Scheduling Data Streams for Low Latency and High Throughput on a Cray XC40 Using Libfabric

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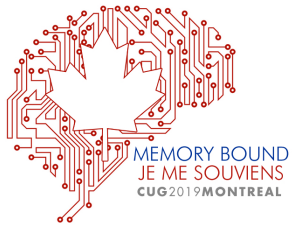

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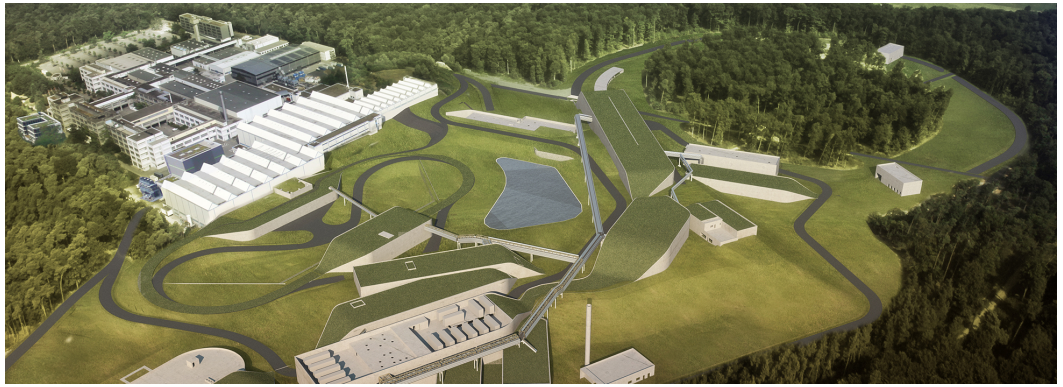
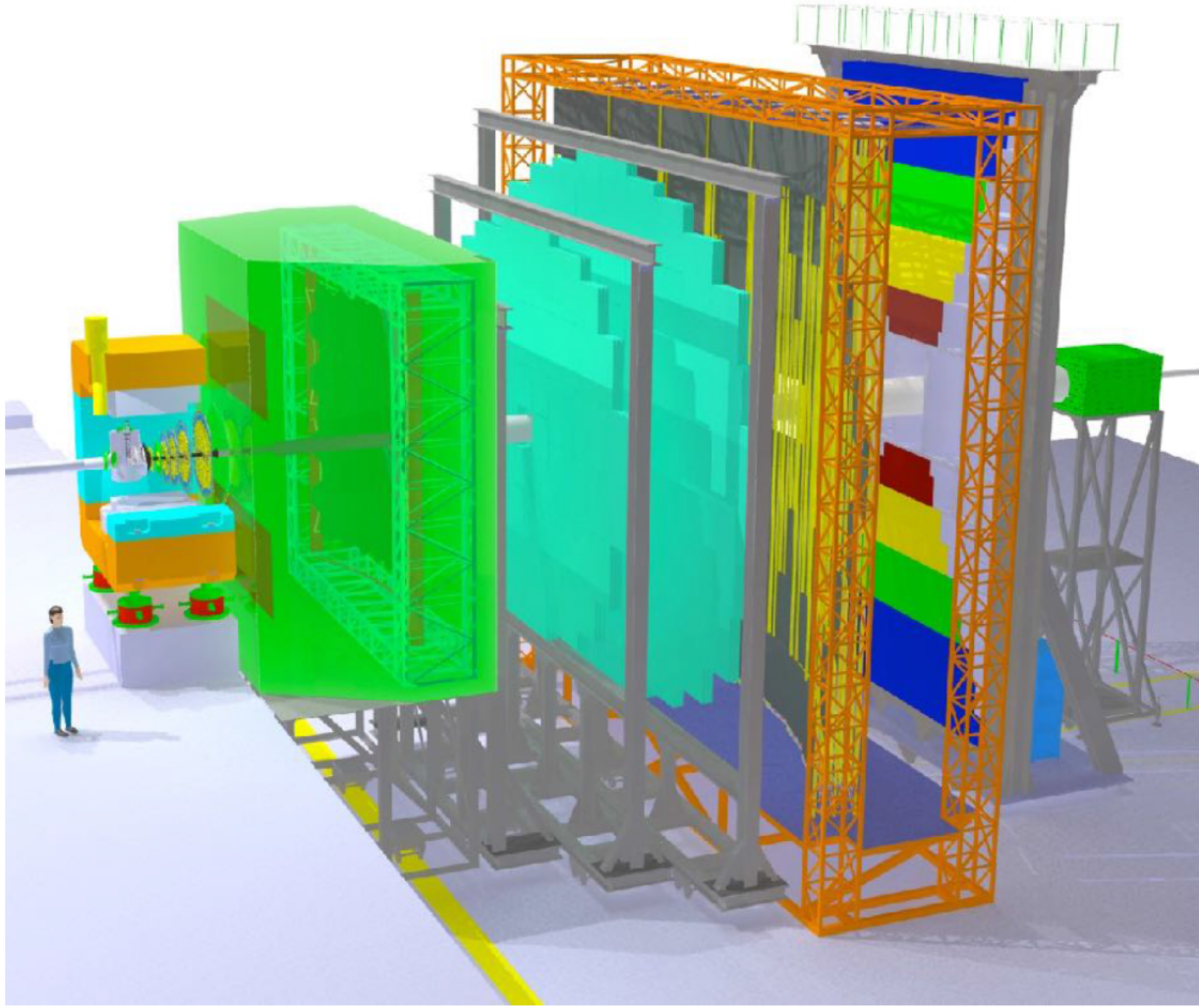
Introduction: Research Project

- The Compressed Baryonic Matter (CBM) Experiment
  - observes high-energy nucleus-nucleus collisions
  - at FAIR in Darmstadt, Germany
    - appr. 150,000 m^2 and up to 24 m depth
    - 20 buildings



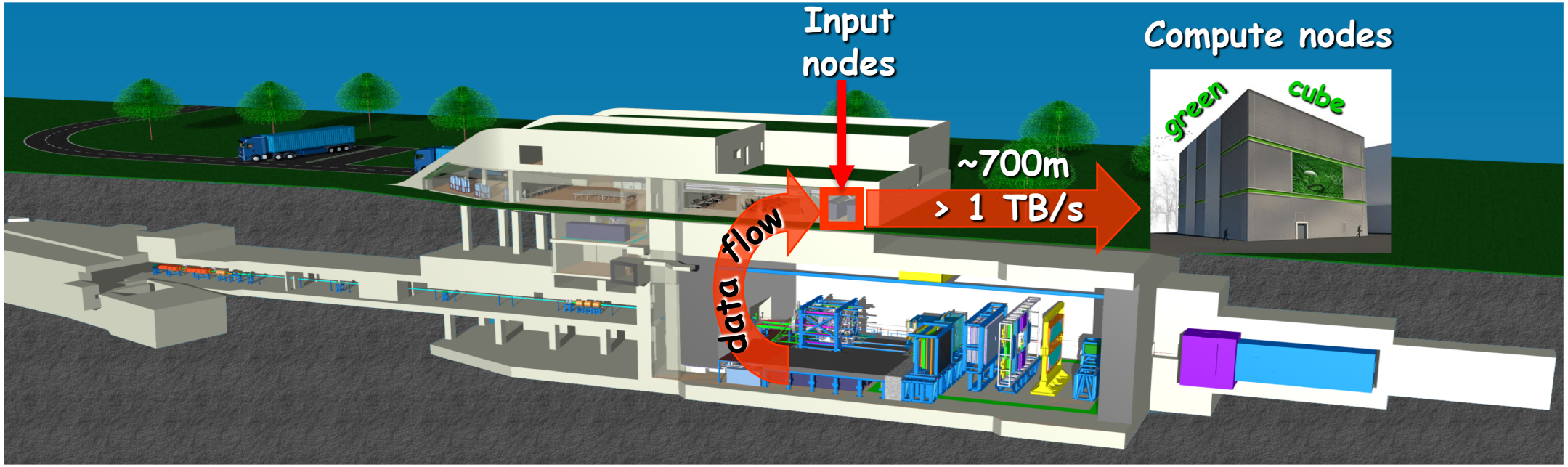
- Many sensors surround the experiment
  - hundreds of data streams
  - > 1 TiB/s of aggregated generated data



Research Project

- Data is received in high performance computing cluster called **First-Level Event Selector** (FLES)
  - builds time-slices for analysis using a software called **FLESnet**

- FLESnet logically consists of:
  - Input nodes: divide data streams into micro time-slices (MTSs)
  - Compute nodes: group MTSs to form complete time-slices

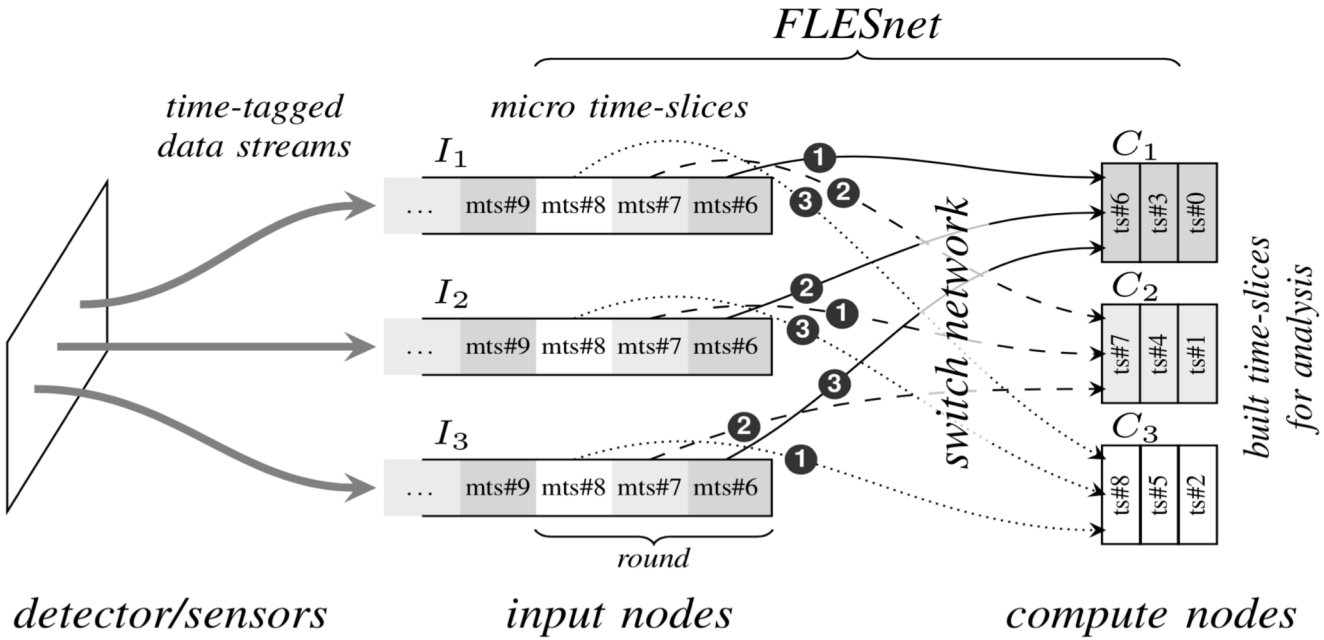


Status Quo: FLESnet Communication Pattern

- The communication follows best-effort approach
  - using round robin schema
  - complete time-slices are given to analysis
- Input nodes maintain a local buffer to receive data from sensors

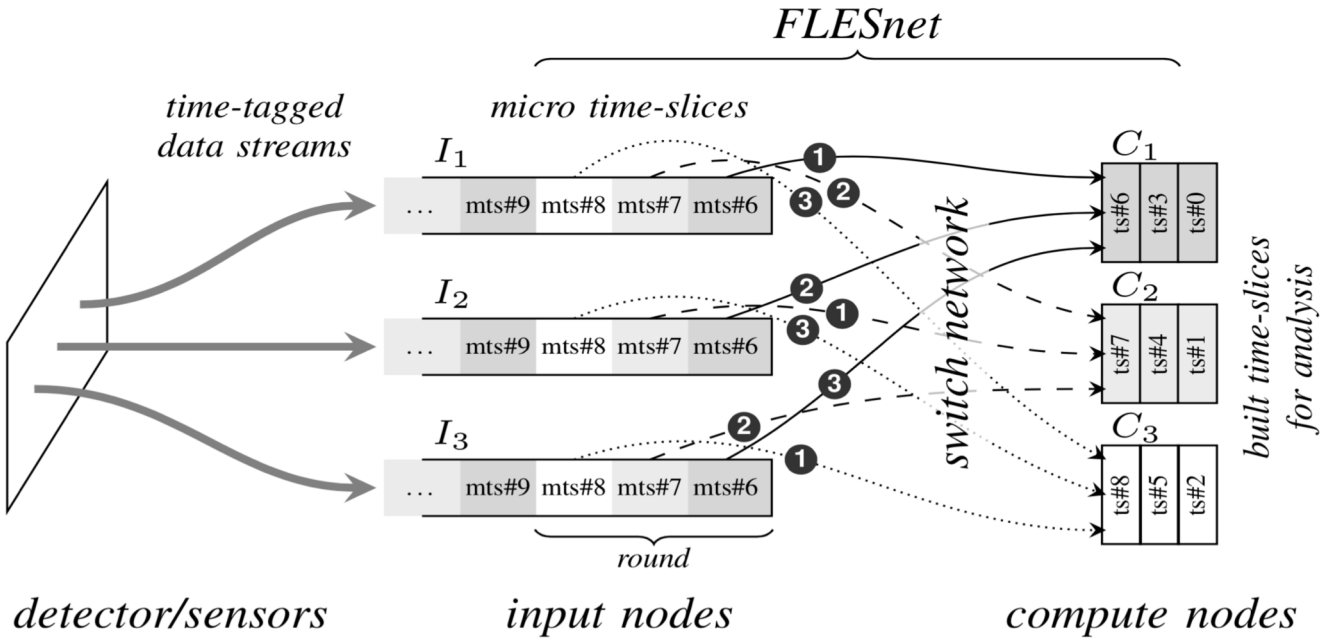
➢ The communication pattern is challenging

- Input nodes continuously transmit MTSs without coordination
  - Local buffer space
  - Ticket-based flow control mechanism is used



Research Challenges

- Compute nodes process only complete time-slices
  - High dependency between nodes
  - Time to complete a time-slice increases with scalability
- Compute nodes have a limited local memory when scaling up
  - Less tickets / input node
  - Implicit higher synchronization
  - Higher influence of stragglers
- Input nodes use part of network links at a time
  - Inefficient network/compute node utilization
  - Network/endpoint congestion



Research Goals

- Achieve good aggregate bandwidth in large systems by
  - saturating all links at all times
  - avoiding endpoint congestion
  - requiring buffer space sparingly

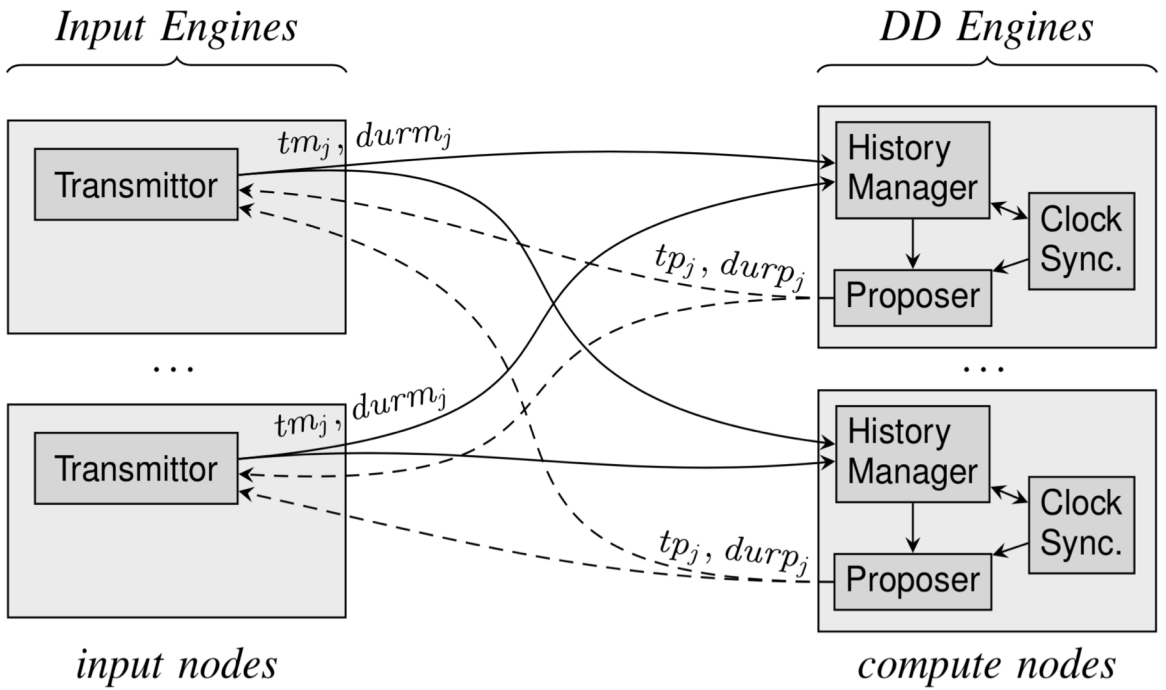
- Gather all micro-timeslices for a time-slice in a short duration by
  - reuse memory buffers quickly
  - keep input nodes synchronized

Our approach: Data-Flow Scheduler (DFS)

- Offset-based round-robin schema
  - avoid endpoint bandwidth sharing
  - use all network links
- Coordinate input nodes in time
  - divide time into intervals
  - via collecting timing data from compute nodes
  - schedule injection rate at input nodes
  - let stragglers follow and catch up
  - consider different clock drifts
- Adopt to network changes (available overall bandwidth)
  - avoid network congestion

Data-Flow Scheduler: Architecture

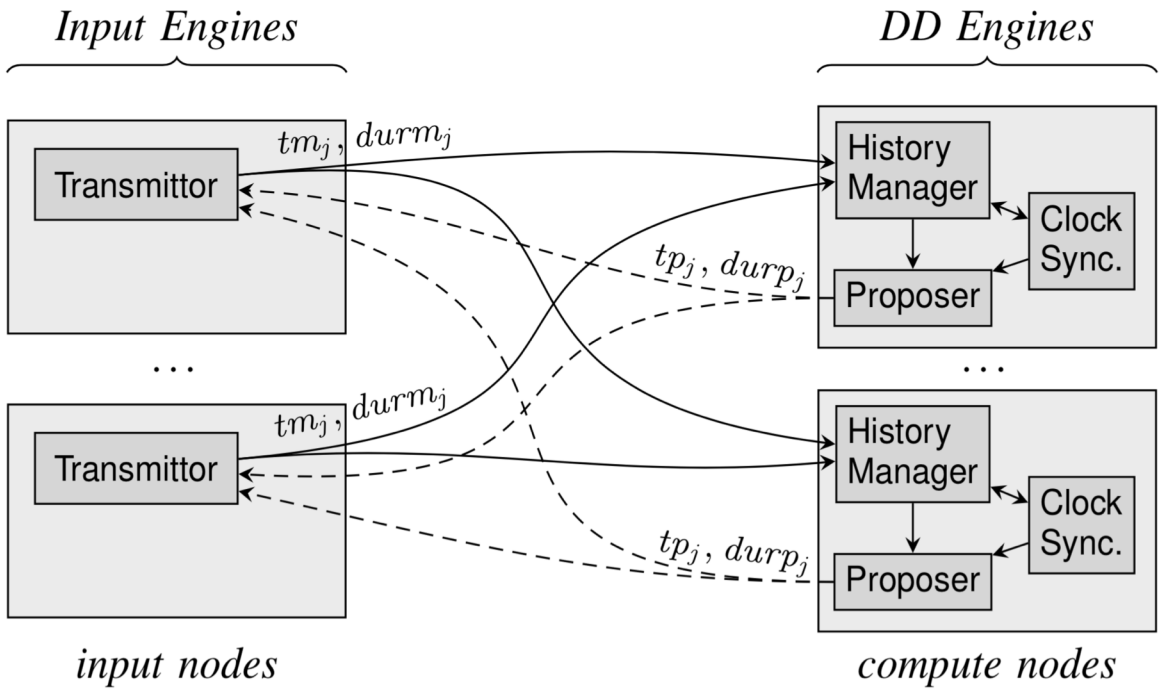
- DFS consists of two engines
  - **Distributed Deterministic Engine**
    - proposes start-time and duration (meta-data) for each interval
  - **Input Engine**
    - follows DD Engines
    - broadcasts the actual meta-data to DD engines



j : interval index
tm : time measured
durm : duration measured
tp : time proposed
durp : duration measured

Data-Flow Scheduler: DD Engine

- **Distributed Deterministic (DD) Engine** consists of three modules:
  - **History Manager**:
    - collects the actual meta-data
    - calculates statistics
  - **Clock Sync.**:
    - triggers the clock drift
    - calculates the clock offsets between nodes
  - **Proposer**:
    - synchronizes the Input Engines
    - calculates interval meta-data of upcoming intervals
    - applies a Staged-SpeedUp (SSU) mechanism
    - broadcasts interval meta-data to Input Engines



j : interval index
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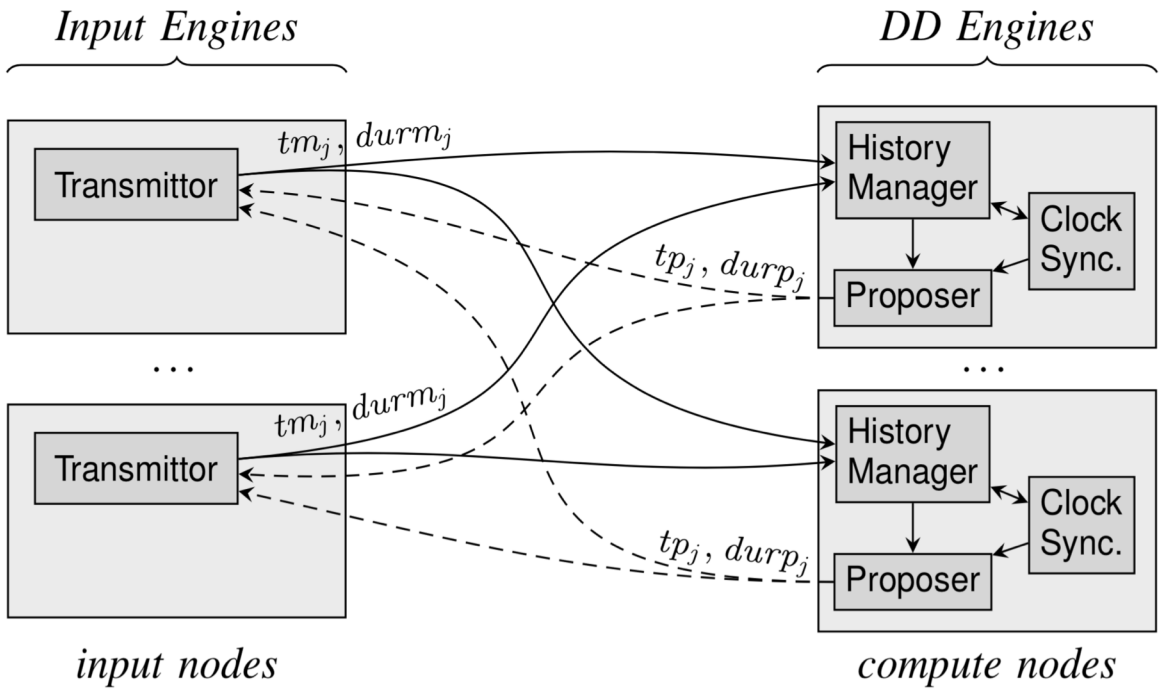
Data-Flow Scheduler: Input Engine

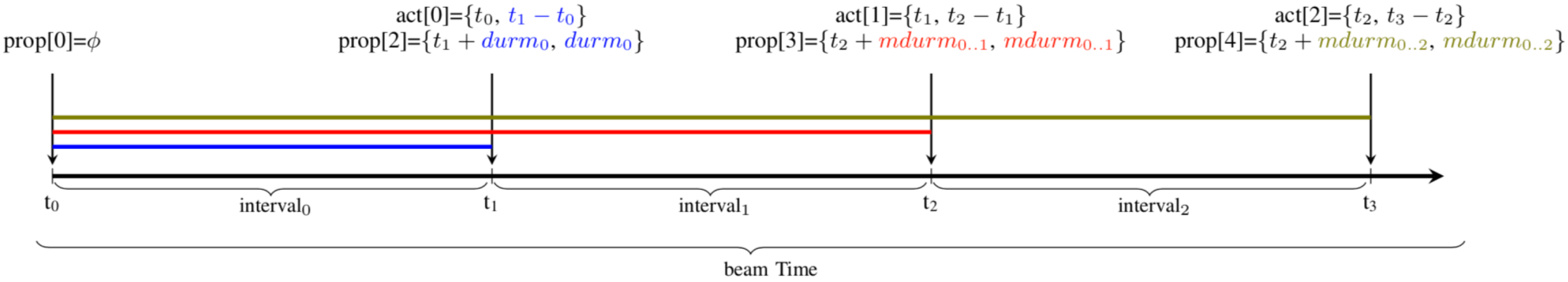
- **Input Engine**
  - transmits first intervals using best-effort approach
  - divides each interval into rounds
  - uses a non-blocking mechanism
  - broadcasts the actual meta-data to DD engines



j : interval index
tm : time measured
durm : duration measured
tp : time proposed
durp : duration measured

Data-Flow Scheduler: Workflow

- prop[x] = {y , z} → proposed meta-data [interval index] = {tp, durp}
- act[x] = {y , z} → Actual meta-data [interval index] = {tm, durm}
- $mdurm_{x..y}$ → median measured durations from interval x to y (sliding window of hist_cnt)



Data-Flow Scheduler: Fault Tolerance

- DD Engines are replicas to each other
  - same meta-data for each interval
  - Input Engines use the first received meta-data

- When a compute node fails
  - Build of history is required
    - Inconsistent meta-data prevention
  - Bandwidth recovery → SSU mechanism

- When an input node fails
  - Failure detection
  - Proposing to use fewer Input Engines

➢ DFS is able to recover the failures in both input and compute nodes

Implementation

- We implemented DFS on top of FLESnet
  - FLESnet used Infiniband Verbs API
  - We ported FLESnet to Libfabric to support modern interconnects
- Input and compute processes run on a separate single cores (single threaded)
- Two types of messages to communicate
  - Remote Direct Memory Access (RDMA): write MTSs
  - Message Passing (SYNC): coordinate between processing nodes
- MPI Barrier to synchronize input and compute processes

Evaluation: Experiment Setup

- CRAY XC40 using up to 384 nodes, each equipped with
  - two Intel Xeon E5-2680v3
  - 64 GiB of main memory
- CRAY mpich v7.5.1
- Libfabric v1.6.2
- Cray GCC v6.2.0
- micro-timeslice size 64 KiB
- Buffer size per node 32 MiB

- We implemented Libfabric and MPI micro-benchmark with the communication pattern of FLESnet
  - To examine the maximum achievable bandwidth without any dependencies or buffer limitations

- FLESnet is tested **with** and **without** the DFS

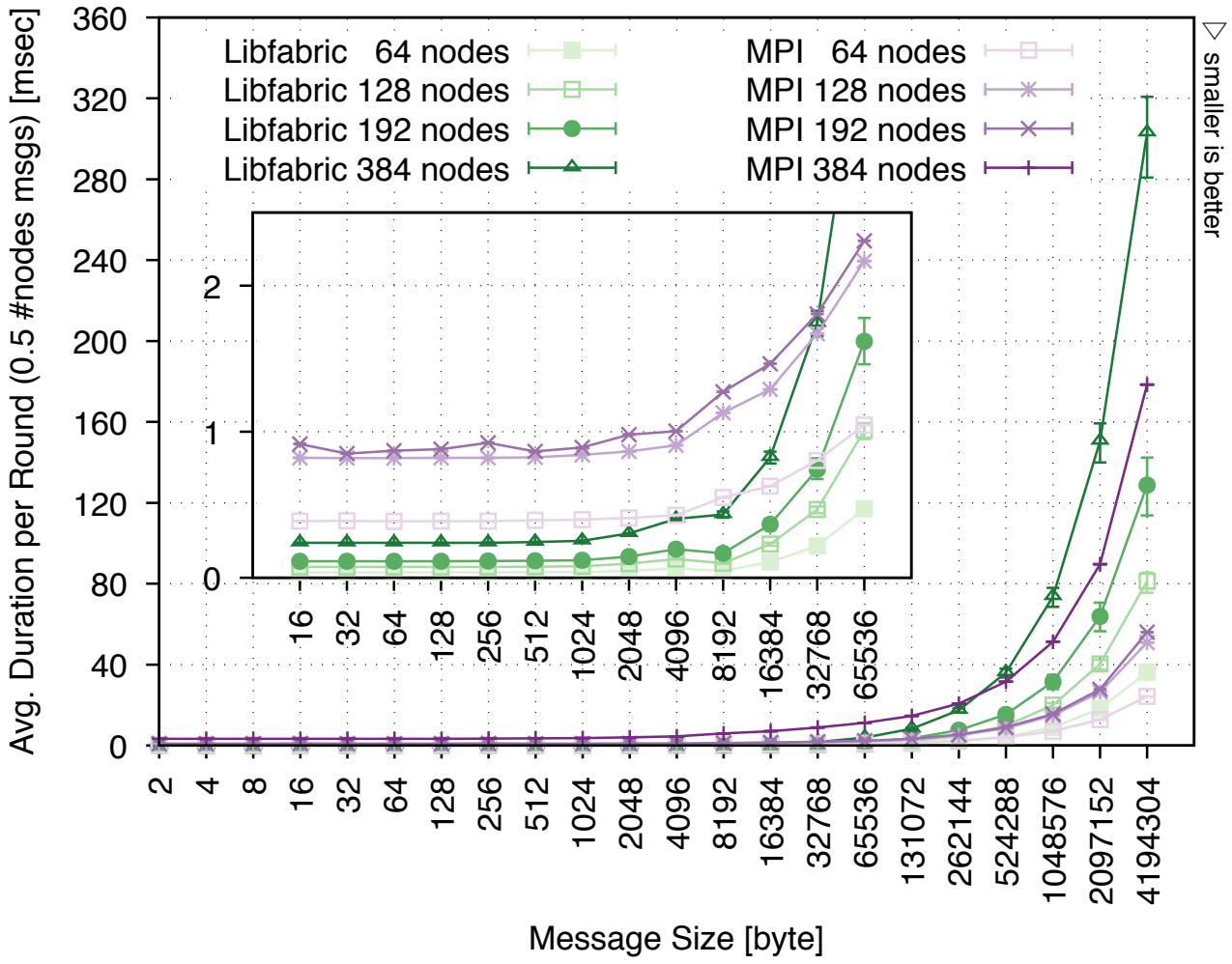
Libfabric/MPI Micro-Benchmark (1)

- The benchmark uses
  - *fi_write* and *MPI_Put*
  - 2 MB of HugePages
  - MPI_Barrier before start transmission
  - Half of nodes as senders and half as receivers
- Each sender finishes writing data independently of other senders

- **MPI achieves shorter duration than Libfabric** when Message Size > 128KiB:

	MPI		
	128n	**192n**	**384n**
64 KiB	⇧ 53.50 %	⇧ 29.84 %	⇧ 65.73 %
128 KiB	⇧ 28.65 %	⇩ 08.70 %	⇧ 43.11 %
1 MiB	⇩ 33.67 %	⇩ 50.65 %	⇩ 43.33 %

⇧ longer duration ⇩ shorter duration



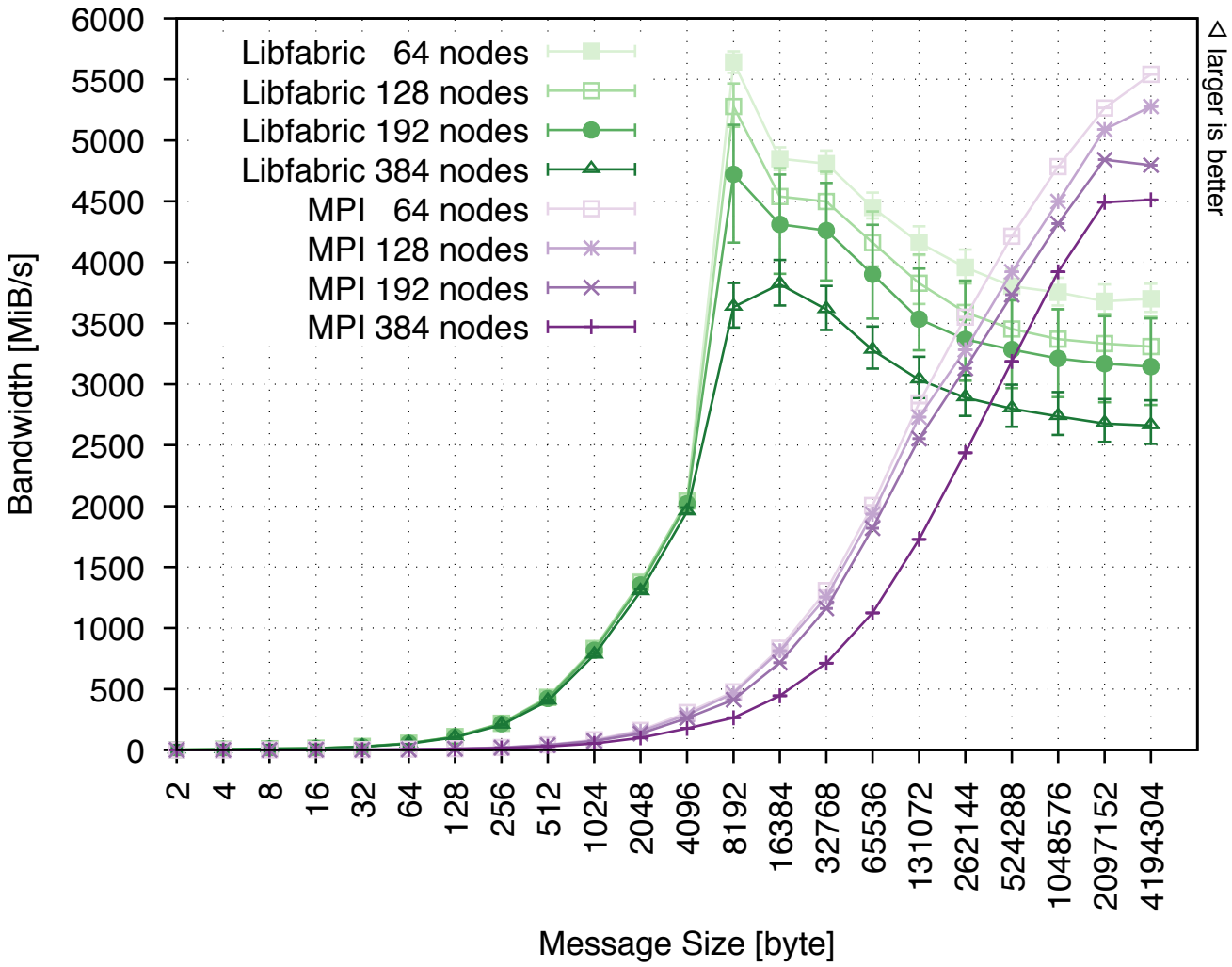
Libfabric/MPI Micro-Benchmark (2)

- A **significant performance drop** with messages larger than 8 KiB using Libfabric

- **Libfabric achieves better bandwidth than MPI** when message size at most **128KiB**:

	Libfabric		
	128n	**192n**	**384n**
64 KiB	⇧ 53.52 %	⇧ 53.38 %	⇧ 65.76 %
128 KiB	⇧ 28.68 %	⇧ 27.76 %	⇧ 43.17 %
1 MiB	⇩ 33.55 %	⇩ 34.44 %	⇩ 43.35 %

⇧more bandwidth ⇩less bandwidth

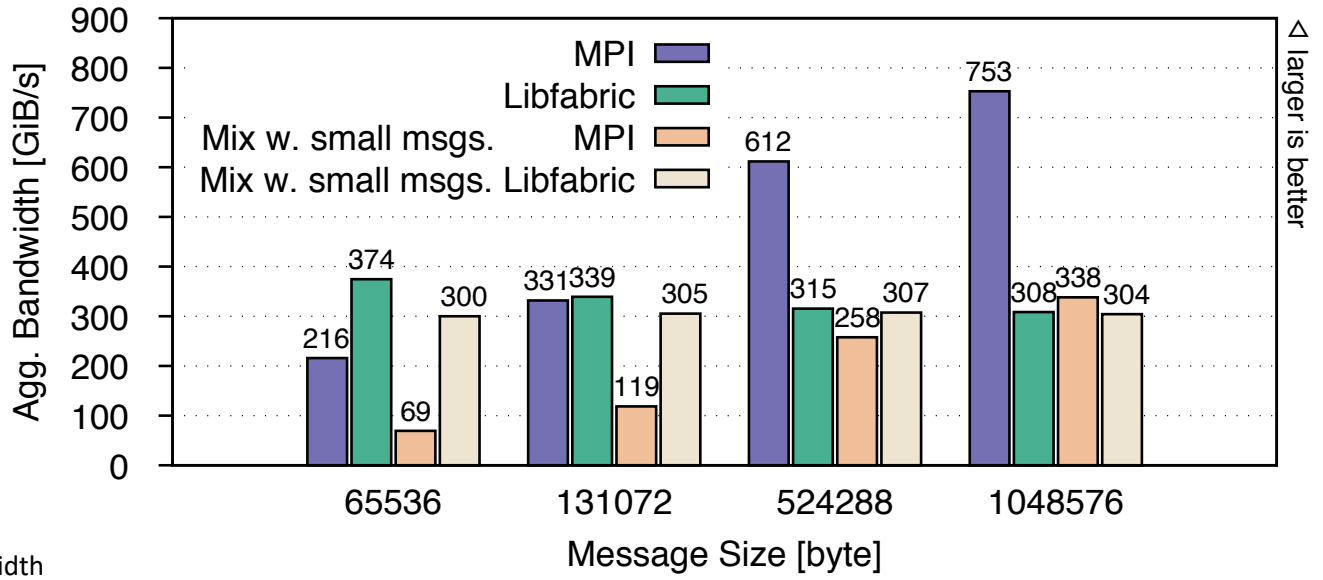


Libfabric/MPI Micro-Benchmark (3)

- A mix of message sizes on Libfabric and MPI for comparison with FLESnet:
  - For each big message (size is variable)
    - One message of 16 bytes
    - Two message of 64 bytes each
- 192 nodes are used
- **Libfabric shows better aggregated bandwidth** than MPI when message size **< 1 MiB**:

	Libfabric
64 KiB	⇧ 77.00 %
128 KiB	⇧ 60.98 %
512 KiB	⇧ 15.96 %
1 MiB	⇩ 11.18 %

⇧ more bandwidth
⇩ less bandwidth



The Data Flow Scheduler
vs
FLESnet

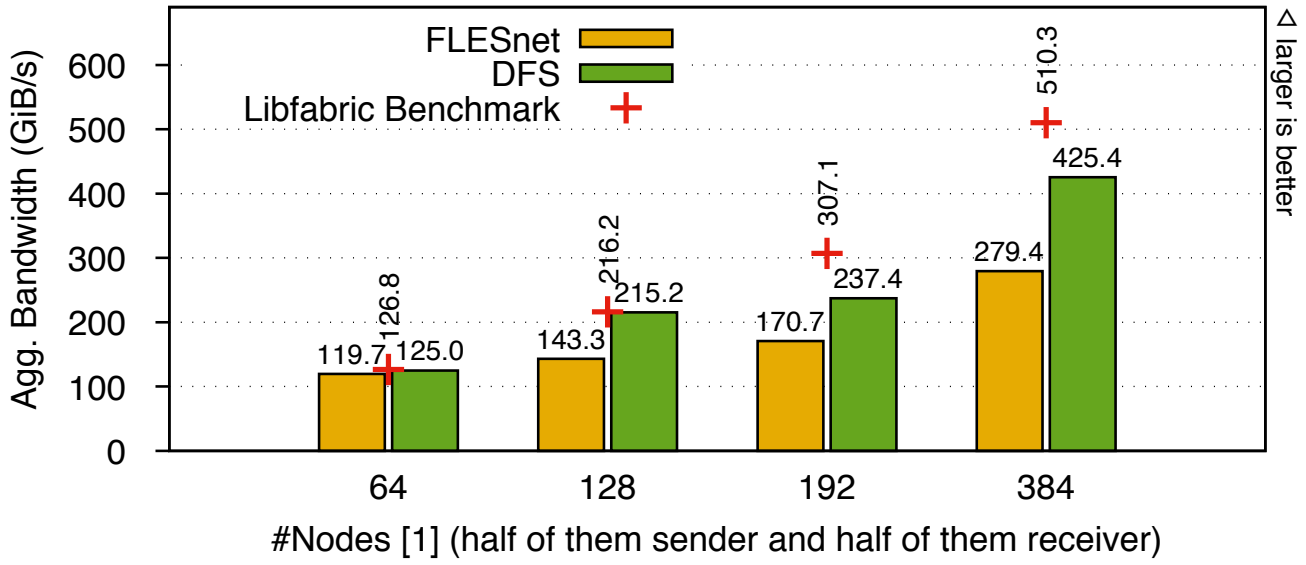
Achieved Throughput

- FLESnet uses a mix of message sizes:
  - MTS size → variable
  - MTS descriptor = 20 bytes
  - SYNC message = 87 bytes

- Libfabric Benchmark is with a mix of same message sizes

- **DFS achieves better aggregated bandwidth than FLESnet** compared to the Libfabric aggregated bandwidth:

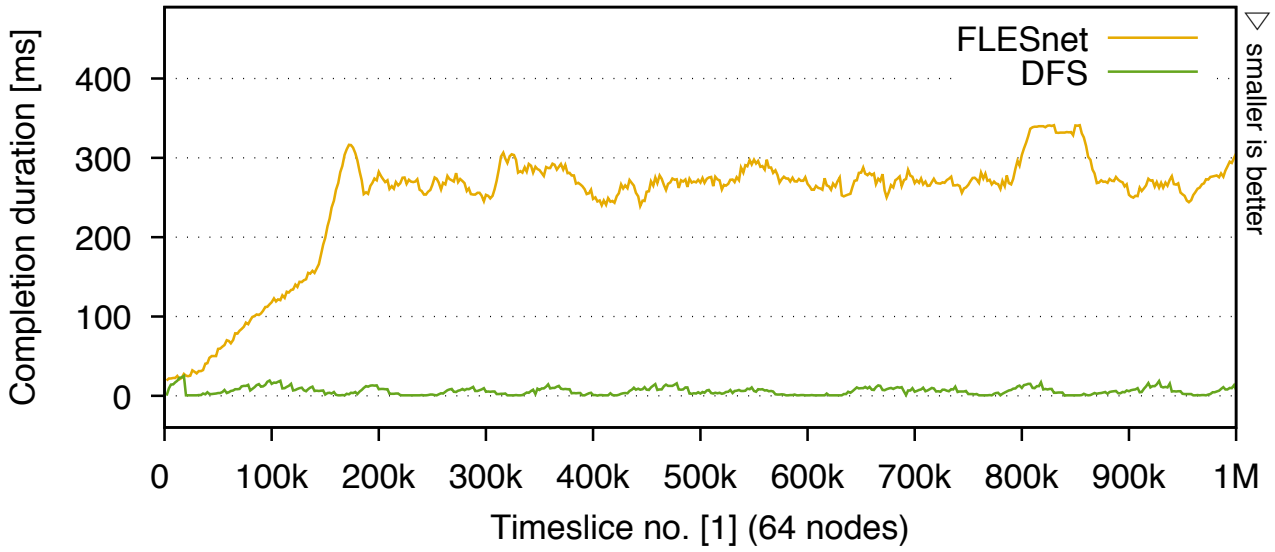
	128n	192n	384n
FLESnet	66 %	55 %	54 %
DFS	99.5 %	77 %	83 %

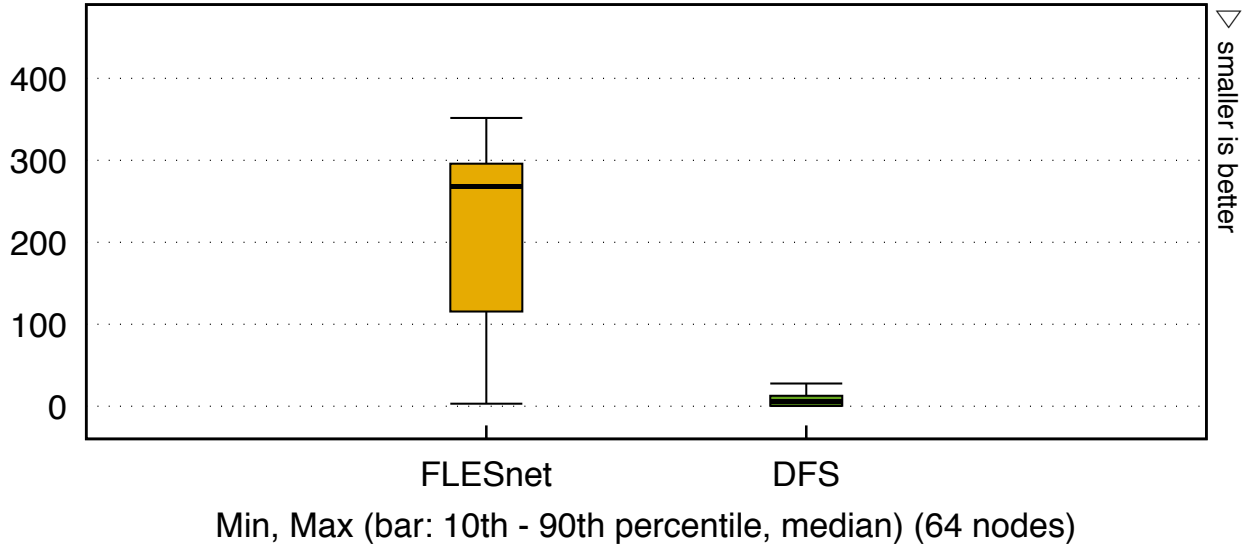


Synchronization Overhead (1)

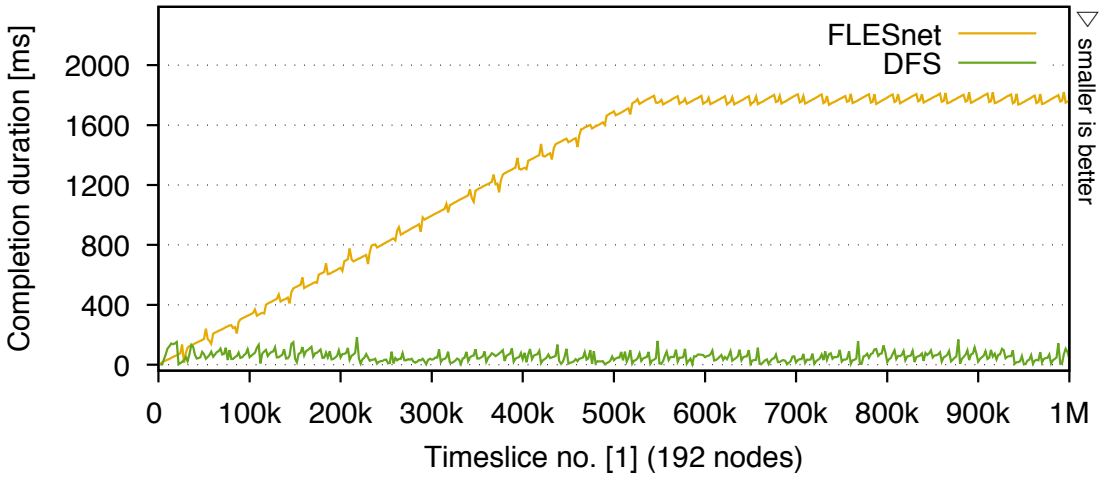
- DFS shortens the duration to receive a complete time-slice at the compute nodes
- At least **30x reduction**
- To receive a complete timeslice (median in ms):

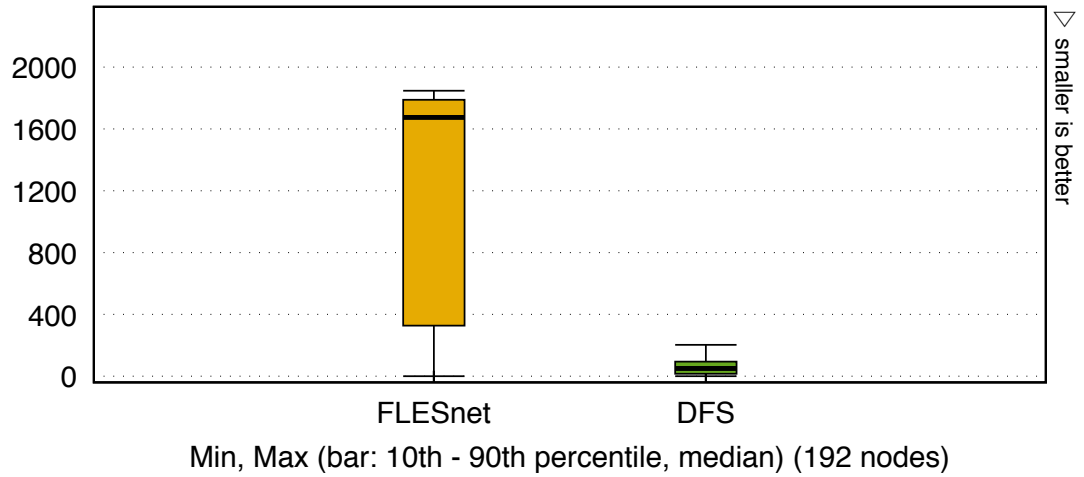
	64n	128n	192n	384n
FLESnet	267.72	957.44	1674.30	4223.63
DFS	5.76	21.29	49.54	138.93

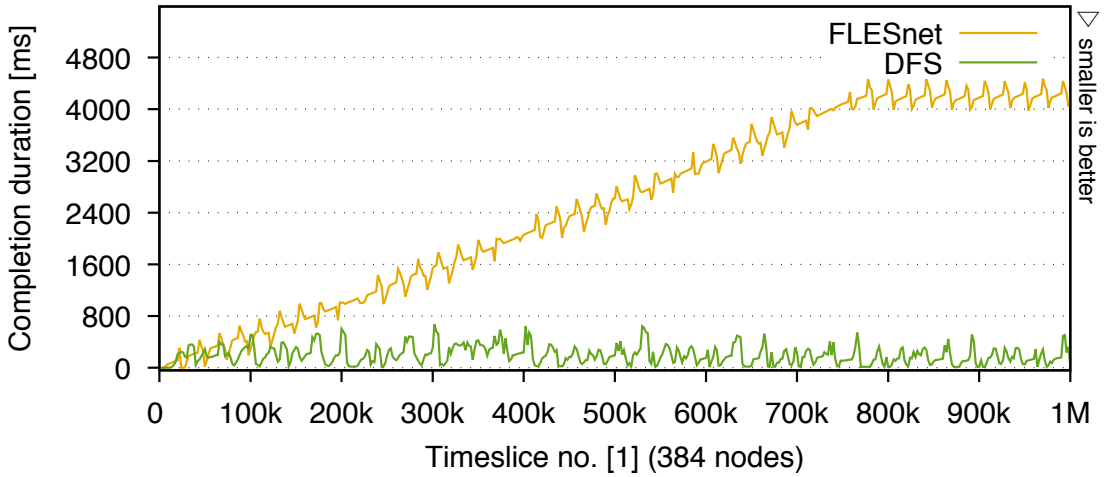


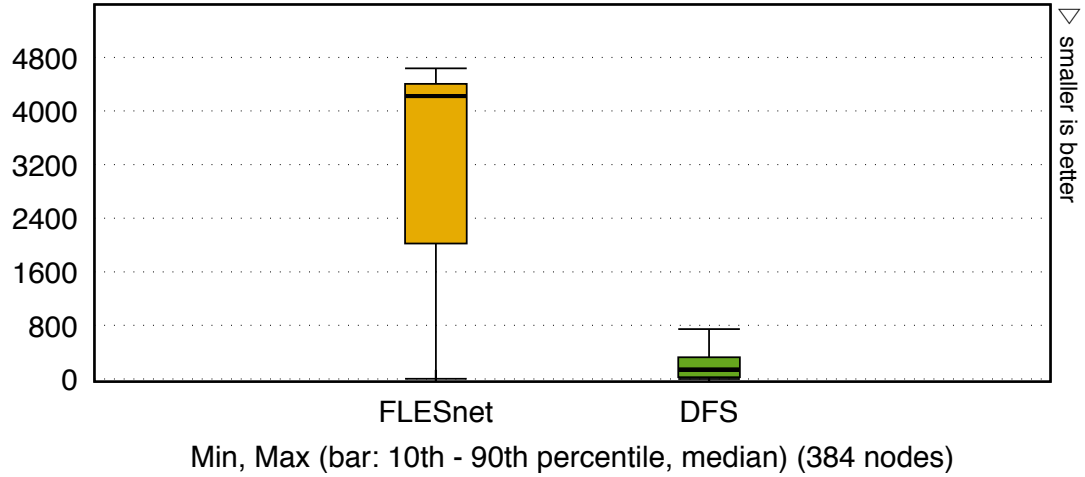


Synchronization Overhead (2)



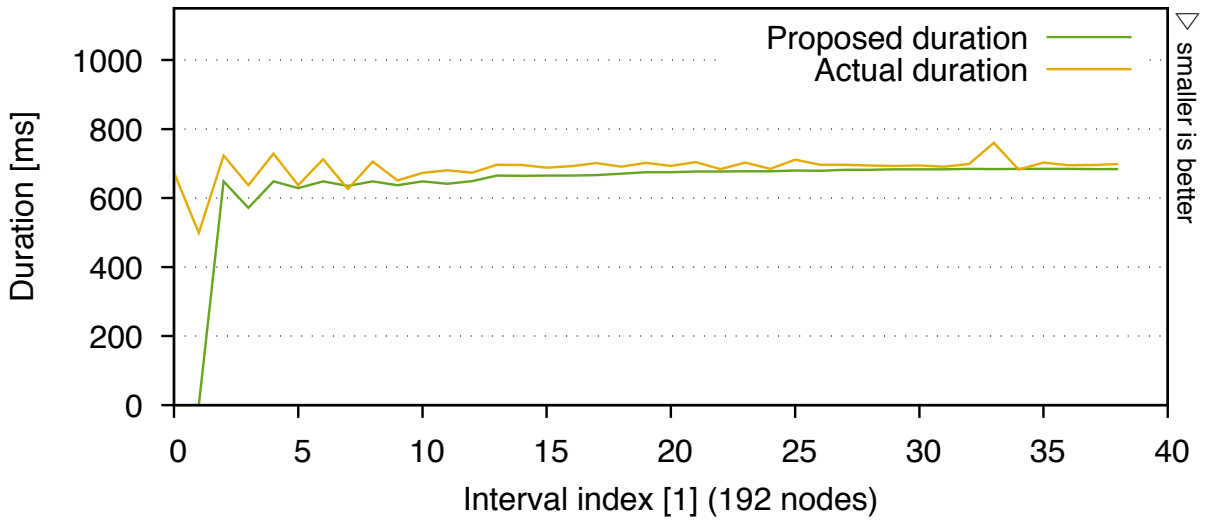


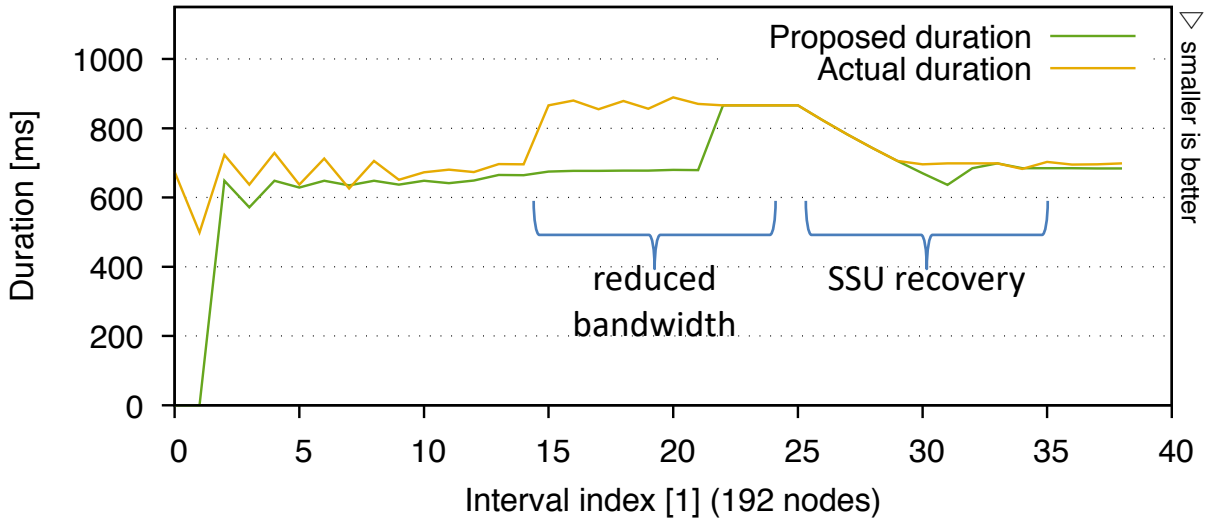




Bandwidth Recovery

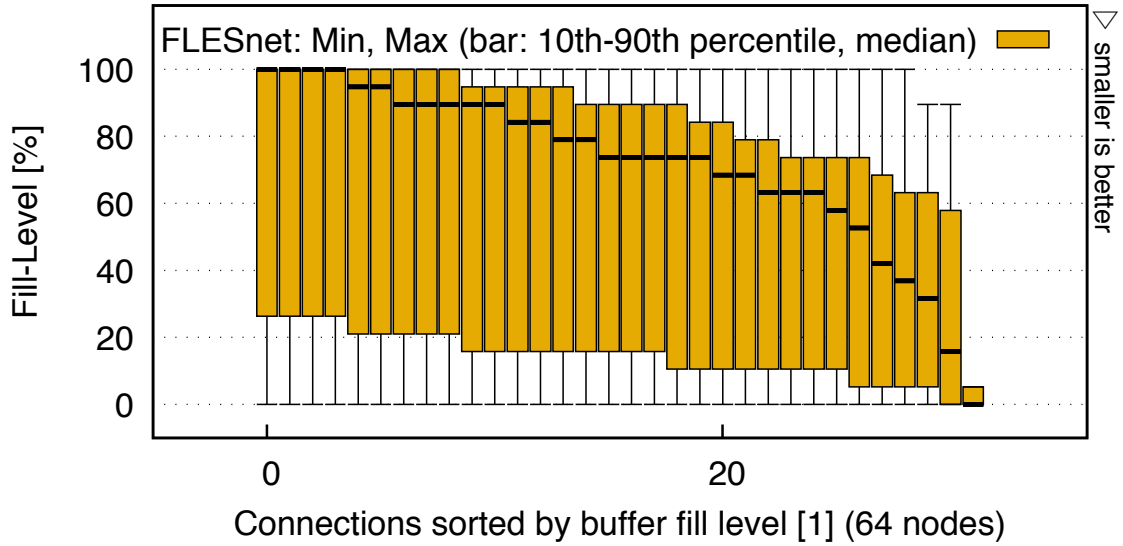
- Input Engines follow the actual proposed meta-data
- When network is stable and SSU is turned off, the duration of intervals stabilizes
- We simulated 25% artificial bandwidth drop for some intervals
  - Recovery of optimal duration

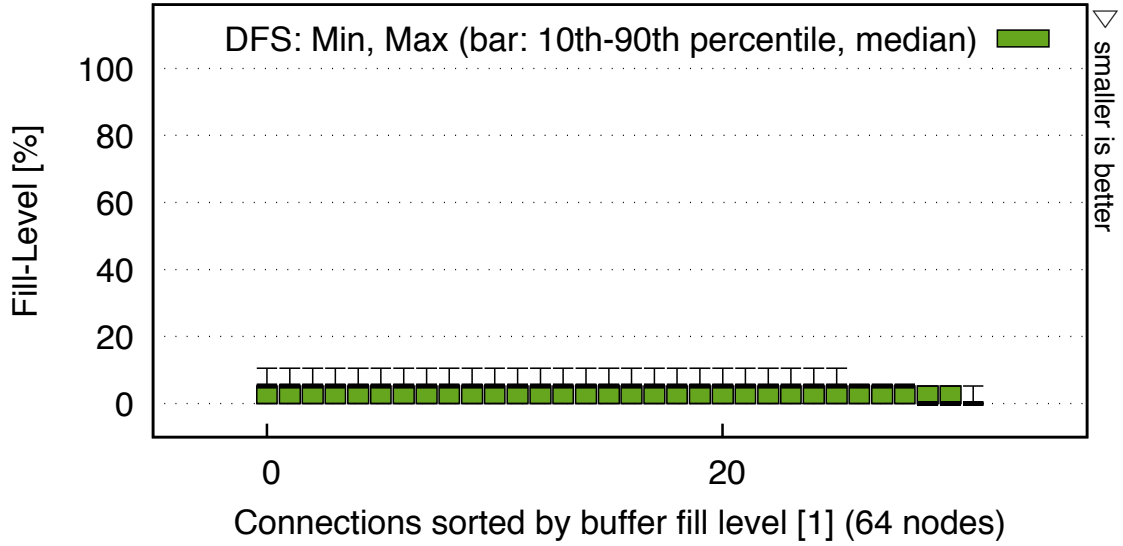




Buffer Usage (1)

- The buffer fill level aggregated across compute nodes shows the significant advantage of DFS
  - the buffer fill level is ordered in descending order.
- With FLESnet: buffers are filled up
  - Input nodes run out of tickets
- With DFS: buffer fill level is only ~ **10 %** for all connections (~ 100 % with FLESnet)





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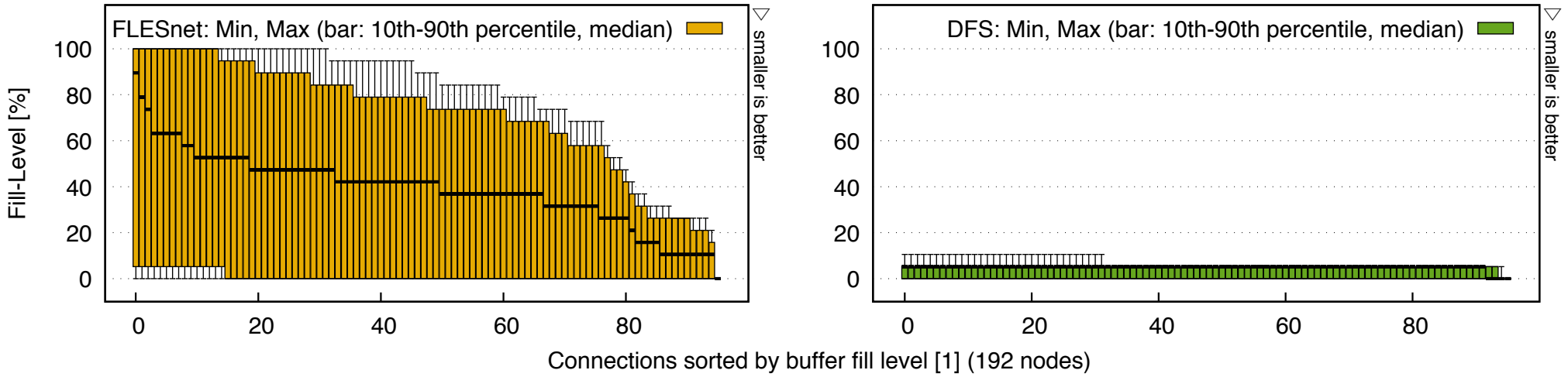
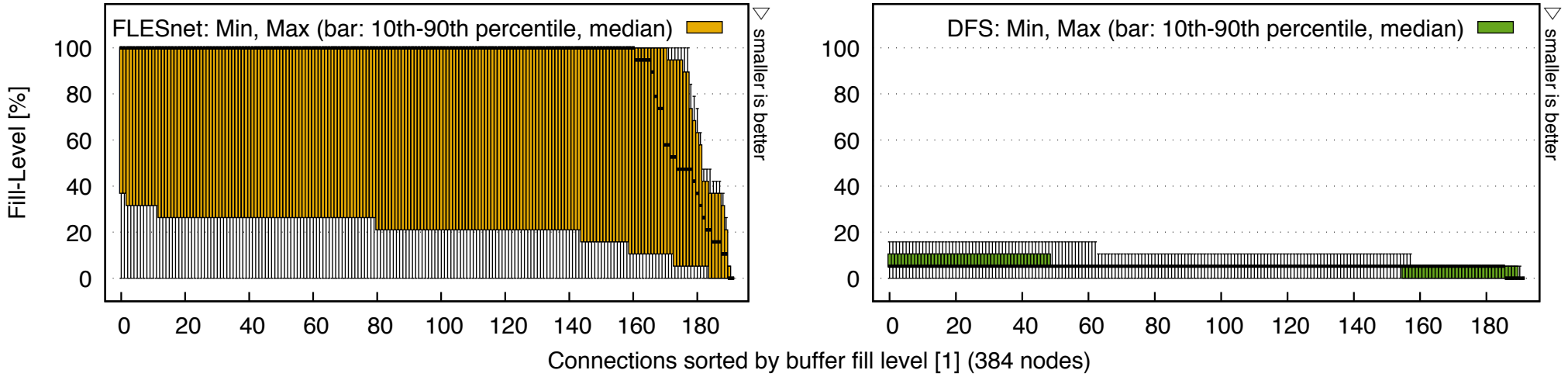
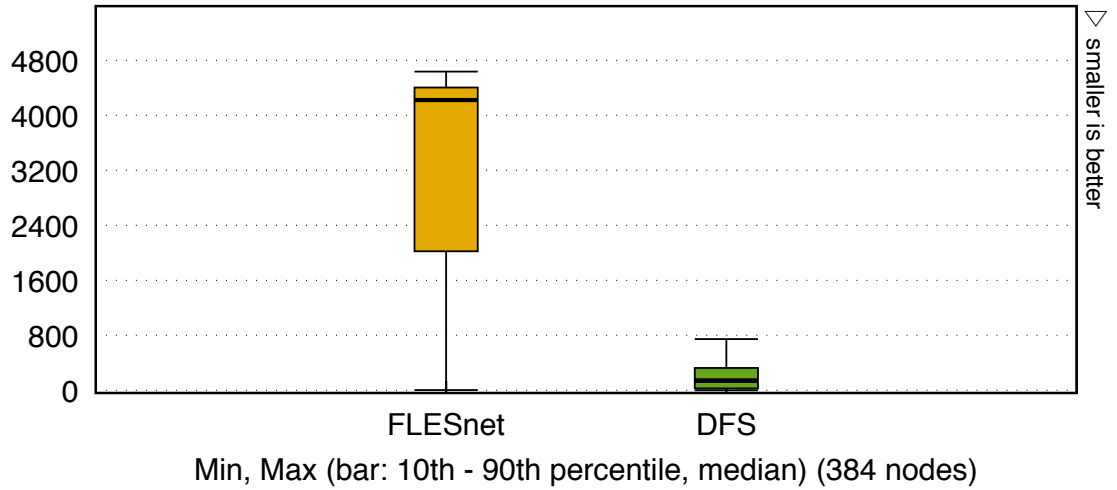




Conclusion

- CBM expected data rate > 1 TiB/s

- The Data-Flow Scheduler (DFS)
  - synchronizes input nodes
  - utilizes the usage of the underlying network
  - reduces endpoint/network congestion



- **Libfabric outperforms MPI** with small messages
- DFS completes time-slices **30x** faster
- DFS needs only **10 % of the buffer space**
- DFS adapts to network changes