Boosting Full-Node Repair in Erasure-Coded Storage

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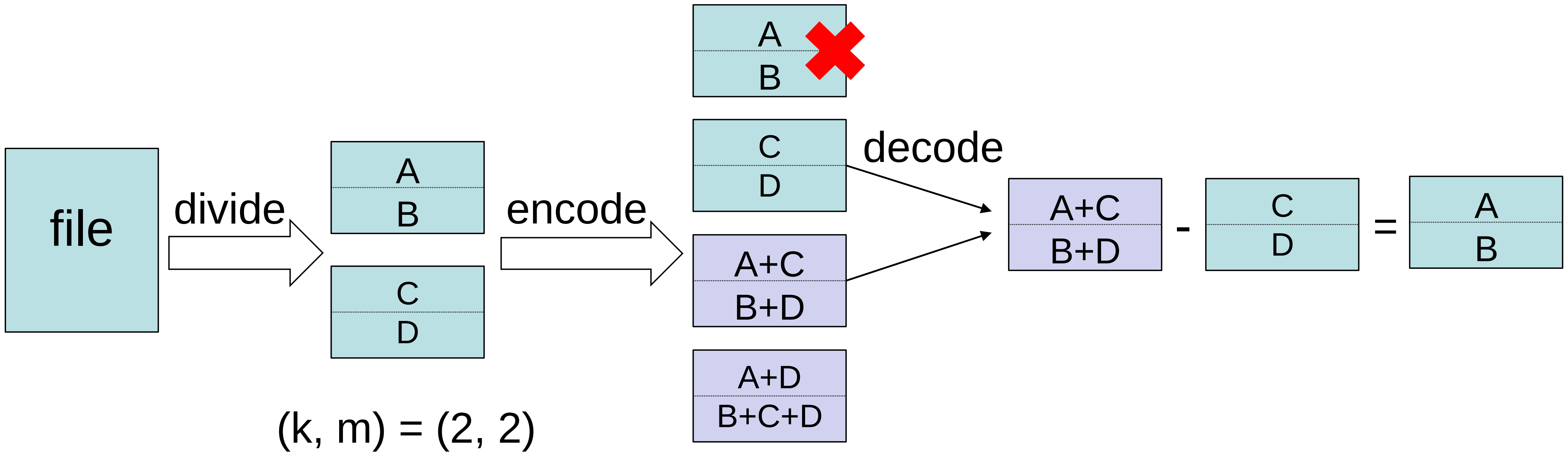
Introduction

- Data volume is growing explosively
  - Failures arise unexpectedly yet prevalently
  - Fault tolerance is critical

- Redundancy techniques
  - Replication: directly keep multiple copies across different nodes
    - Triple replication requires 3x of storage redundancy
  - **Erasure coding**: introduce slightly computational operations
    - Lower storage overhead with the same reliability guarantee
    - Deployed in Google, Facebook, etc.

Erasure Coding

- Divide a data file to **k** data chunks
- Encode k chunks to another redundant **m** parity chunks
- Distribute k+m chunks (forming a stripe) across k+m nodes
- Tolerate *any* m nodes failures



Erasure Coding

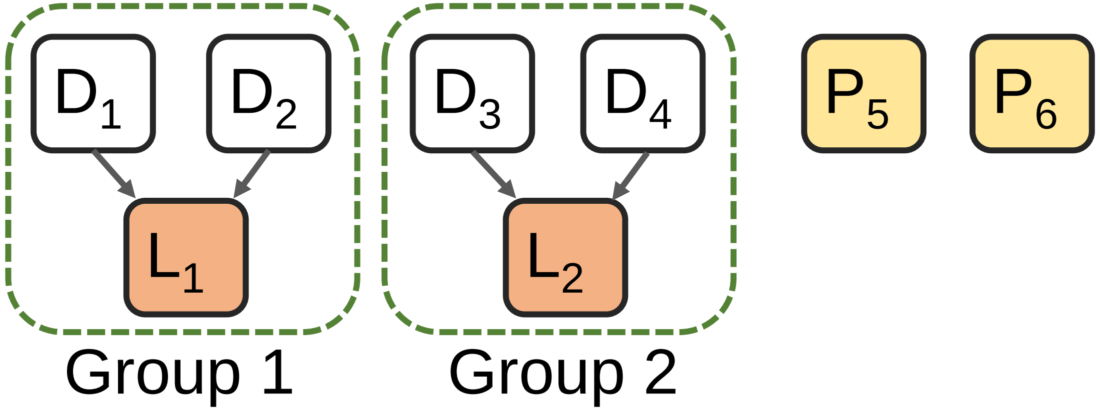
- Drawback: substantial repair traffic
  - Retrieve k chunks to repair a single failed chunk

- Relieve the I/O amplification problem in repair
  - Repair-efficient codes with reduced repair traffic (What to retrieve?)
    - Locally Repairable Codes [ATC’12, PVLDB’13]
    - Regenerating Codes [TIT’10, TIT’11]
  - Efficient repair algorithms to parallelize the repair process (How to retrieve?)
    - Partial-Parallel-Repair (PPR) [Eurosys’16]
    - Repair pipelining (ECPipe) [ATC’17]

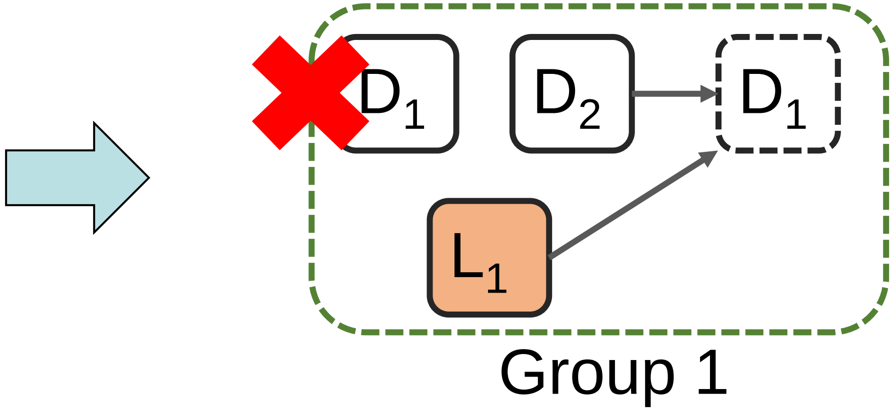
Repair-Efficient Codes

➢ Locally Repairable Codes (LRCs)

- Generate *local parity chunks* to facilitate repair at the expense of additional storage cost



(k, l, m) = (4, 2, 2)



Retrieve two chunks for repair

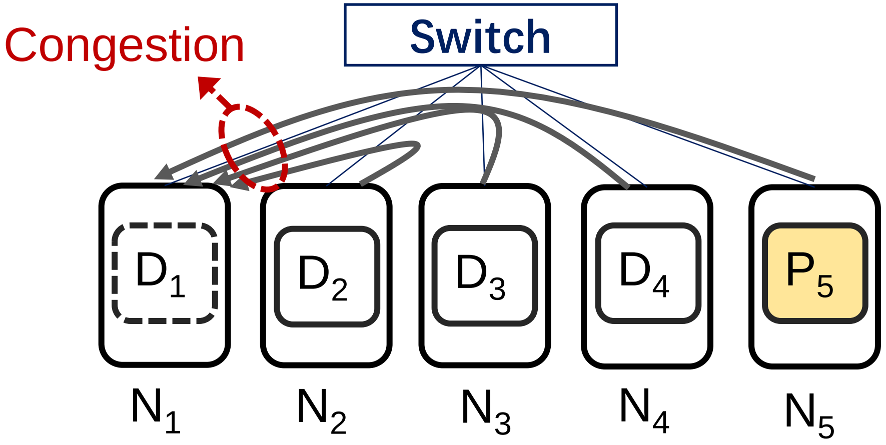
Repair Algorithms

- Single-chunk repair algorithm
  - Accelerate the repair without reducing the repair traffic
  - Introduce transmission dependency

T1: $N_3 \longrightarrow N_2$, $N_5 \longrightarrow N_4$

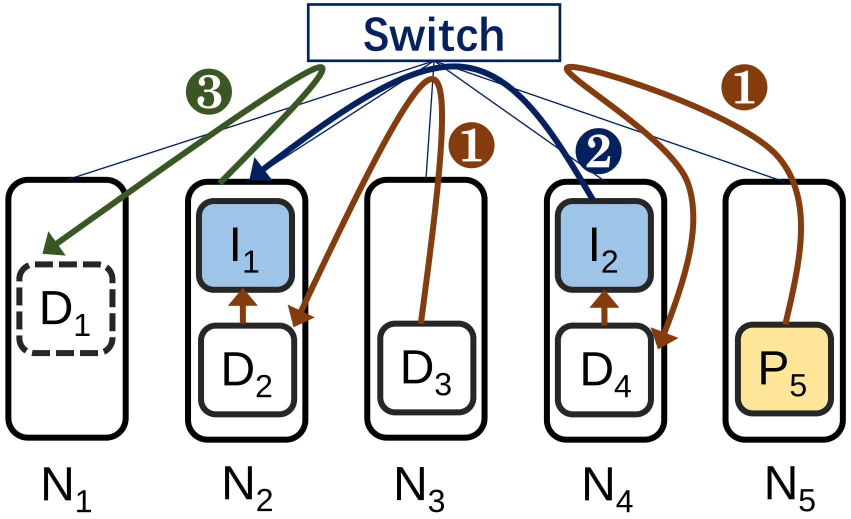
T2: $N_4 \longrightarrow N_2$

T3: $N_2 \longrightarrow N_1$



Conventional Repair (CR)

Repair time : 4 timeslots



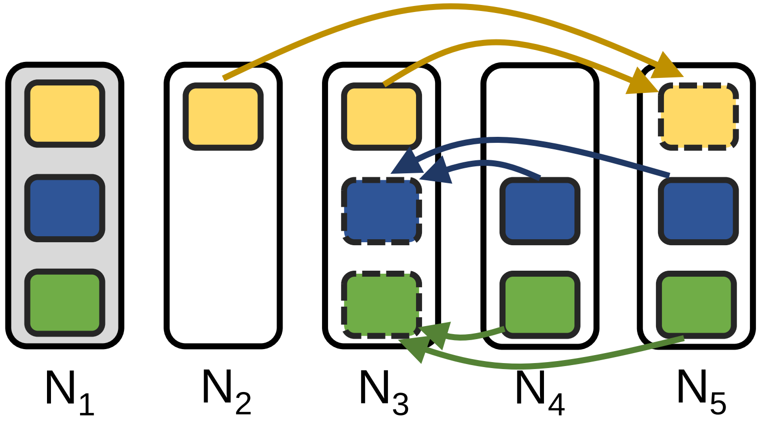
Partial-Parallel-Repair (PPR)

Repair time : $log_2(4+1) = 3$ timeslots

Introduce **transmission dependency**: D_4 should wait for P_5 for aggregation

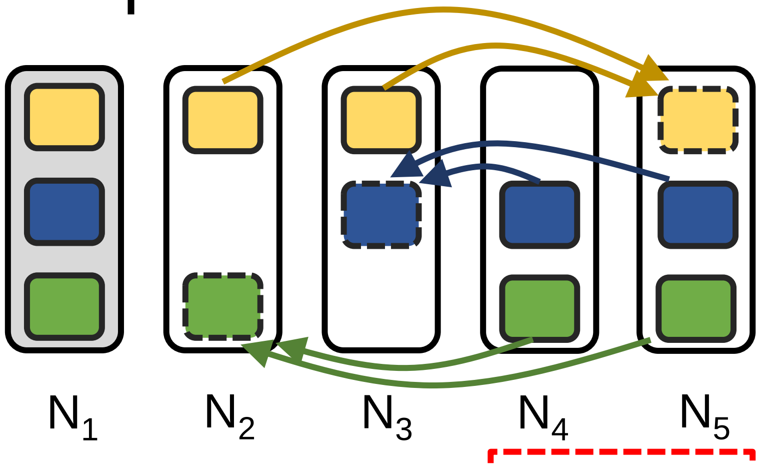
Motivation

- **Limitation 1:** Failing to utilize the full duplex transmission



	N1	N2	N3	N4	N5
Upload		1	1	2	2
Download		0	**4**	0	2

(a) Unbalanced repair solutions



	N1	N2	N3	N4	N5
Upload		1	1	**2**	**2**
Download		**2**	**2**	0	**2**

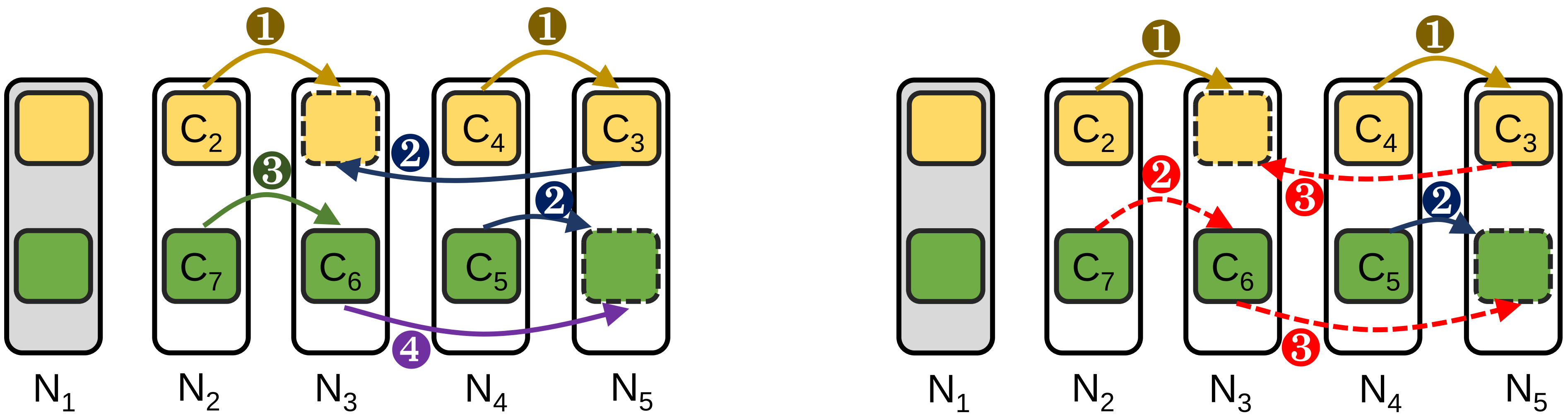
(b) Balanced repair solutions

Two chunks' repair under the conventional repair (CR)

The repair time is determined by the most loaded node

Motivation

- **Limitation 2:** Failing to fully utilize the bandwidth at each timeslot



(a) Repair using four timeslots (b) Repair using three timeslots

Two chunks' repair under the partial-parallel-repair (PPR)

Transmission scheduling affects bandwidth utilization

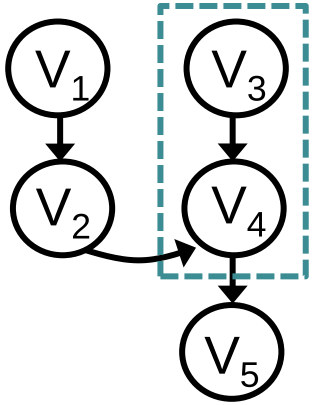
Our Contributions

- **RepairBoost:** a framework to speed up the full-node repair
  - Tech#1: Repair abstraction (for generality and flexibility)
  - Tech#2: Repair traffic balancing (for load balancing)
  - Tech#3: Transmission scheduling (for saturating bandwidth utilization)
- A prototype RepairBoost integrated with HDFS
- Tackle multiple node failures and facilitate the repair in heterogeneous environments
- Experiments on Amazon EC2
  - Increase the repair throughput by 35.0-97.1%

Repair Abstraction

- Formalize a single-chunk repair through a *repair directed acyclic graph* (RDAG)
  - Characterize the data routing over the network and the dependencies among the requested chunks
  - e.g., for RS(k, m), k+1 vertices
    - $\{v_1, v_2, \cdots, v_k\}$: k nodes that retrieve chunks
    - v_{k+1} : destination node for repairing the lost chunk
  - Directed edges represent the data routing directions specified in repair algorithms

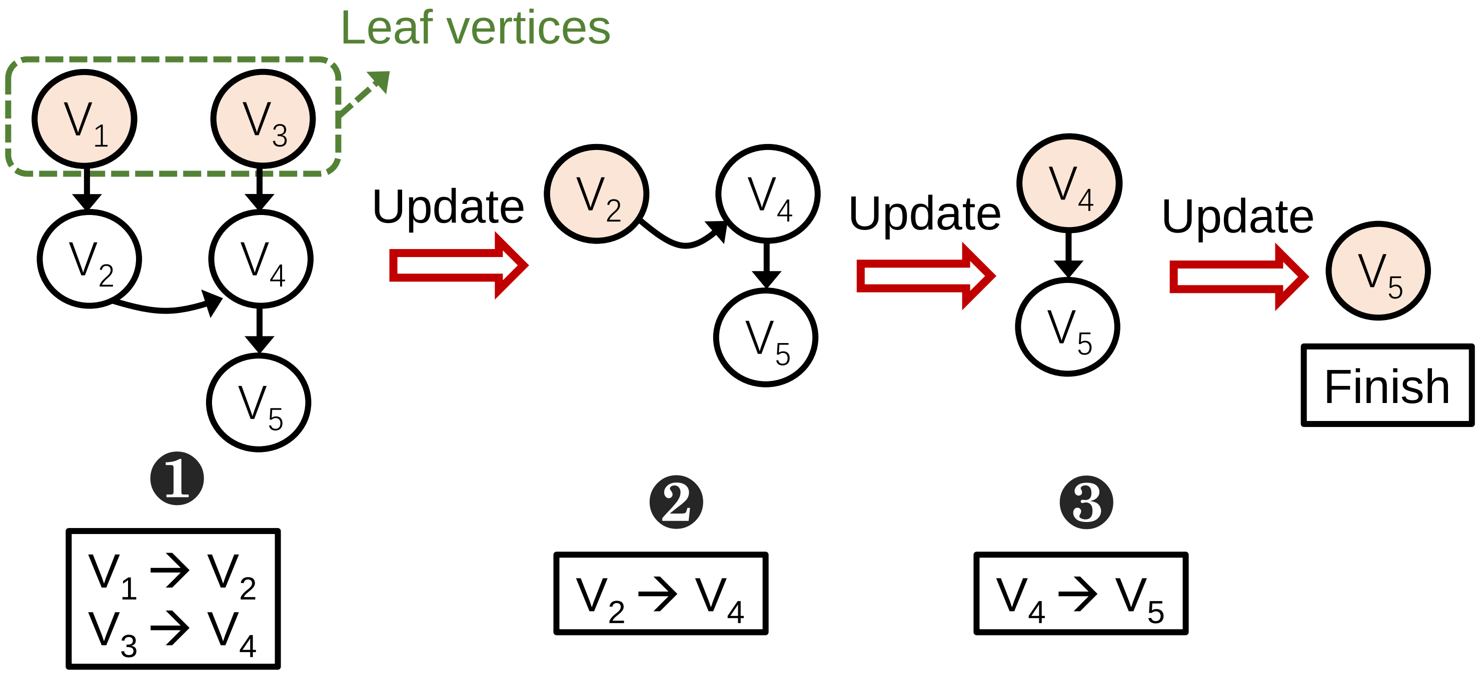
An RDAG of PPR when k=4



① V_3 is a child of V_4
② V_4 should collect all its children before sending its data to its parent (i.e., V_5)

Repair Abstraction

- Repair process guided by RDAG
  - The repair starts from the *leaf vertices* (without predecessor dependency)
  - As the repair proceeds, iteratively remove edges and vertices from an RDAG



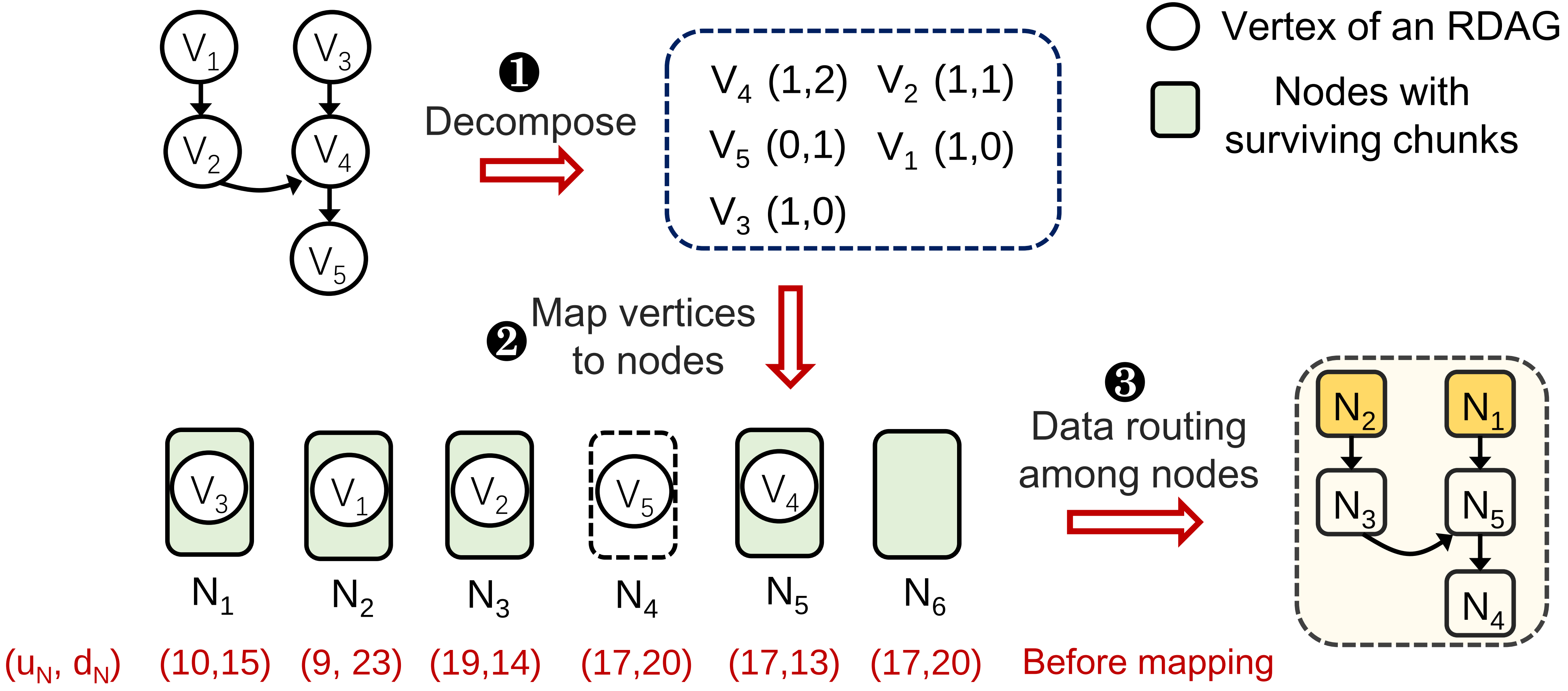
Repair Traffic Balancing

- Decompose RDAGs into vertices(with different upload and download traffics) and map the vertices to storage nodes
  - Ob#1: Retaining fault tolerance degree
  - Ob#2: Balance the upload and download repair traffic

- The vertices of RDAGs are classified and given different priorities according to degree
  - Intermediate vertices ($u = 1 \text{ and } d > 0$)
  - Root vertex ($u = 0 \text{ and } d > 0$)
  - Leaf vertices ($u > 0 \text{ and } d = 0$)

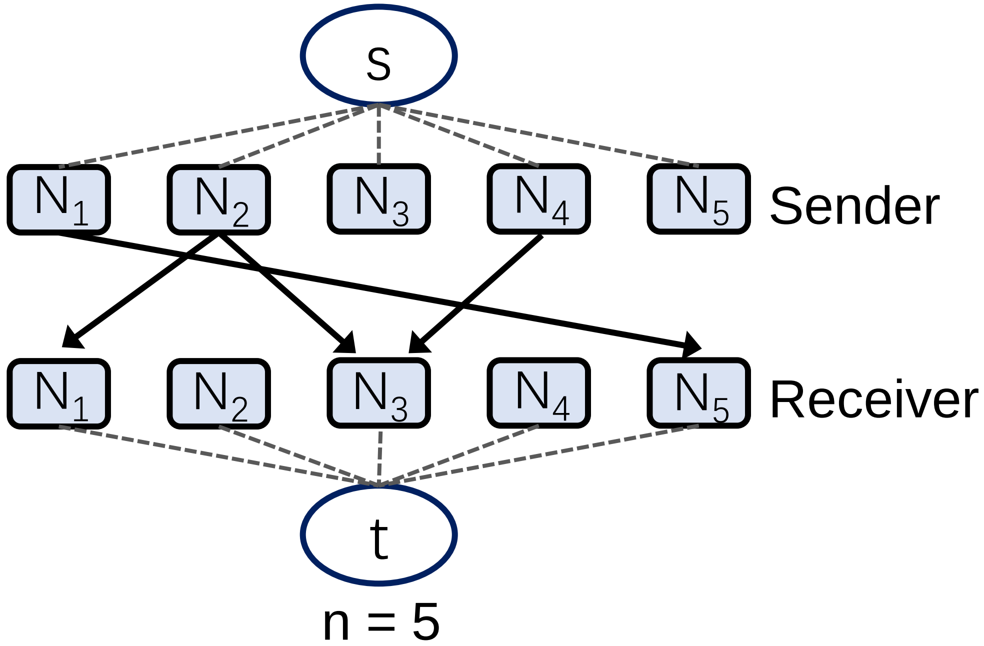
Repair Traffic Balancing

- Example of mapping vertices of an RDAG to nodes



Transmission Scheduling

- The bandwidth may not be utilized at each timeslot during the repair (Limitation 2)
- Formulate as a maxflow problem
  - 2n+2 vertices
    - n senders: potentially send data for repair
    - n receivers: potentially receive data at the same time
  - Establish the connection between senders and receivers according to the RDAGs



Transmission Scheduling

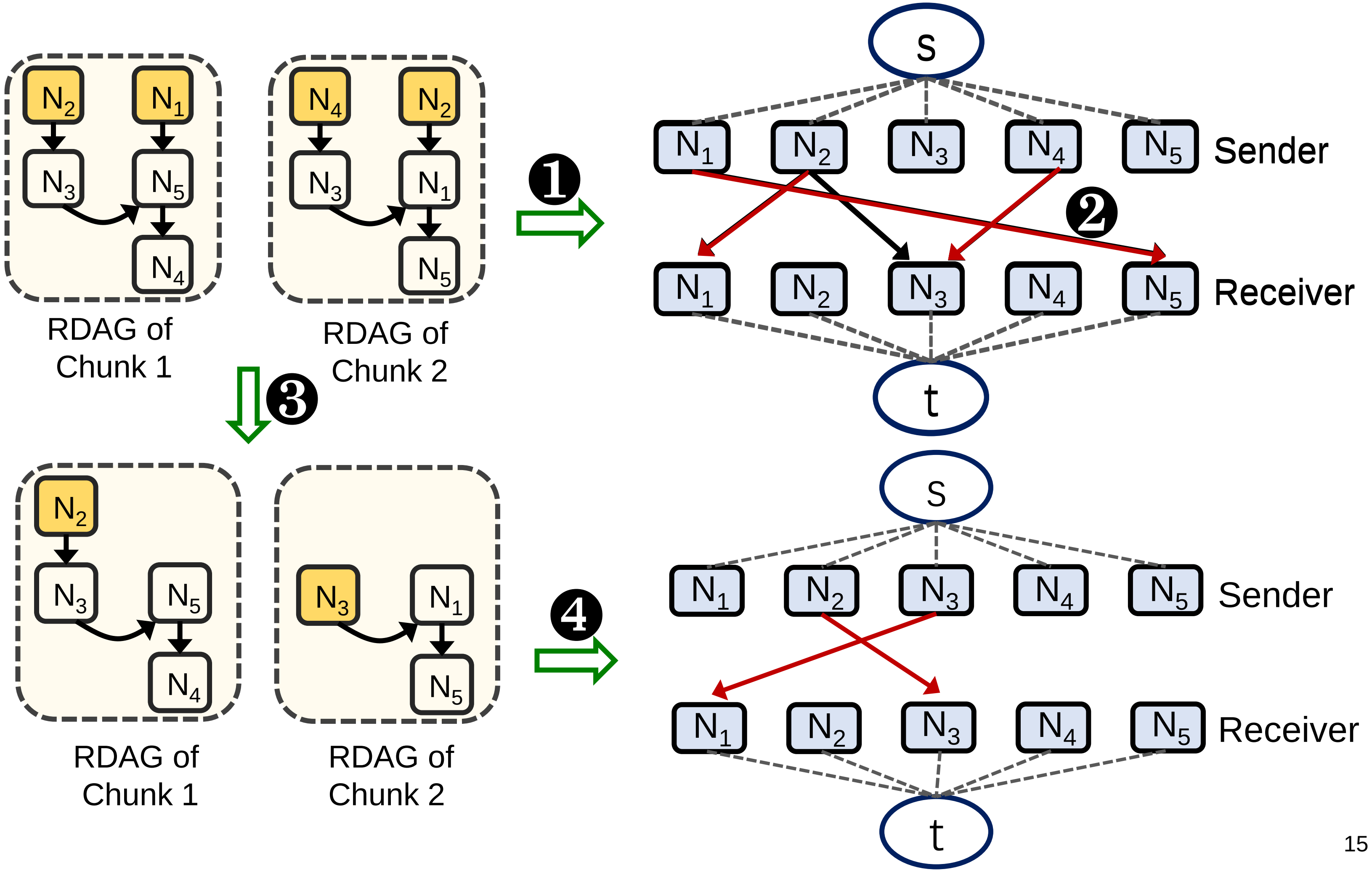
➢ Example of repairing two chunks among five surviving nodes

❶ Construct a network

❷ Establish a maximum flow

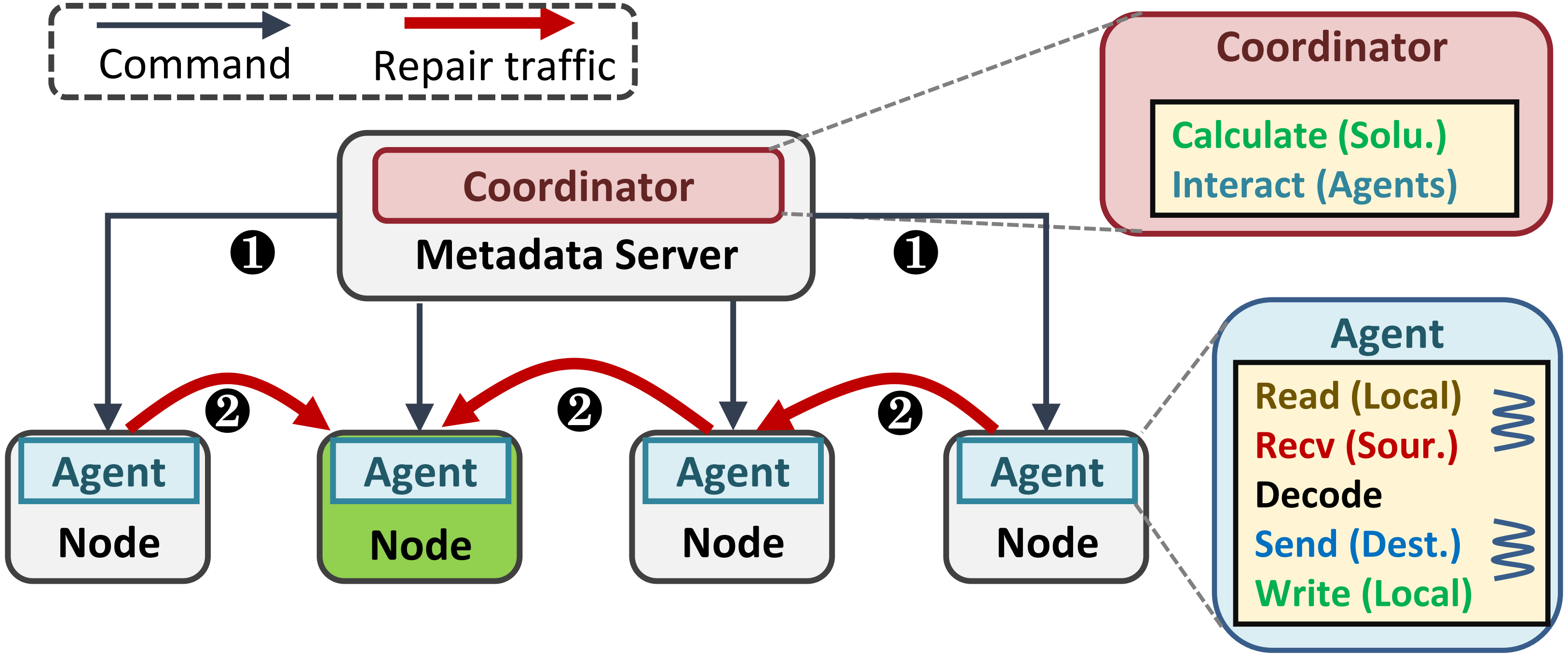
❸ Update the RDAG

❹ Construct a new network



Implementation

➢ RepairBoost serves as an independent middleware running atop existing storage

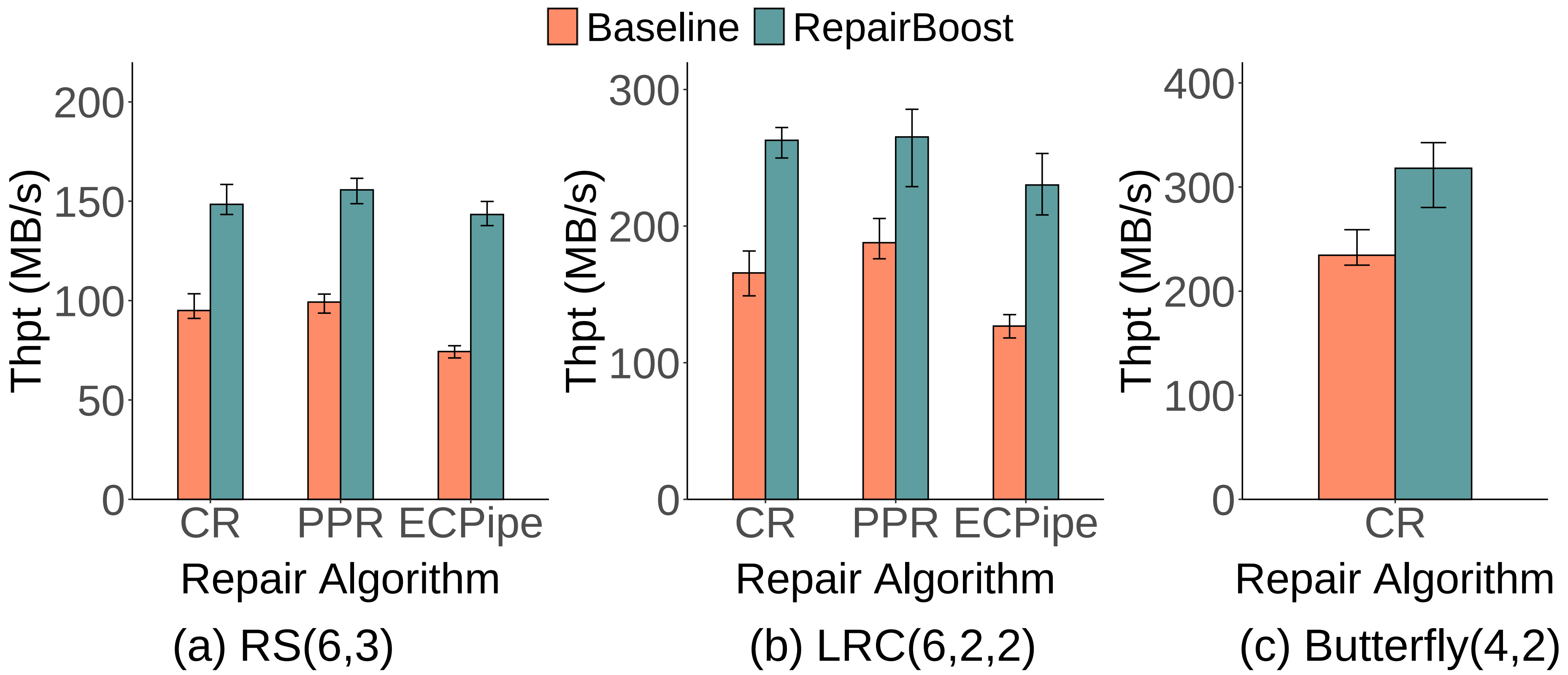


- The coordinator manages the metadata of stripes
- The agents are standby to wait for the repair commands and perform the repair operations cooperatively

Evaluation Setup

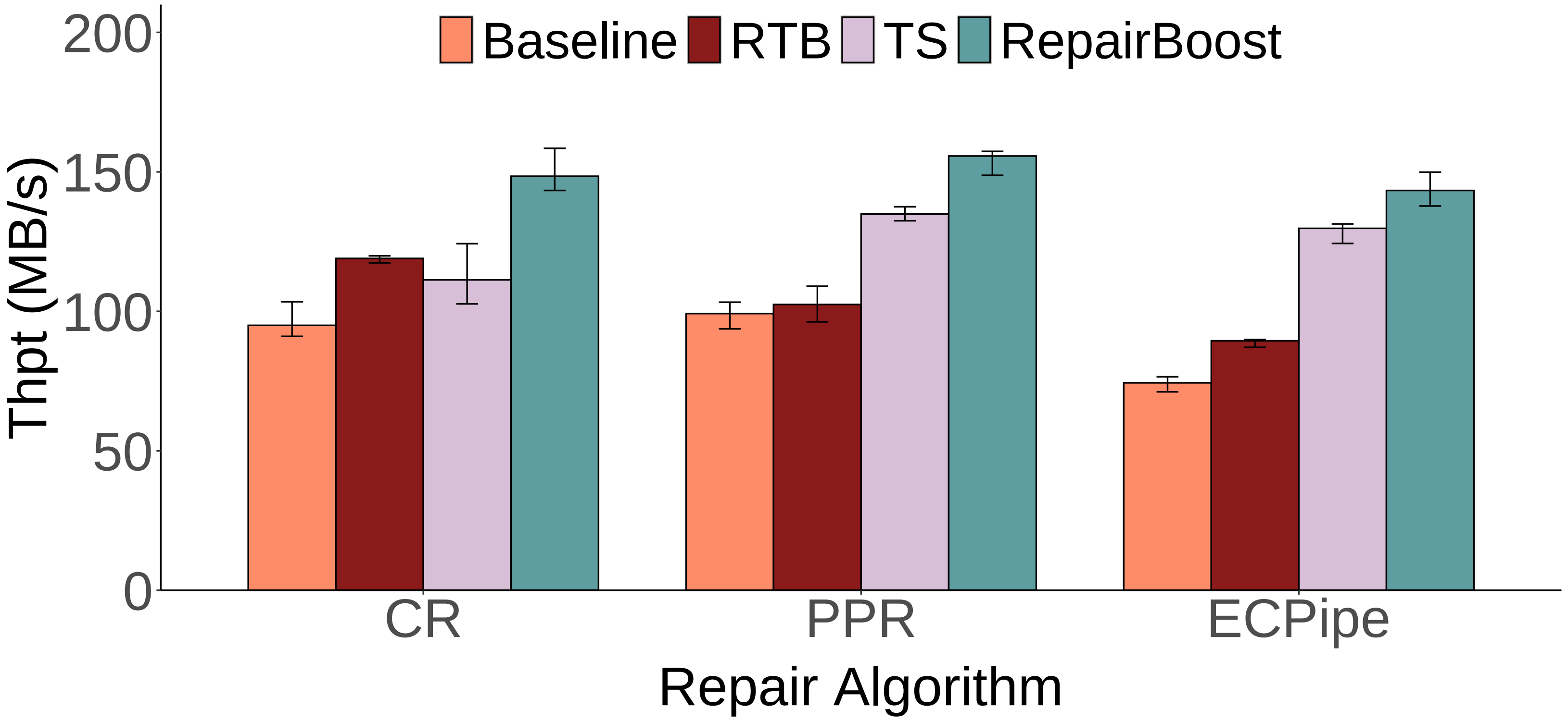
- Amazon EC2
  - 17 m5.large machines (1 coordinator and 16 agents)
- Default configurations
  - Chunk size: 64MB, Packet size: 1MB
  - RS(6, 3)
- Single-chunk repair algorithms
  - Conventional repair (CR)
  - Partial-Parallel-Repair (PPR)
  - Repair pipelining (ECPipe)
- Baseline: random selection
- Metric: repair throughput (size of data repaired per time unit)

Performance Results



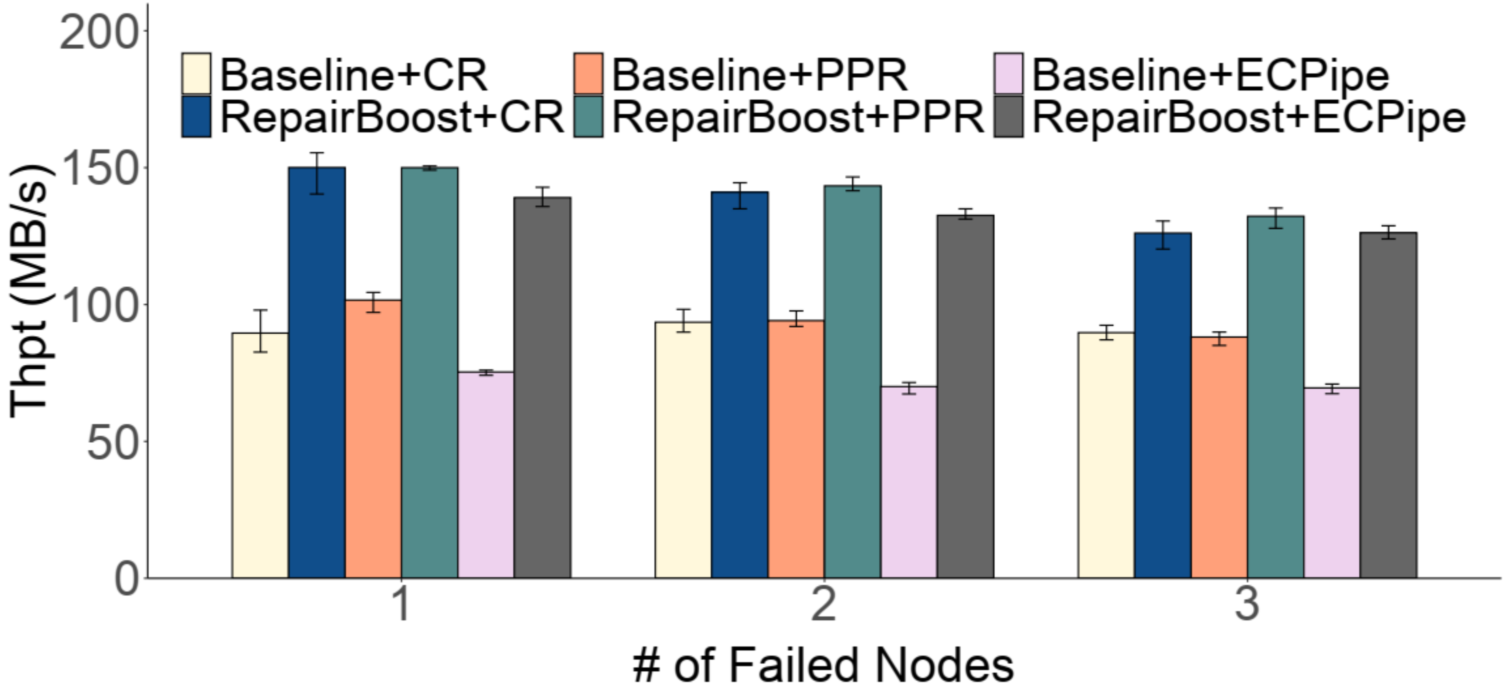
- Ob#1: Butterfly(4,2) reaches the highest repair throughput
  - as it needs to fetch only half of the data
- Ob#2: RepairBoost can improve the repair throughput by an average of 60.4% for different erasure codes

Breakdown Analysis



- Ob#1: The effectiveness of RTB and TS varies across different repair algorithms.
- Ob#2: RepairBoost achieves 45.7% and 19.8% higher repair throughput than RTB and TS, respectively.

Multi-Node Repair



- Ob#1: RepairBoost improves the repair throughput by 39.5% (a single node failure) and by 35.7% (triple node failures)
- Ob#2: The repair throughput of RepairBoost drops slightly when more nodes fail
  - Fewer selected nodes can participate in the repair

Conclusion

- RepairBoost, a scheduling framework that boosts the full-node repair for various erasure codes and repair algorithms
  - Employ graph abstraction for single-chunk repair
  - Balance the upload and download repair traffic
  - Schedule the transmission of chunks to saturate unoccupied bandwidths

- Source code:

  https://github.com/shenzr/repairboost-code

Thank You!
Q & A