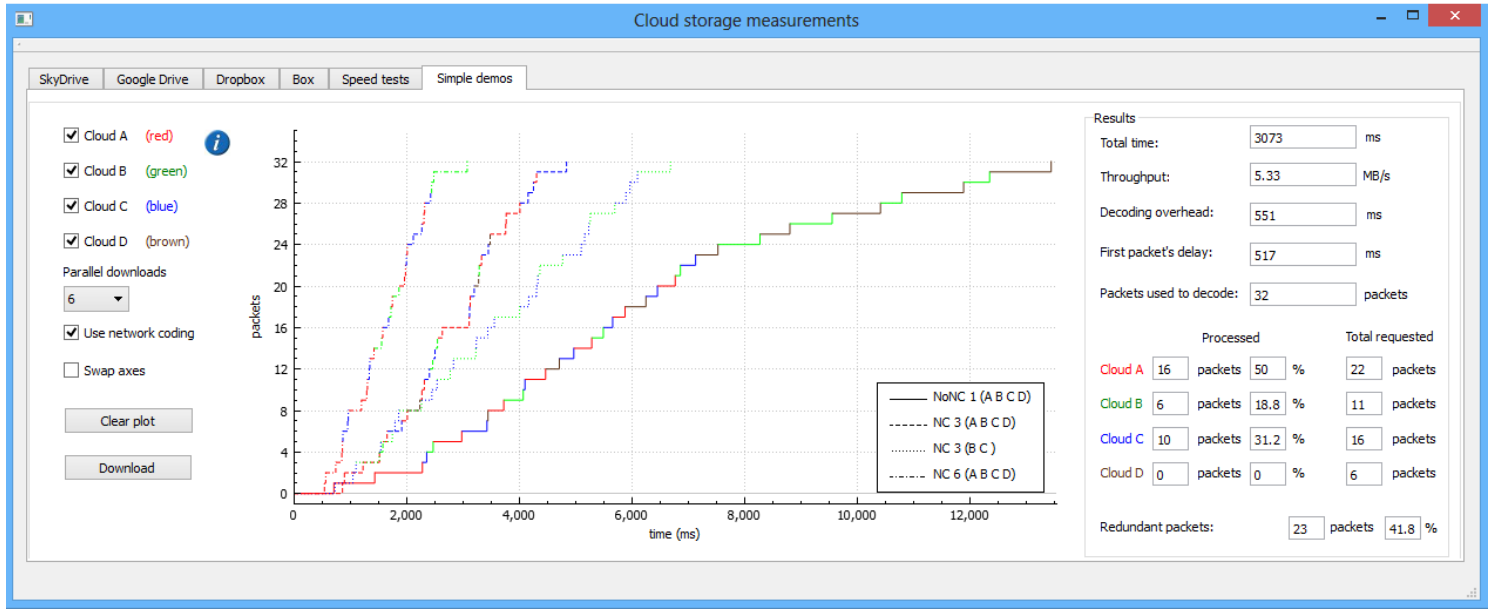
Distributed/Agile

Example: Distributed Cloud

Measurement campaign

Implementation using commercial cloud solution (Dropbox, Box, Skydrive, and Google Drive) to:

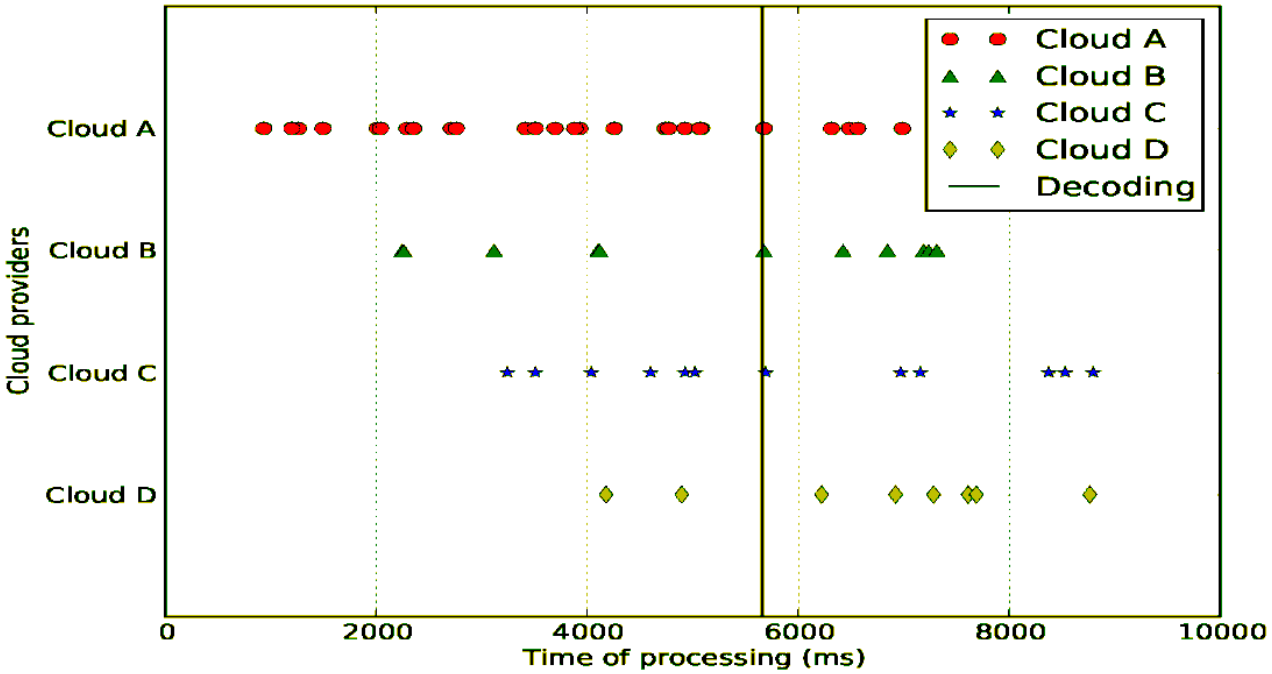
- Showcase theoretical results
- Perform practical measurements



Simple UI to be able to quickly explore different scenarios.

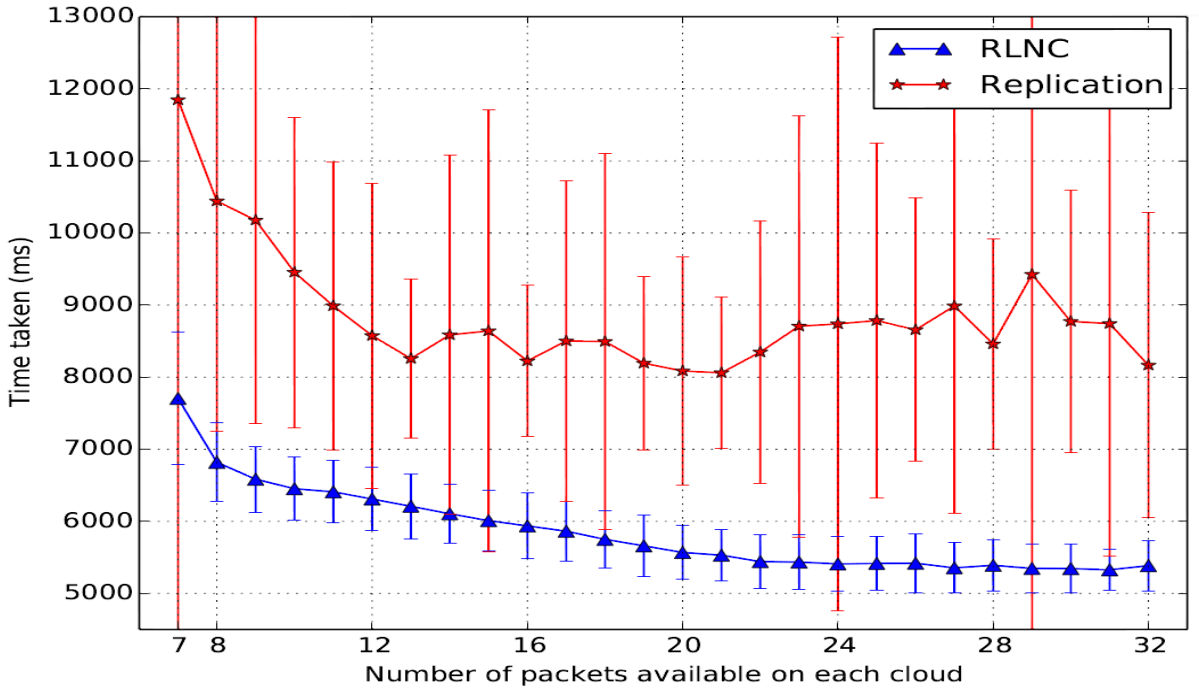
Example: Distributed Cloud

- Heterogeneity (4 clouds)



- Speed-Up (5 clouds)

  RLNC does not need full degree of freedom



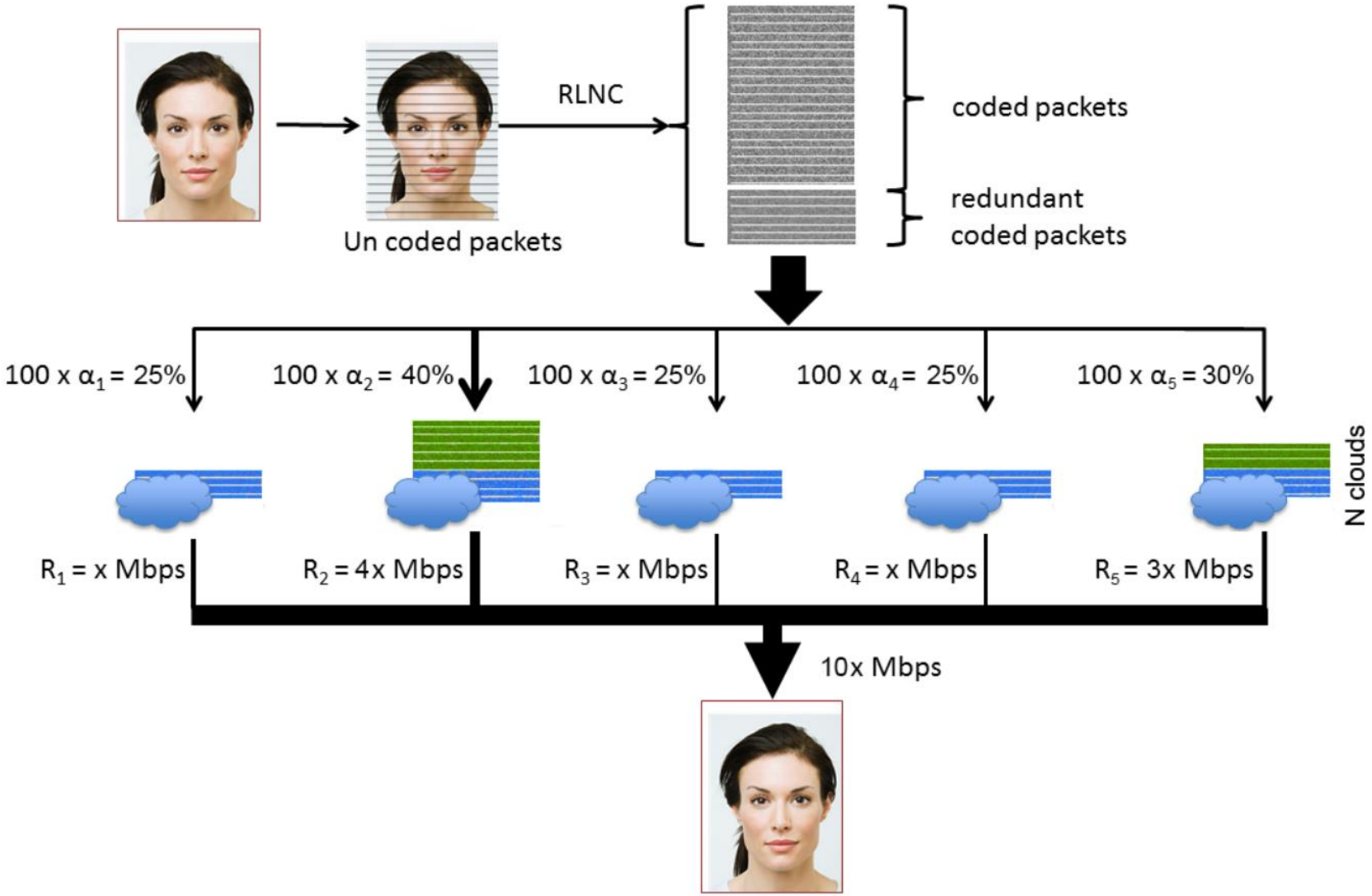
- M. Sipos, F.H.P. Fitzek, D. Lucani, and M.V. Pedersen, “Dynamic Allocation and Efficient Distribution of Data Among Multiple Clouds Using Network Coding,” in IEEE International Conference on Cloud Networking (IEEE CloudNet’14), Oct. 2014.
- M. Sipos, F.H.P. Fitzek, D. Lucani, and M.V. Pedersen, “Distributed Cloud Storage Using Network Coding,” in IEEE Consumer Communication and Networking Conference, Jan. 2014.

Storage Benefits in Dynamic Settings

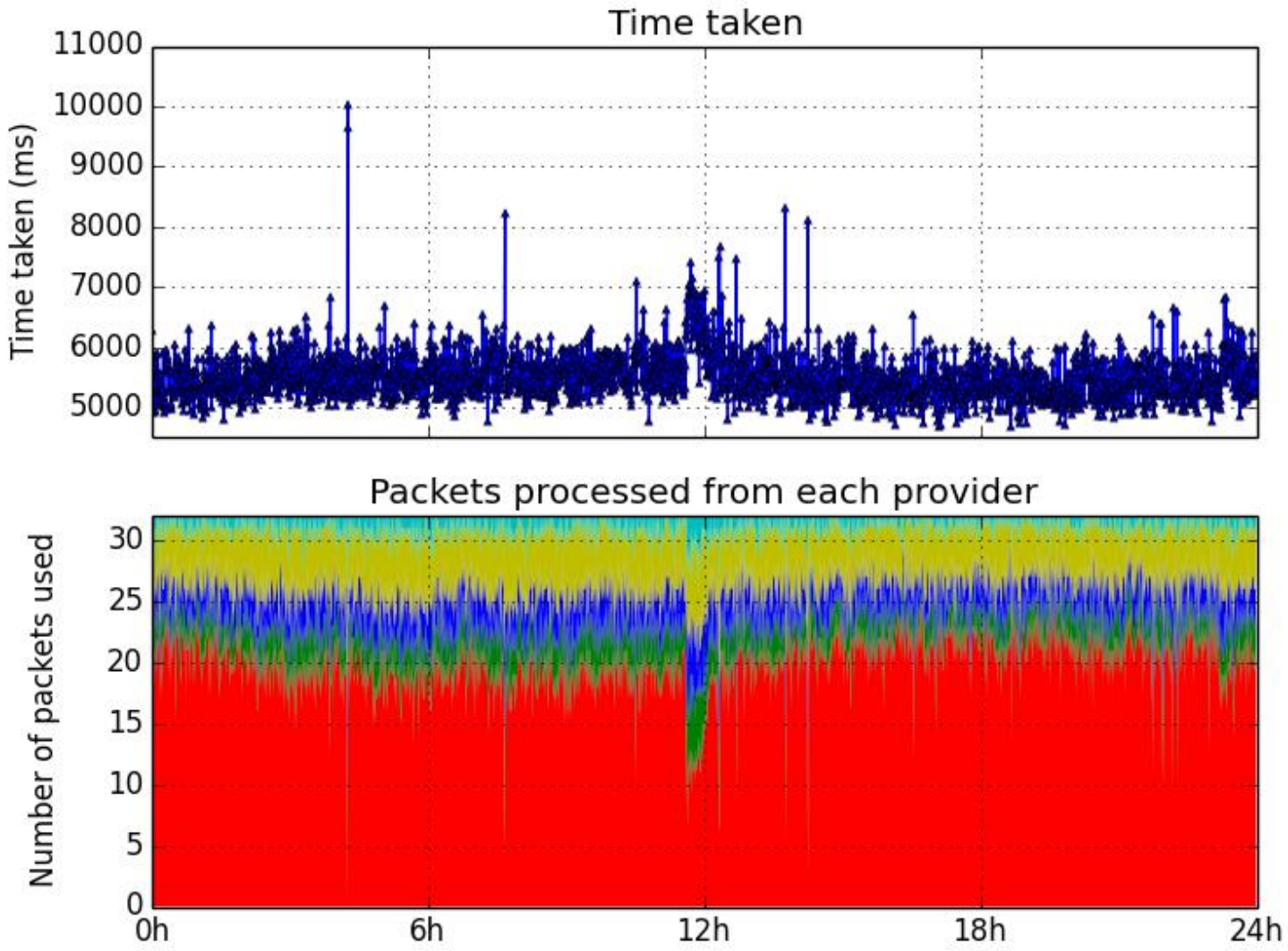
Comparing a FULLY decentralized approach (no coding, RS, RLNC) versus a centralized version (no coding, RS).

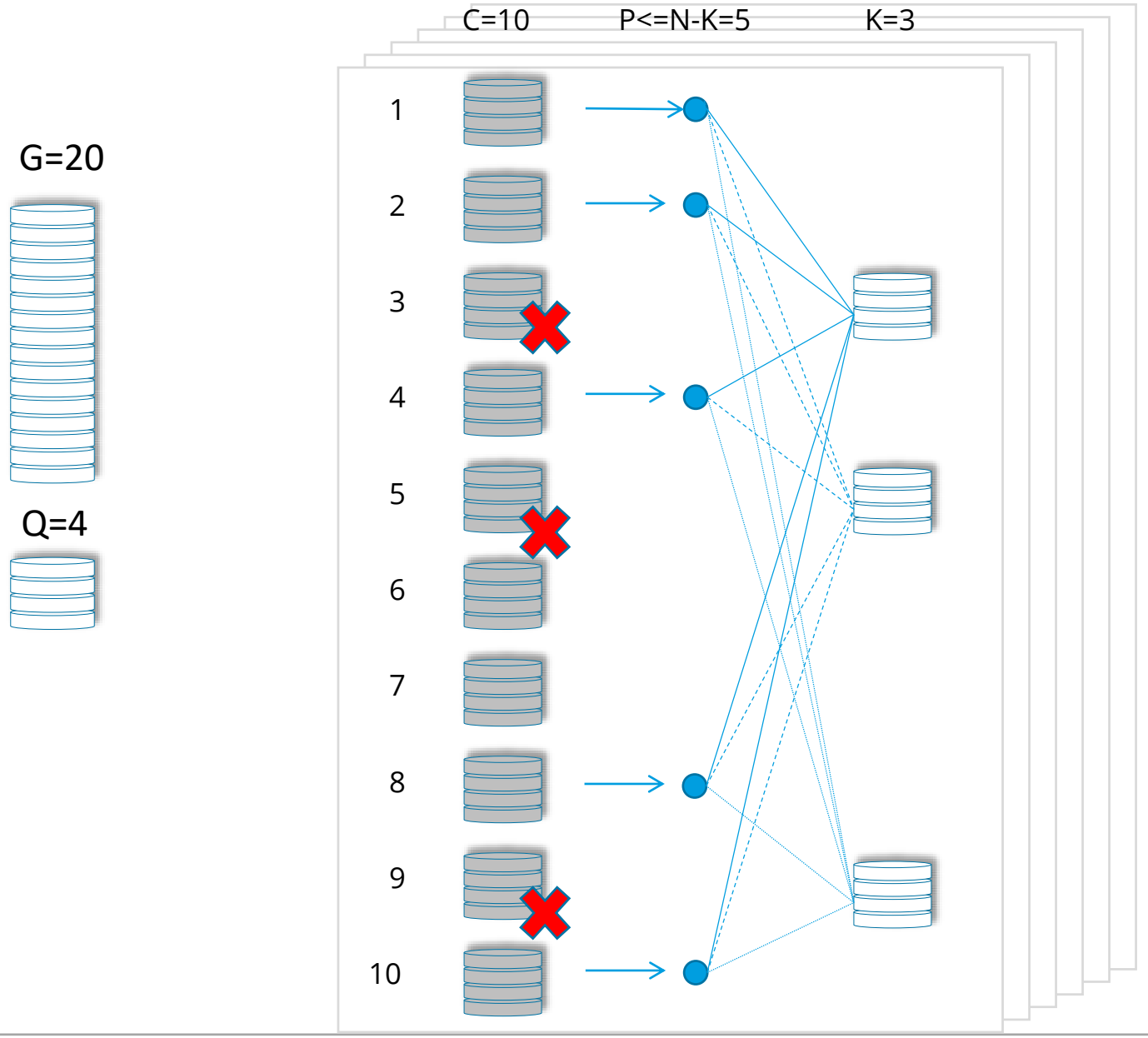
Dynamic: Not all racks are available temporarily (load, traffic, power)

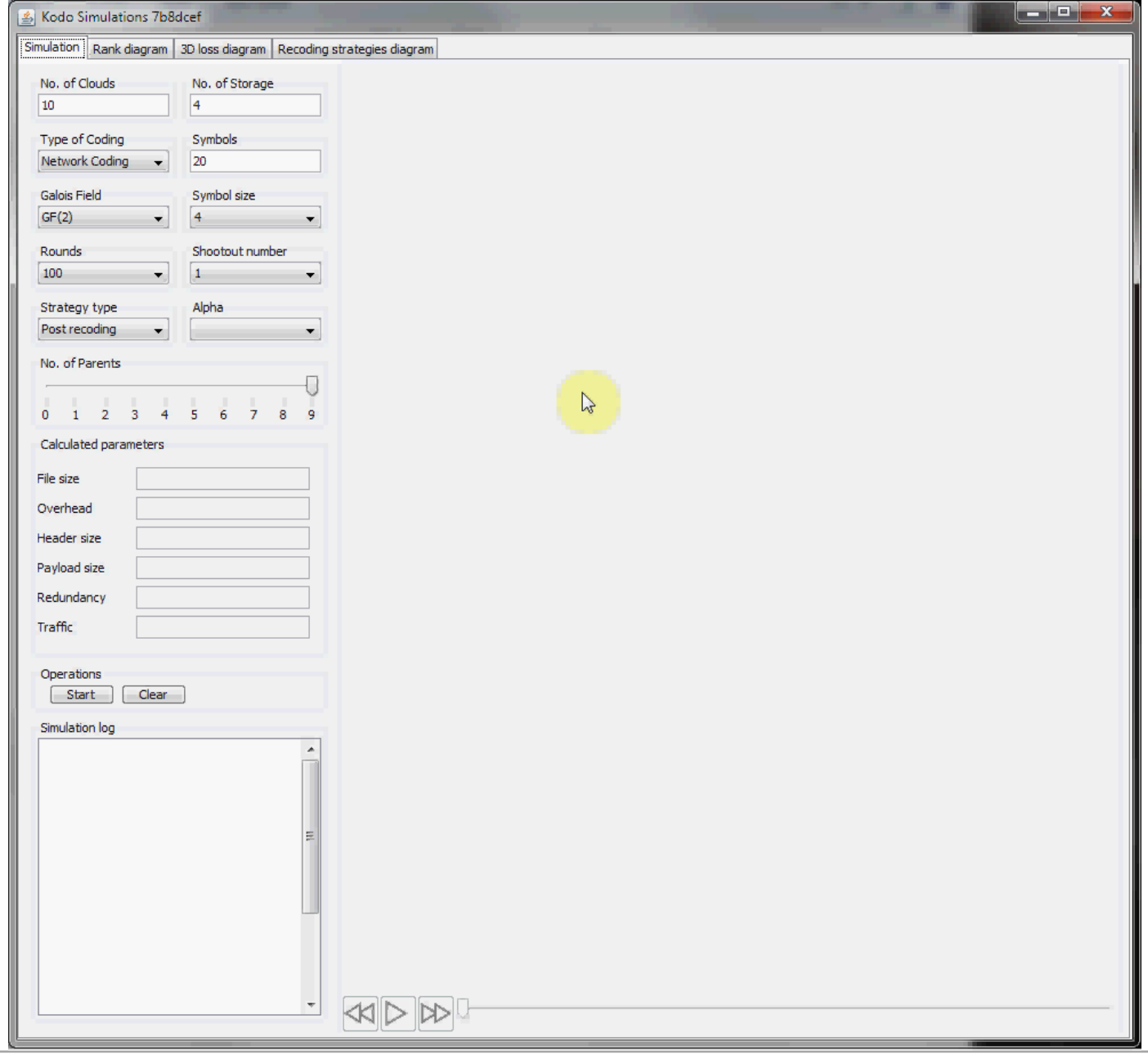
Dynamics in Distributed Clouds



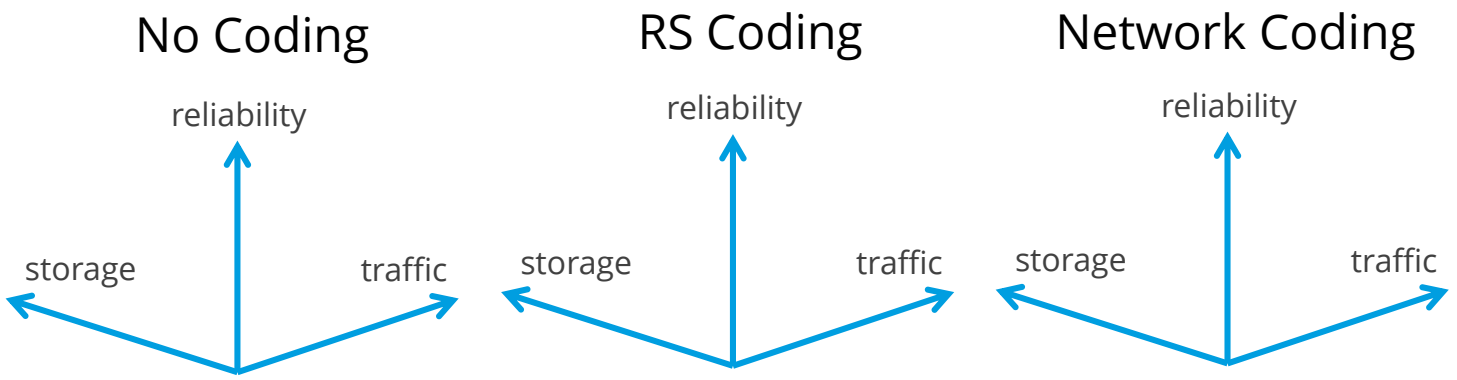
Dynamics in Distributed Clouds




G=20
Q=4
C=10
P<=N-K=5
K=3
1
2
3
4
5
6
7
8
9
10
Rounds


Kodo Simulations 7b8dcef
Simulation
Rank diagram
3D loss diagram
Recoding strategies diagram
No. of Clouds
10
No. of Storage
4
Type of Coding
Network Coding
Symbols
20
Galois Field
GF(2)
Symbol size
4
Rounds
100
Shootout number
1
Strategy type
Post recoding
Alpha
No. of Parents
0 1 2 3 4 5 6 7 8 9
Calculated parameters
File size
Overhead
Header size
Payload size
Redundancy
Traffic
Operations
Start
Clear
Simulation log

Data Survival Over Time

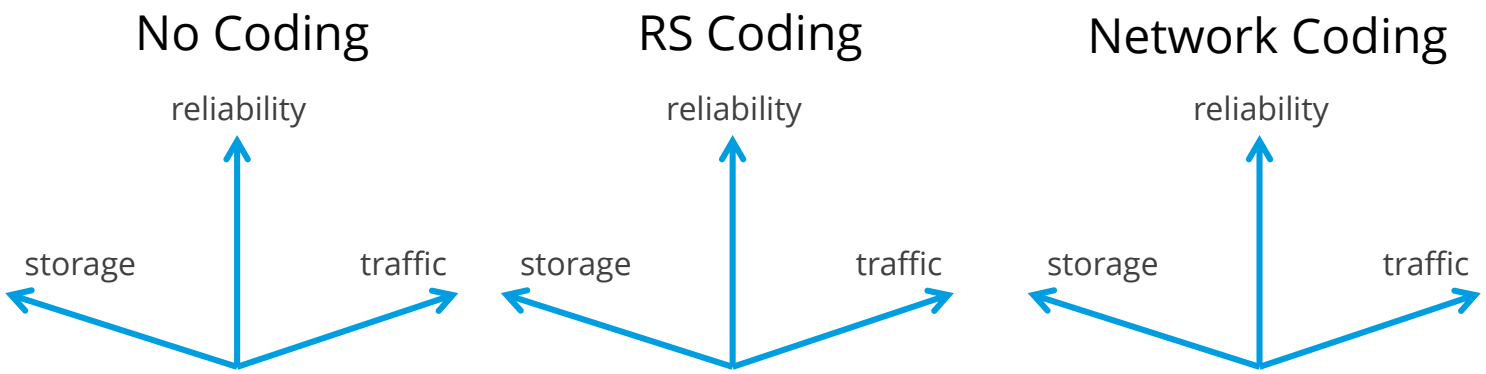


Distributed Policy

Limited knowledge of network state

Local decisions

Practical, scales well



„Genie“ Policy

Perfect knowledge of network state (high cost to update)

Optimal decisions

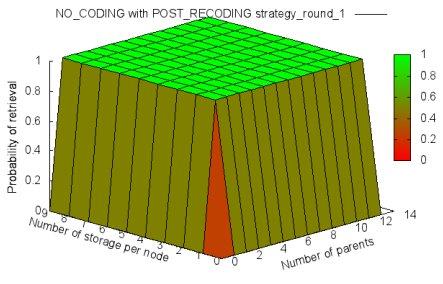
Not practical in large scale, dynamic systems

Current systems are somewhere in between these two policies

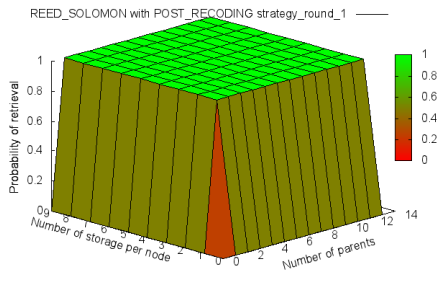
Data Survival Over Time

Distributed Policy

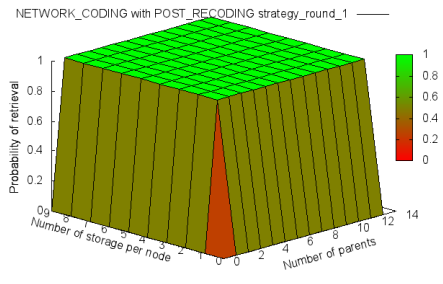
No Coding



RS Coding

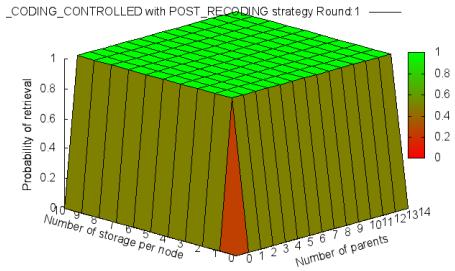


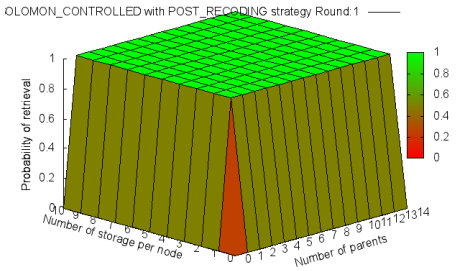
Network Coding

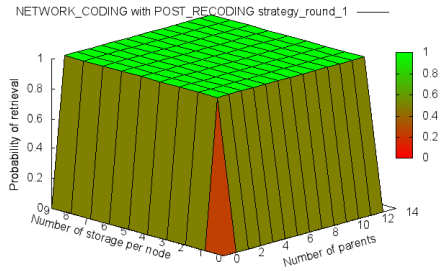


state-less

„Genie“ Policy







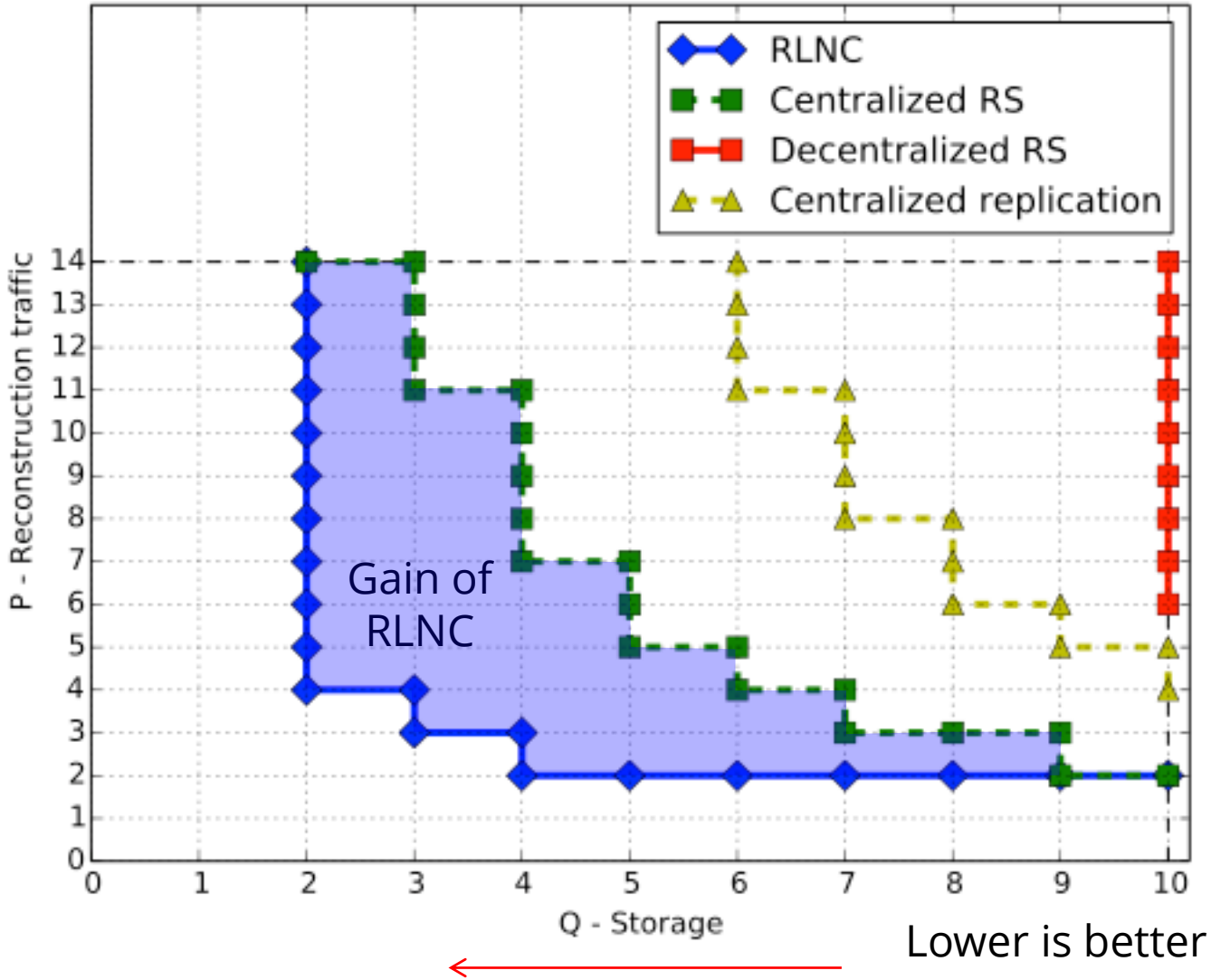
Over best alternative, NC buys you:

- Up to 65% reduction in storage
- Up to 71% reduction in network use

No costly methods to maintain a perfect knowledge of network state

Data Survival (large # of runs)

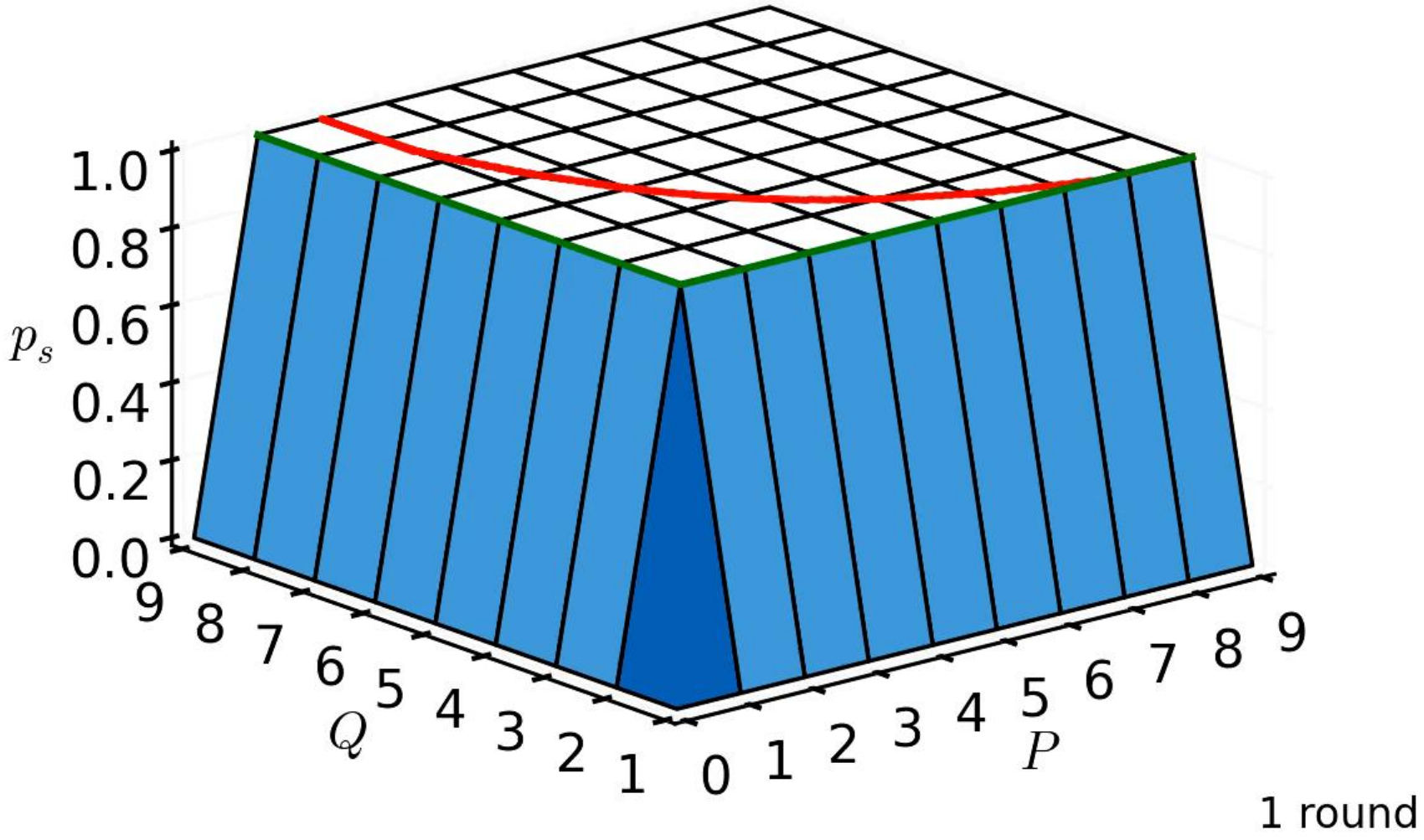
Lower is better



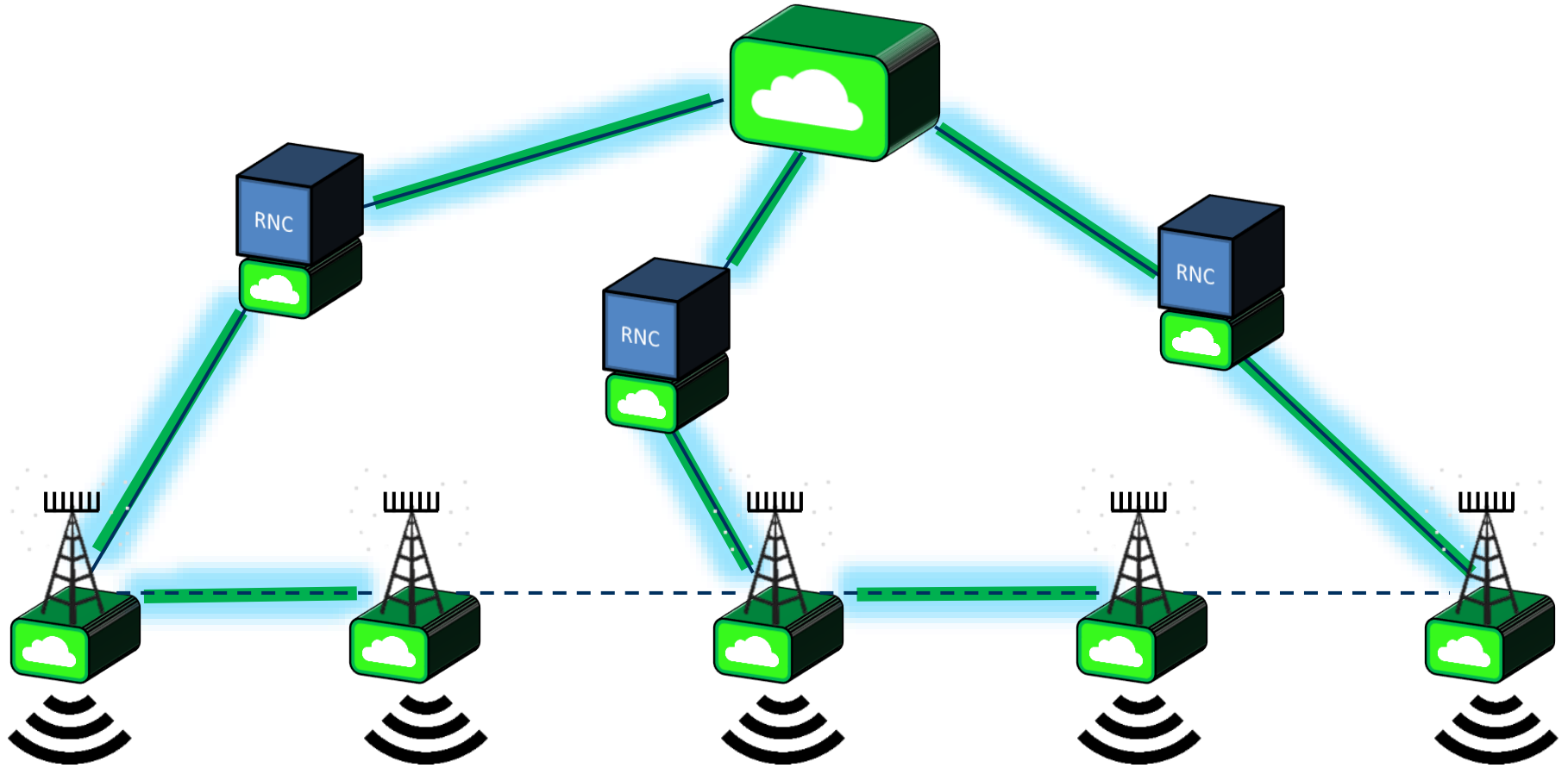
Top view of 3D plots

Lower is better

Ongoing Research



Mobile Edge Cloud / Micro Cloud / Cloud



Updating Coded Stored Data

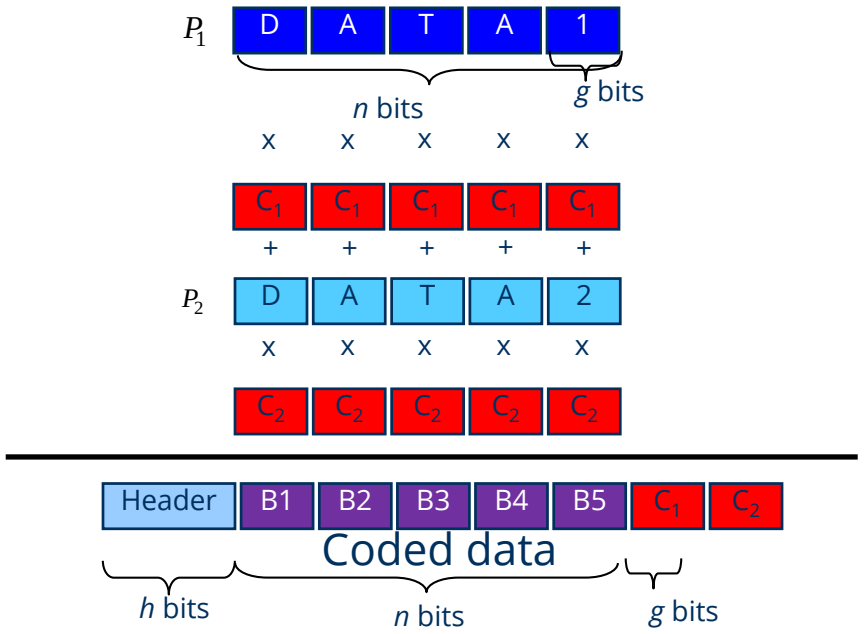
Generating a Coded Packet

Generating a Network Coded Packet

Operations over Finite Fields

$$CP_j = \sum_i C_i P_i$$

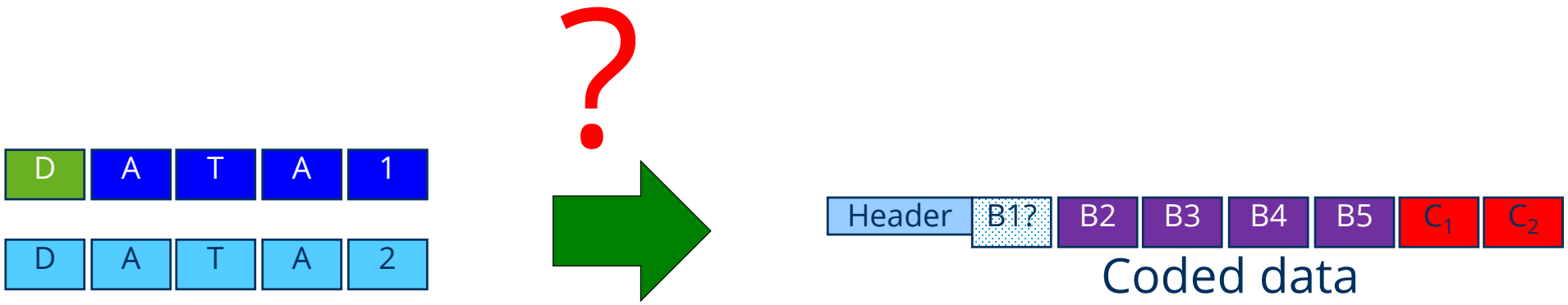
e.g. g = 8 bits, q = 256



Updating the Data

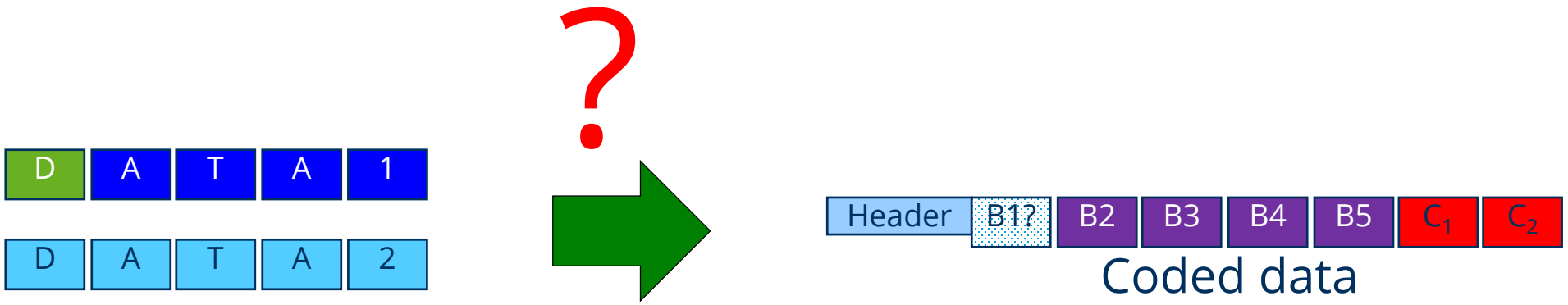
If one of the packets changed

- What do we need to transmit over the network?
- How do we update the data at the storage node?



Updating the Data

The storage node must compute the new value. How?

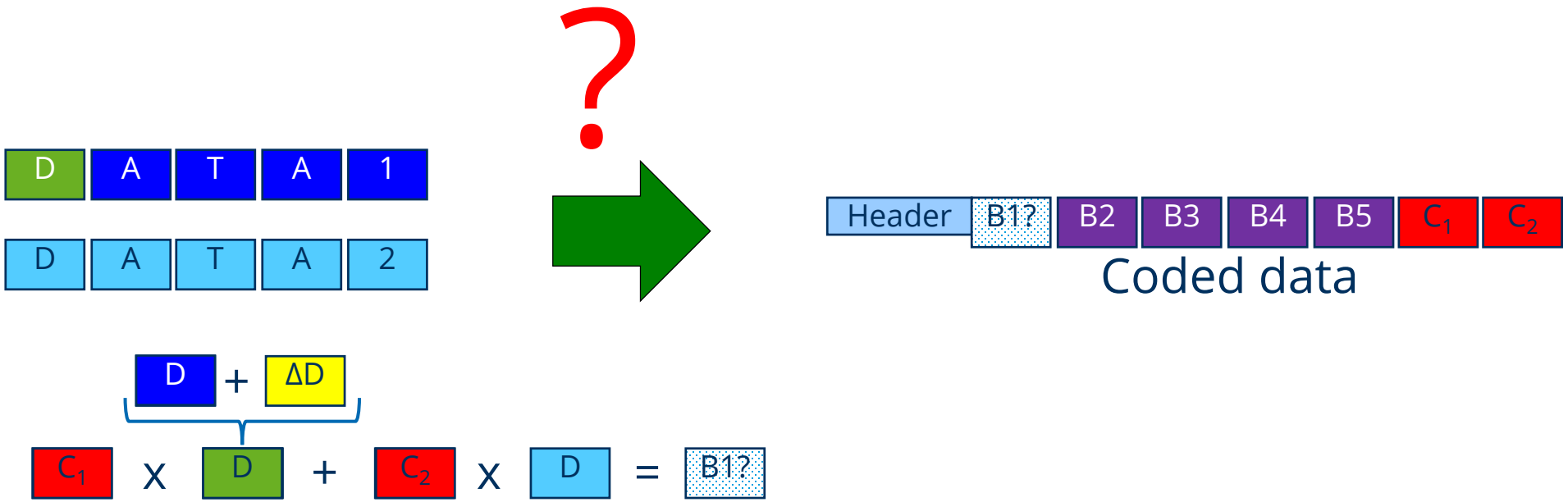


C_1 x D + C_2 x D = B1?

Updating the Data

The storage node must compute the new value. How?

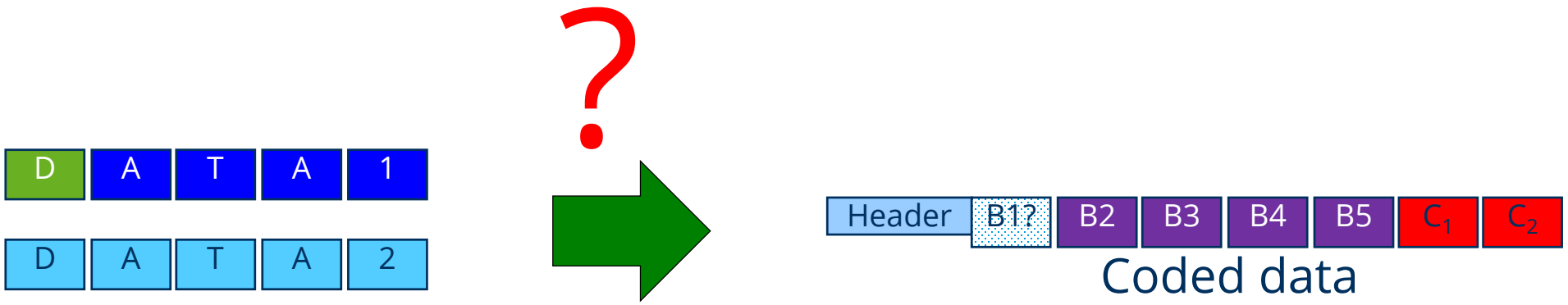
- The changed information is the old value plus a delta



Updating the Data

The storage node must compute the new value. How?

- The changed information is the old value plus a delta
- If we expand the expression, we get:

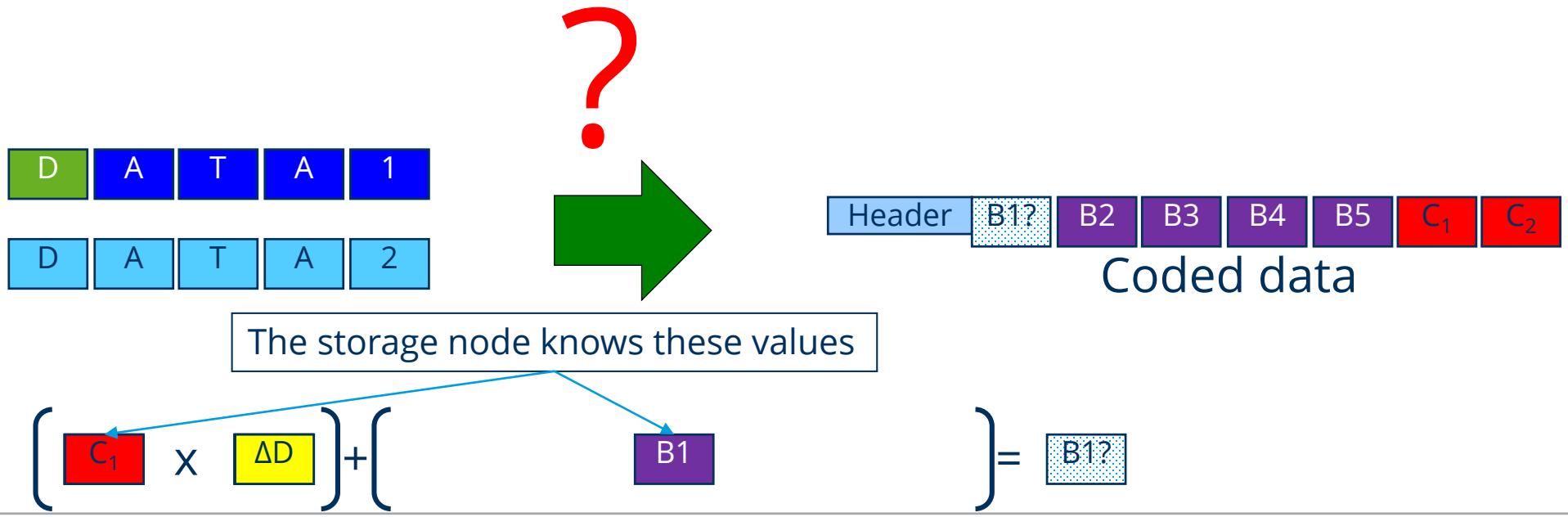


$$\left(C_1 \times \Delta D \right) + \left(C_1 \times D + C_2 \times D \right) = B1?$$

Updating the Data

The storage node must compute the new value. How?

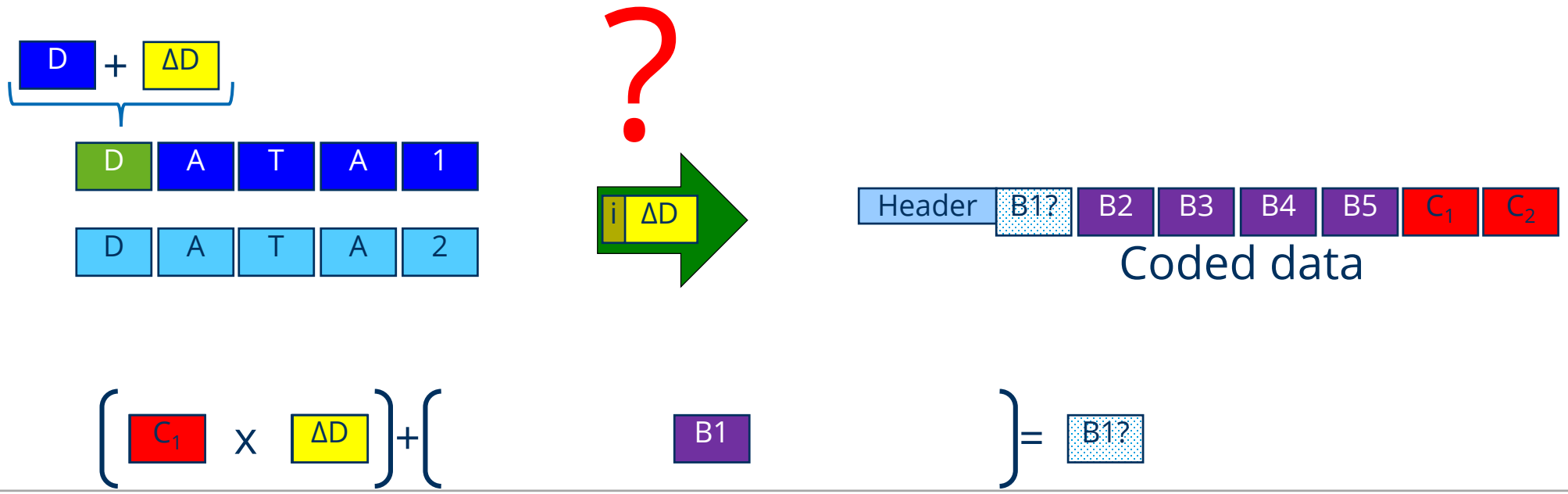
- The changed information is the old value plus a delta
- If we expand the expression, we get:
- The second part of the expression is equal to the old value



Updating the Data

The storage node must compute the new value. How?

- Therefore, we only need to broadcast over the network the deltas of the changes
- The storage nodes can compute the new values



On Network Traffic Considerations

Update Traffic:

- Replication:
  - The system must broadcast the new changed symbols. One byte to change one byte
- Reed-Solomon:
  - The system must encode again the information, and transmit the new packets
  - Many bytes transported to change one byte
- Network Coding:
  - The system must broadcast the new changed symbols. One byte to change one byte
  - Same as replication

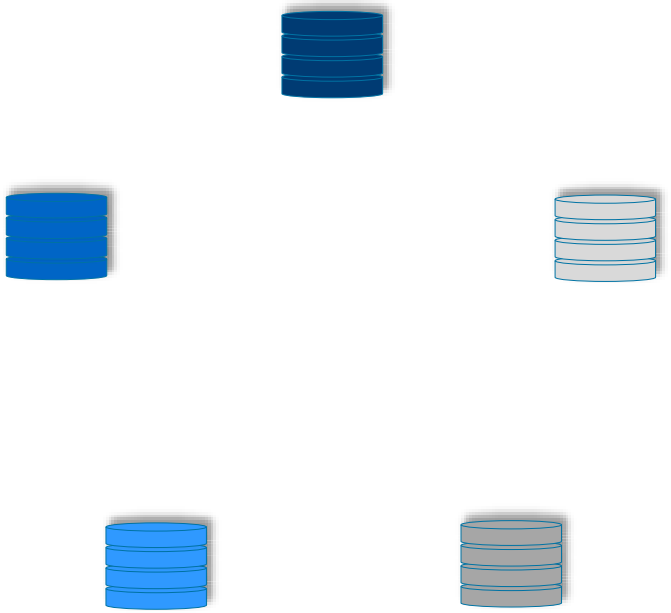
On Network Traffic Considerations

	Storage Costs	Repair Costs	Update Costs
Replication	X	✓	✓
Reed-Solomon	✓	X	X
Network Coding	✓ Optimal	✓	✓

INTER RACK / INTER CENTER

More on Regenerating Codes

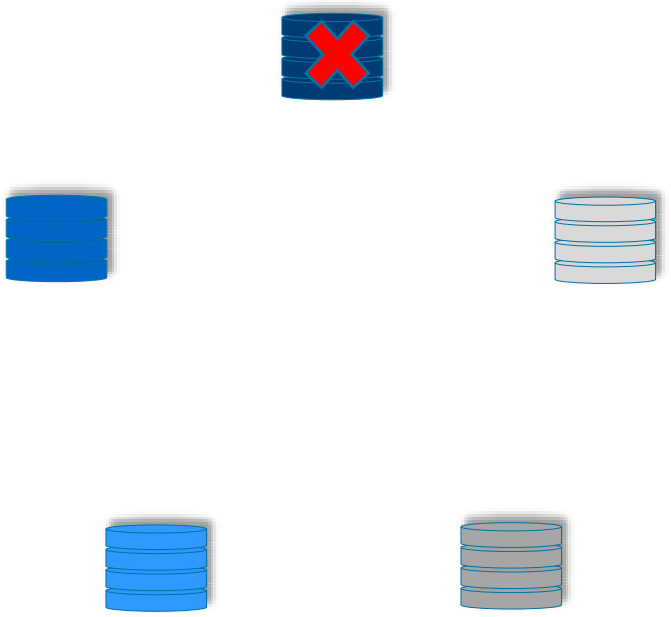
File made up of 15 chunks



Stored in 5 racks,
4 chunks each
Redundancy 33%

Example 1

File made up of 15 chunks

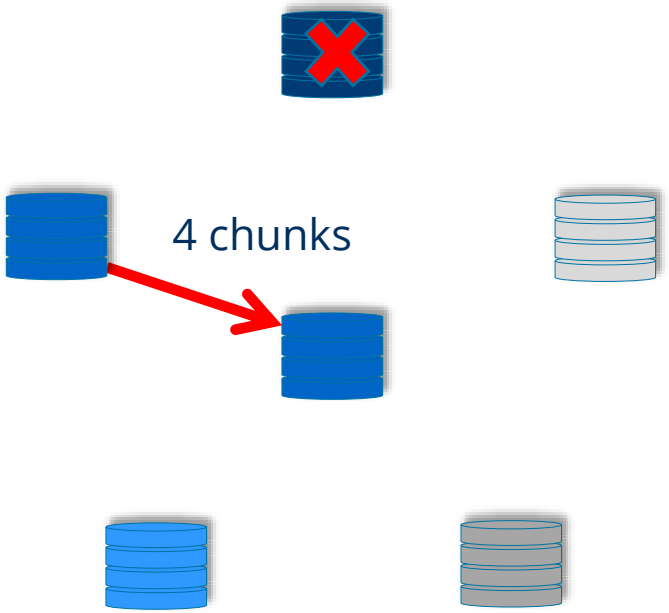


Stored in 5 racks,
4 chunks each
Redundancy 33%

Example 1: Reed-Solomon

File made up of 15 chunks

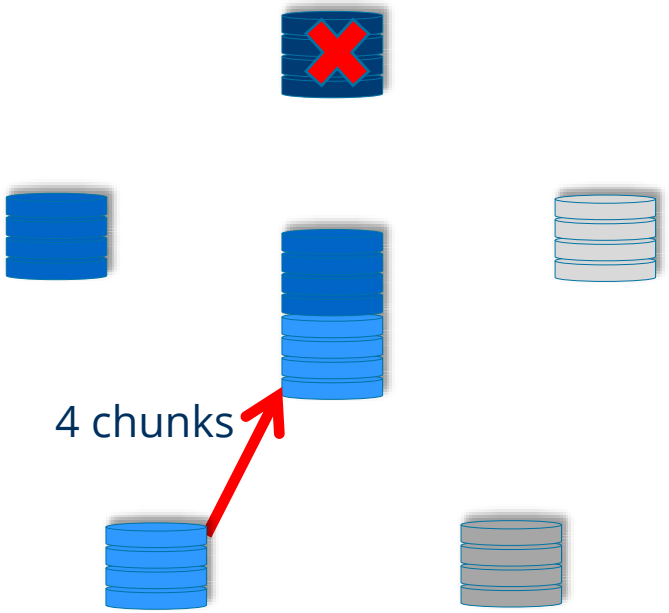
Stored in 5 racks,
4 chunks each
Redundancy 33%



Example 1: Reed-Solomon

File made up of 15 chunks

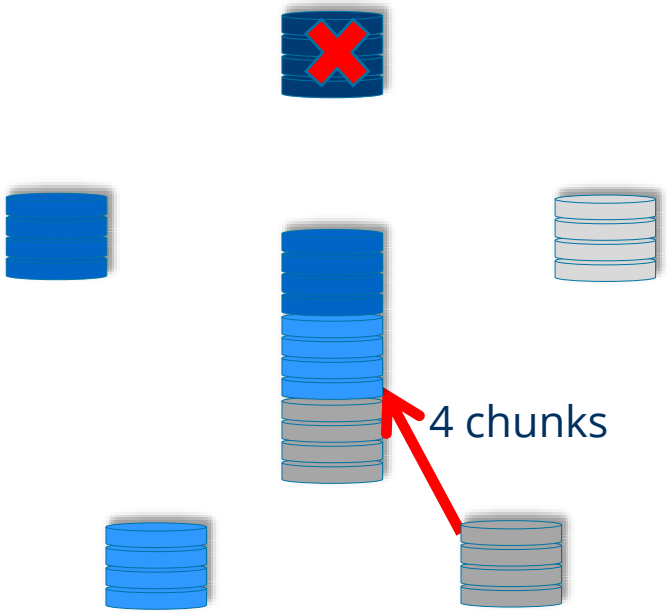
Stored in 5 racks,
4 chunks each
Redundancy 33%



Example 1: Reed-Solomon

File made up of 15 chunks

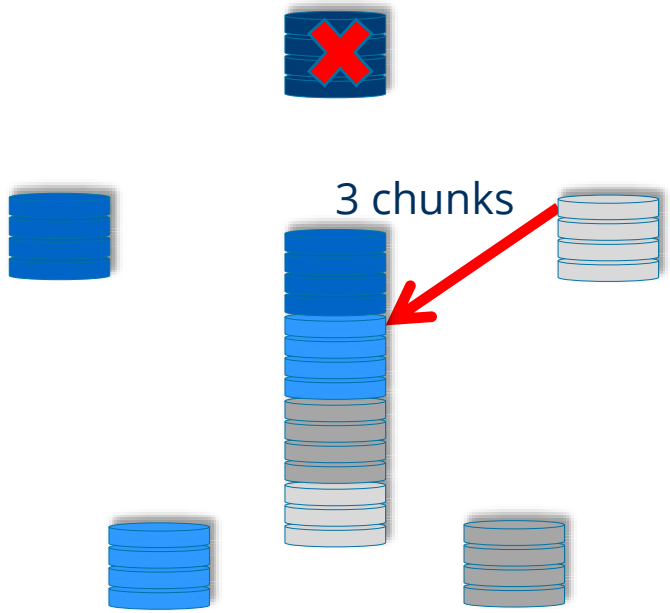
Stored in 5 racks,
4 chunks each
Redundancy 33%



Example 1: Reed-Solomon

File made up of 15 chunks

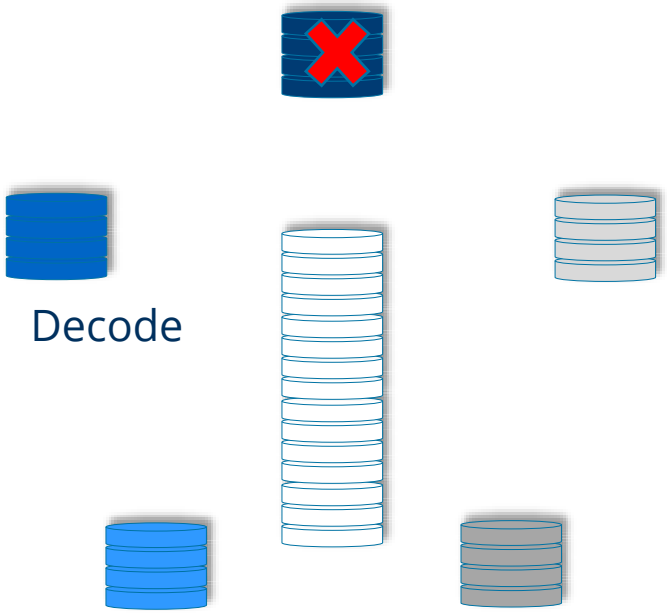
Stored in 5 racks,
4 chunks each
Redundancy 33%



Example 1: Reed-Solomon

File made up of 15 chunks

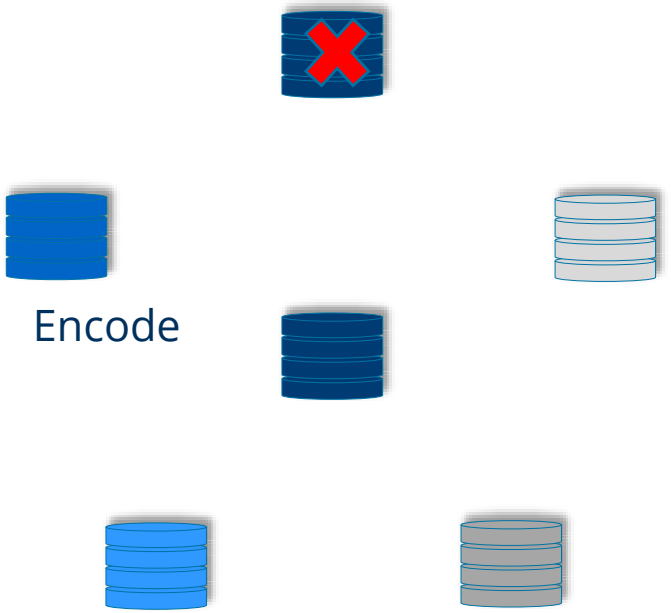
Stored in 5 racks,
4 chunks each
Redundancy 33%



Example 1: Reed-Solomon

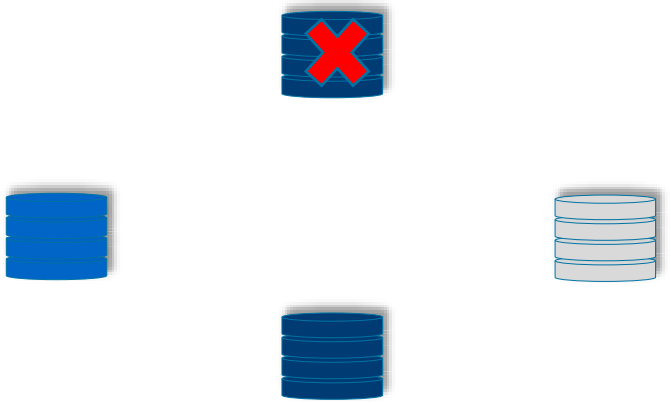
File made up of 15 chunks

Stored in 5 racks,
4 chunks each
Redundancy 33%



Example 1: Reed-Solomon

File made up of 15 chunks



Stored in 5 racks,
4 chunks each
Redundancy 33%

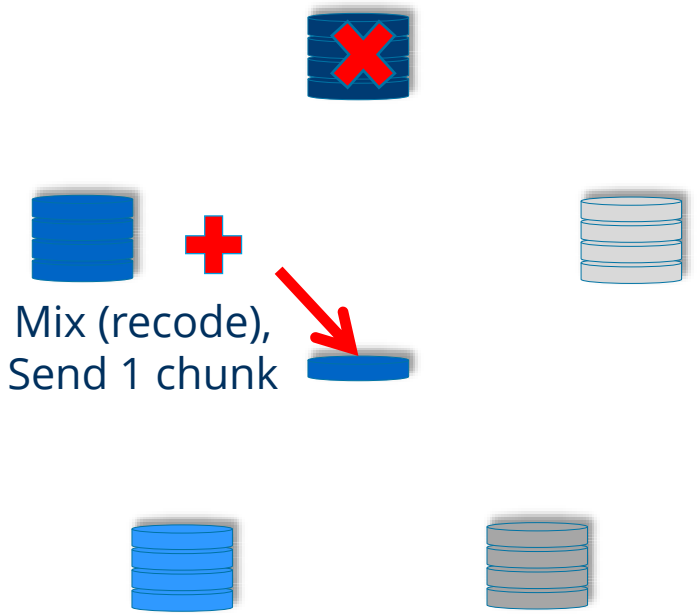
	I/O	Network: Intra-Rack	Inter-Rack	Processing
RS:	15	0*	15	Decode + Encode 15x15 matrix (new rack)
RLNC:				

* May require some intra-rack transfer depending on structure

Example 1: RLNC

File made up of 15 chunks

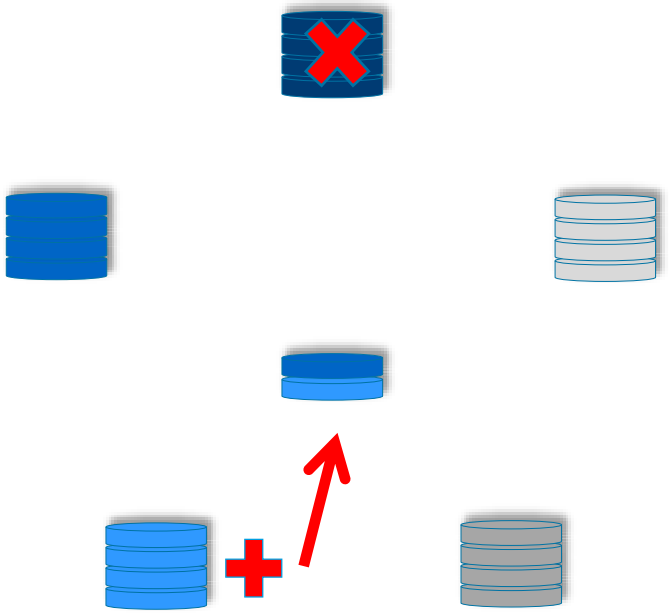
Stored in 5 racks,
4 chunks each
Redundancy 33%



Example 1: RLNC

File made up of 15 chunks

Stored in 5 racks,
4 chunks each
Redundancy 33%

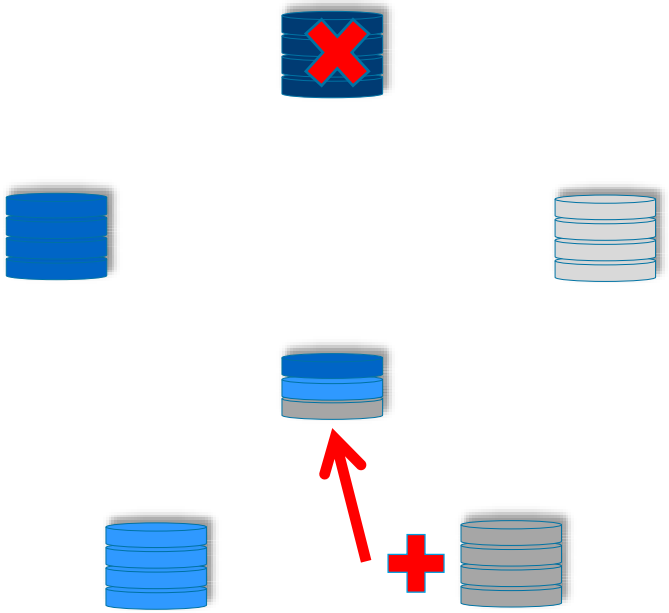


Mix (recode),
Send 1 chunk

Example 1: RLNC

File made up of 15 chunks

Stored in 5 racks,
4 chunks each
Redundancy 33%

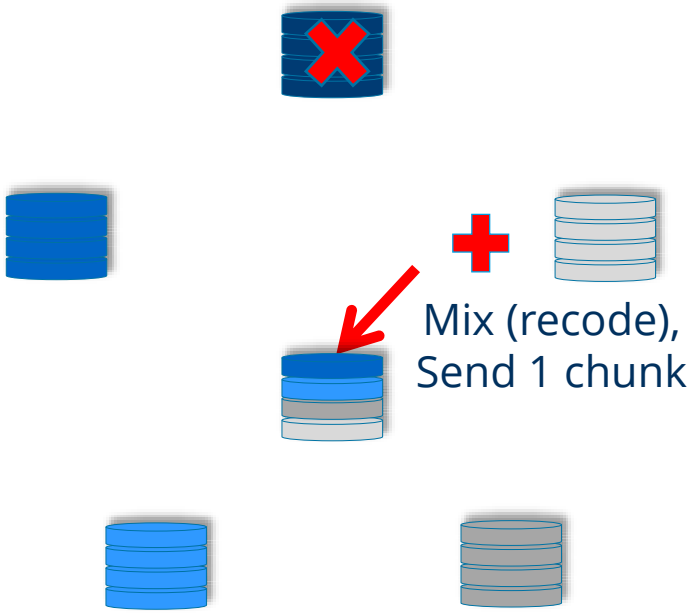


Mix (recode),
Send 1 chunk

Example 1: RLNC

File made up of 15 chunks

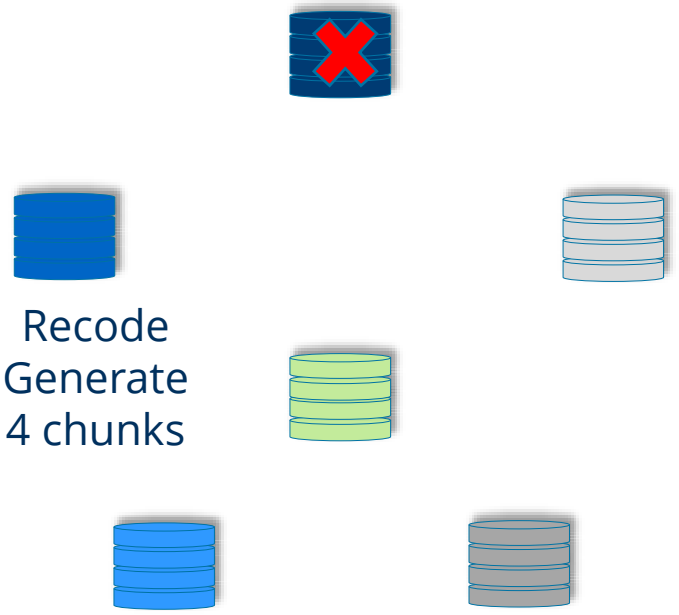
Stored in 5 racks,
4 chunks each
Redundancy 33%



Example 1: RLNC

File made up of 15 chunks

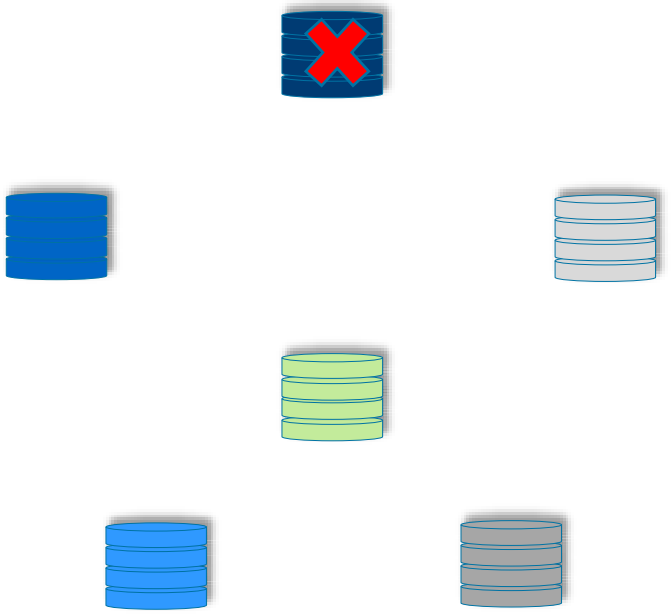
Stored in 5 racks,
4 chunks each
Redundancy 33%



Recode
Generate
4 chunks

Example 1: RLNC

File made up of 15 chunks



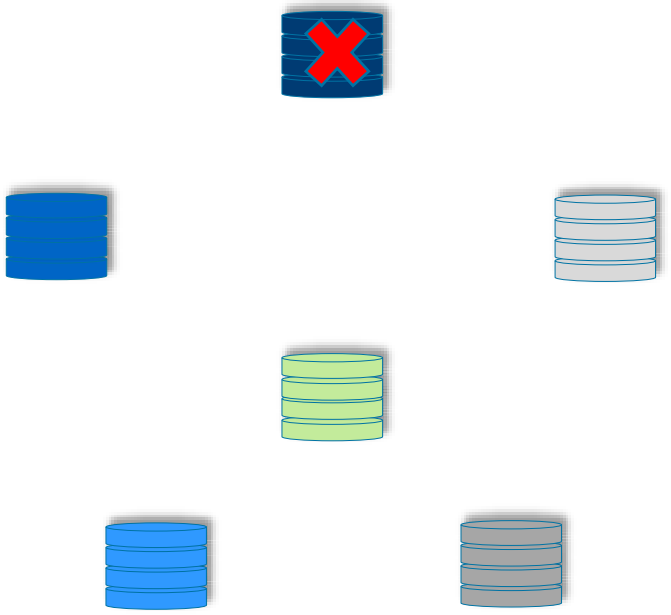
Stored in 5 racks,
4 chunks each
Redundancy 33%

	I/O	Network: Intra-Rack	Inter-Rack	Processing
RS:	15	0*	15	Decode + Encode 15x15 matrix (new rack)
RLNC:	15	11	4	Encode 4x4 matrices (4 times), and one 3x3 matrix

* May require some intra-rack transfer depending on structure

Example 1: RLNC

File made up of 15 chunks

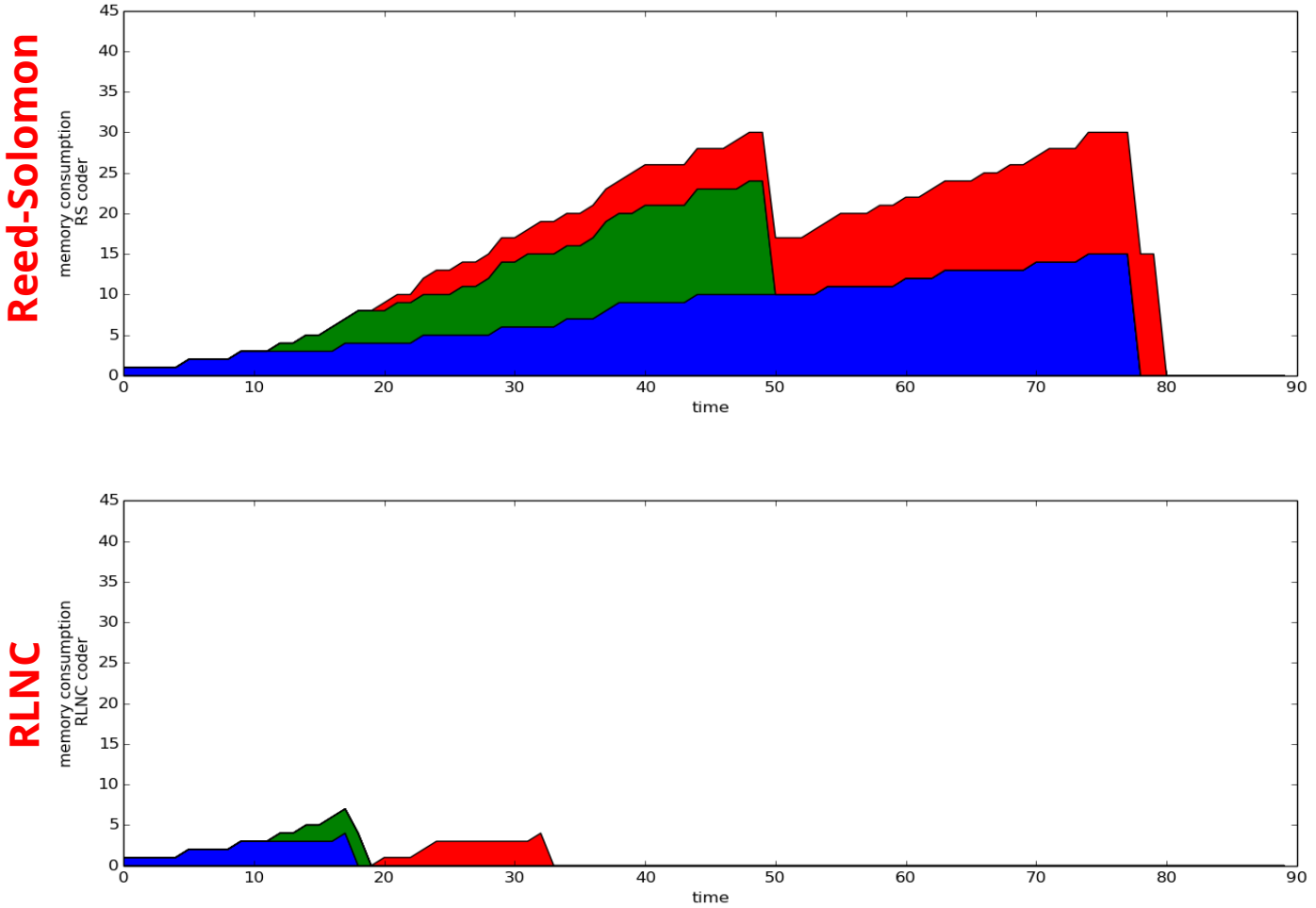


Stored in 5 racks,
4 chunks each
Redundancy 33%

	I/O	Network: Intra-Rack	Inter-Rack	Processing
RS:	15	0*	15	Centralized in new rack
RLNC:	15	11	4	Distributed in old and new racks

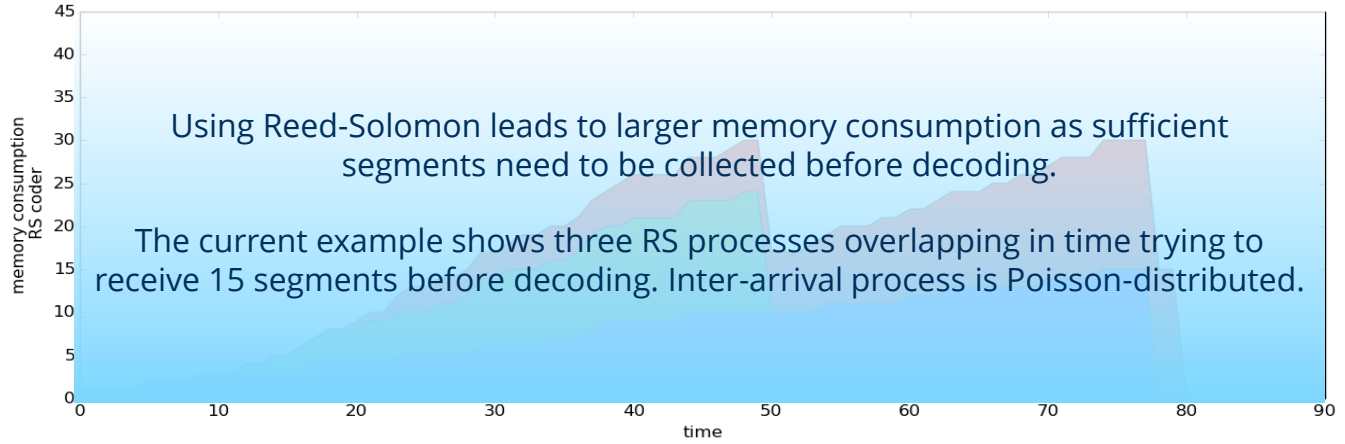
* May require some intra-rack transfer depending on structure

Memory Consumption RS vs RLNC



Memory Consumption RS vs RLNC

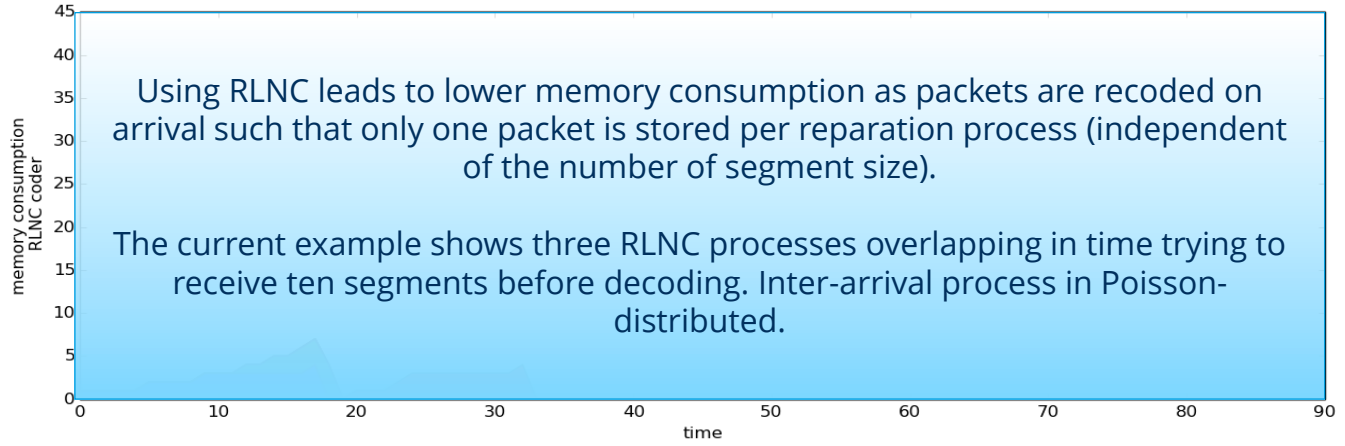
Reed-Solomon



Using Reed-Solomon leads to larger memory consumption as sufficient segments need to be collected before decoding.

The current example shows three RS processes overlapping in time trying to receive 15 segments before decoding. Inter-arrival process is Poisson-distributed.

RLNC

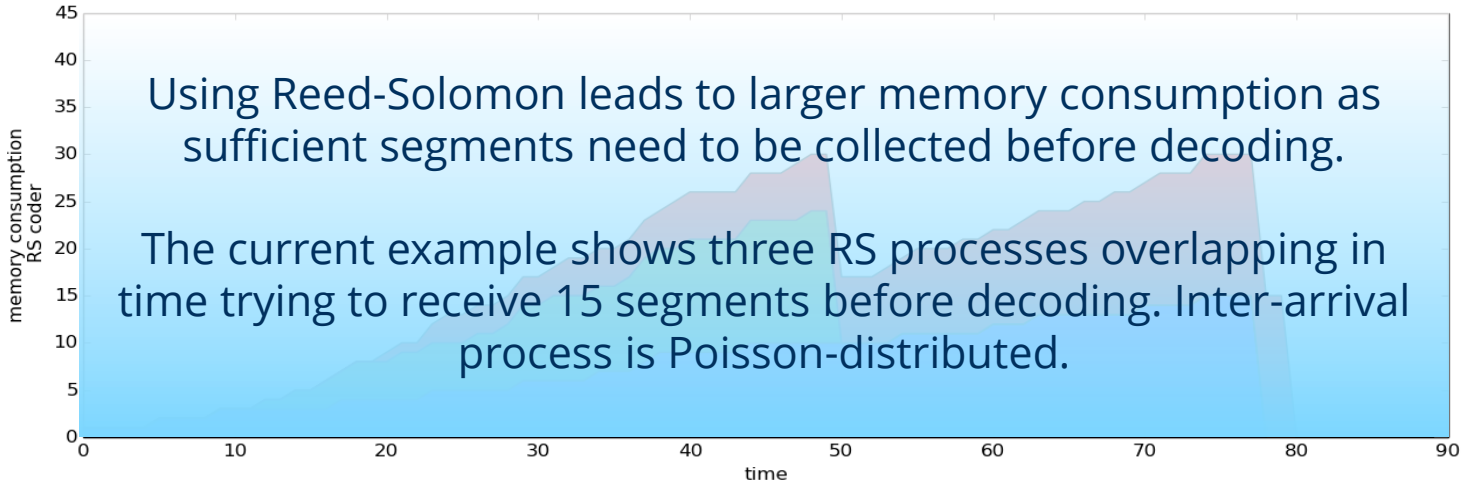


Using RLNC leads to lower memory consumption as packets are recoded on arrival such that only one packet is stored per reparation process (independent of the number of segment size).

The current example shows three RLNC processes overlapping in time trying to receive ten segments before decoding. Inter-arrival process in Poisson-distributed.

Memory Consumption RS vs RLNC

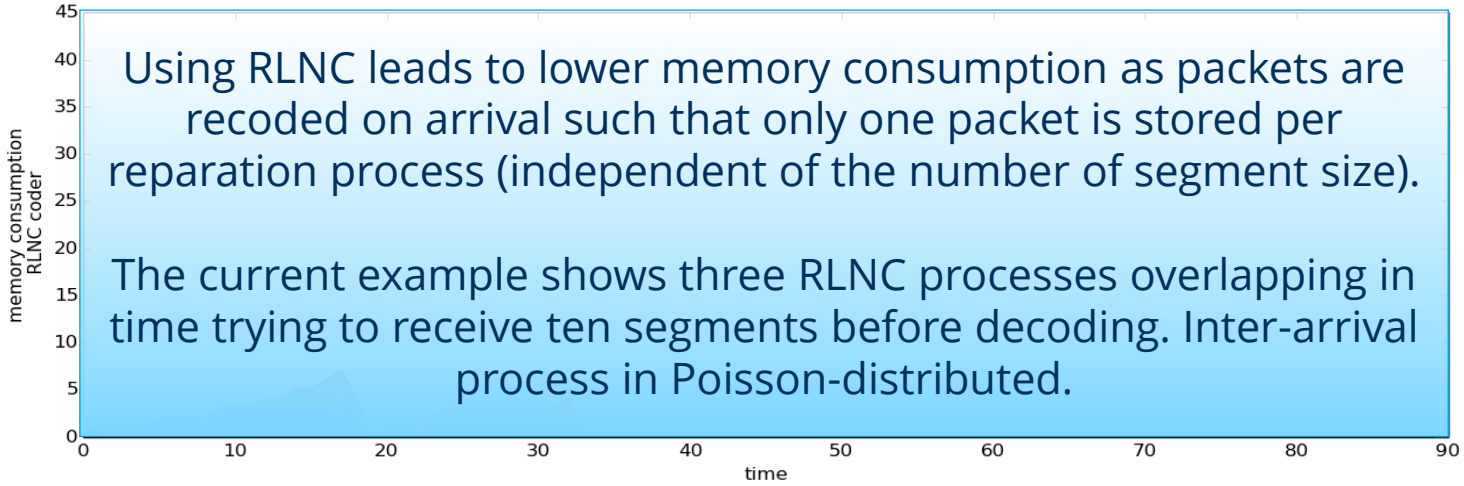
Reed-Solomon



Using Reed-Solomon leads to larger memory consumption as sufficient segments need to be collected before decoding.

The current example shows three RS processes overlapping in time trying to receive 15 segments before decoding. Inter-arrival process is Poisson-distributed.

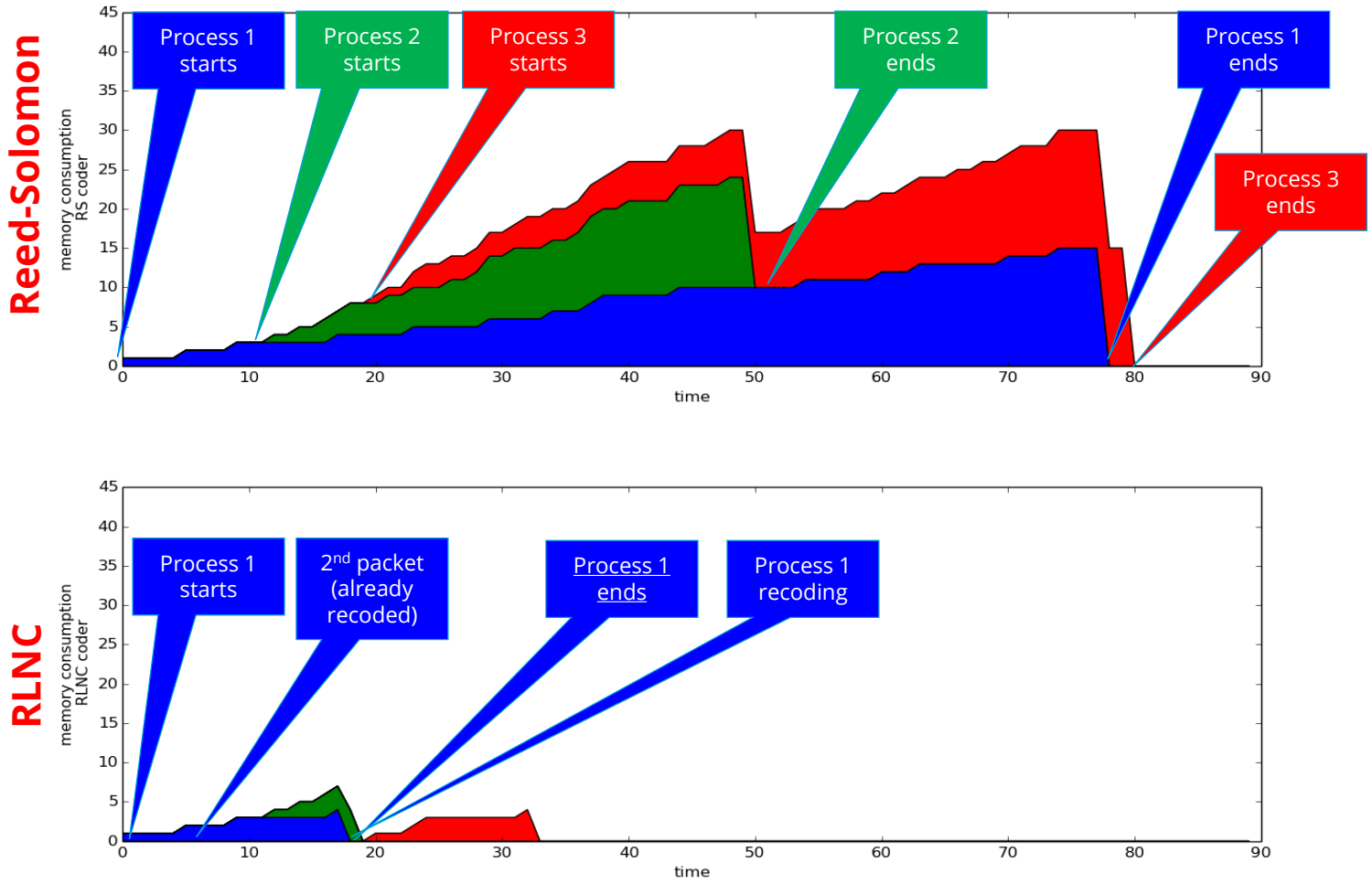
RLNC



Using RLNC leads to lower memory consumption as packets are recoded on arrival such that only one packet is stored per reparation process (independent of the number of segment size).

The current example shows three RLNC processes overlapping in time trying to receive ten segments before decoding. Inter-arrival process in Poisson-distributed.

Memory Consumption RS vs RLNC

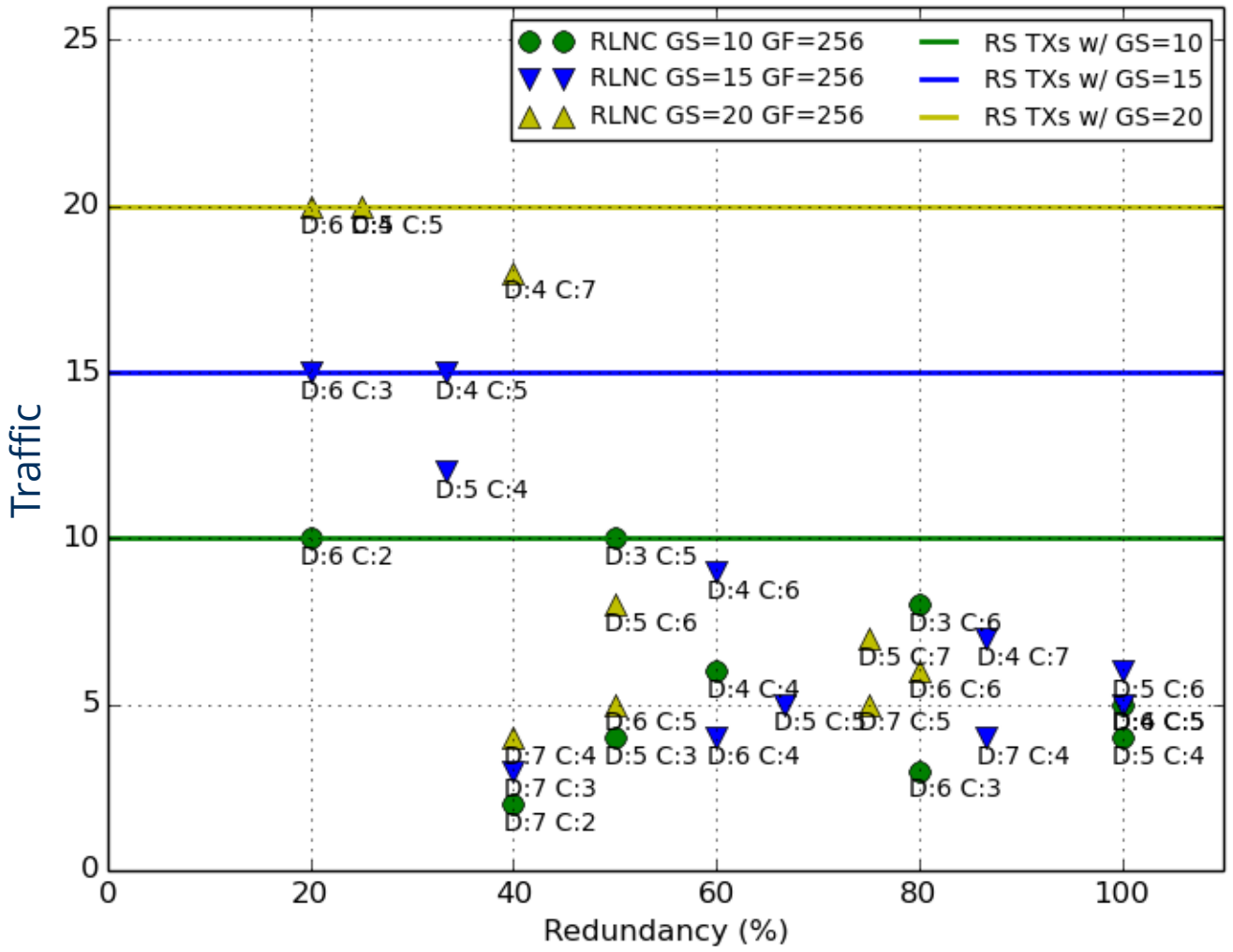


Memory Consumption RS vs RLNC

Advantages for recoding on the fly

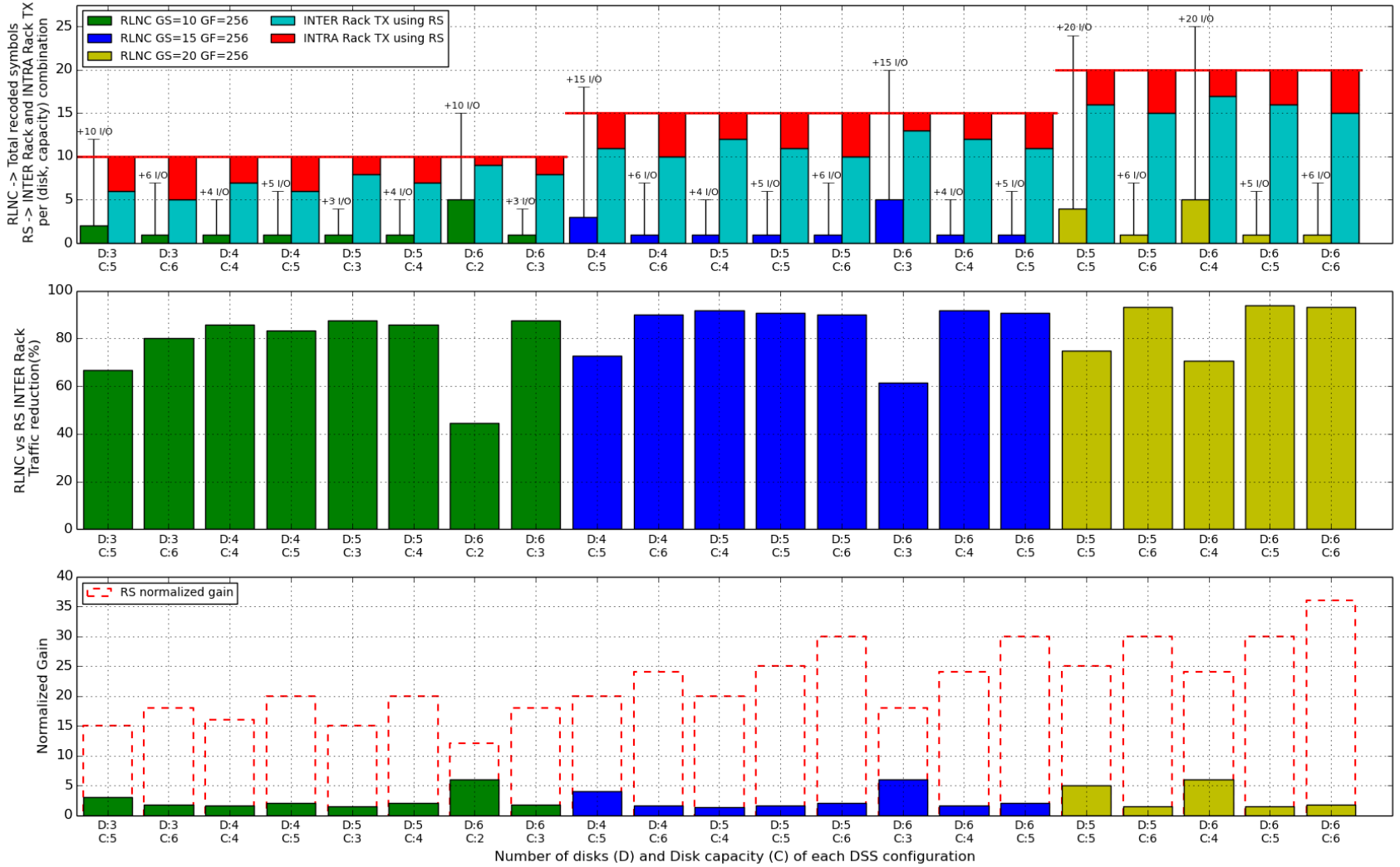
- Less memory consumption during recovery process
- Workload can be distributed during recovery process (across racks), while RS will have large workload in the end
- Less delay after last packet arrives for RLNC as only one packet need to be coded, while RS need to code over multiple packets.

Gains Beyond the Example



D: # of racks
C: # fragments of the file

Gains Beyond the Example

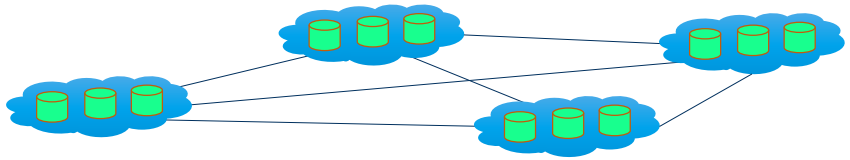


Another Example showing advantage of RLNC over RS/XORBAS

Example 2

8 segments (plus redundancy) in 4 clouds

Example: 4 clouds with 3 disks (12 disk storage).



Coding Scheme	Disk Storage (less is better)	Inter (Intra) Cloud Bandwidth (less is better)	
		Cloud failure	Disk failure
RS 8:4	12	8	6
XORBAS 8:4:2	16	8	0(1)
RLNC v1a 8:4 systematic	12	6	2
RLNC v1b 8:8 systematic	16	4	1
RLNC v2 dense	12	3	1

- Conclusion: RLNC approaches will reduce the traffic at comparable storage situations.
- Staircase/LDPC need significant storage - **unable even to reach 16 in storage**

Conclusion

- NC can reduce the amount of traffic and/or storage needed to maintain a certain resilience
- NC is robust against unforseen changes in the system