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Center for Information Services and High Performance Computing (ZIH)

Scalable High-Quality 1D Partitioning

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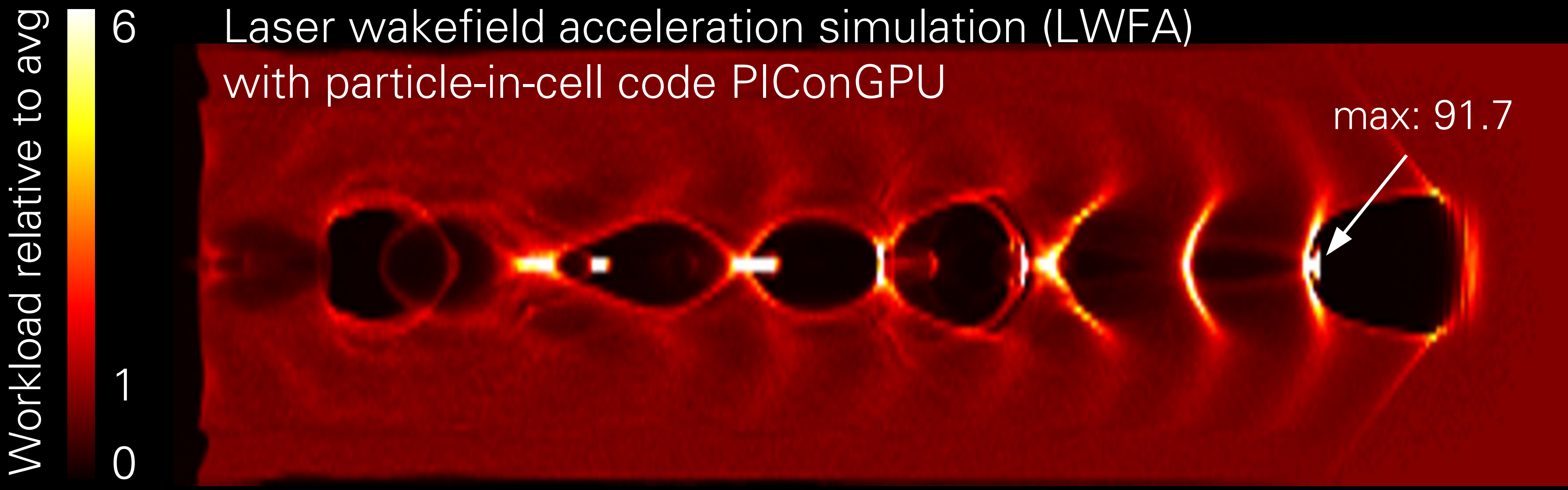
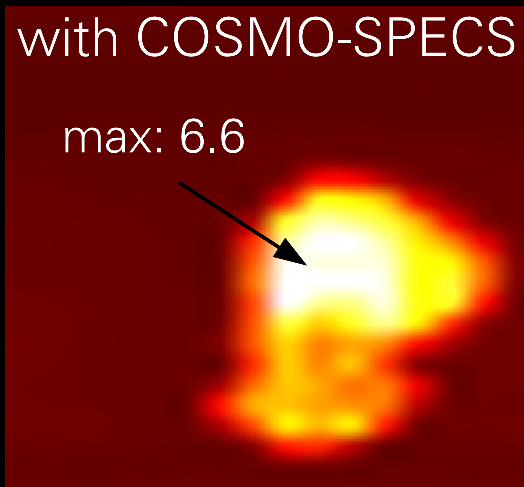
Load balance is a major challenge for scalable HPC applications, especially if the workload changes dynamically.



Laser wakefield acceleration simulation (LWFA)
with particle-in-cell code PIConGPU

Sources of workload variations:
- Adaptive spacial grids (e.g. AMR)
- Adaptive time stepping techniques
- Complex models for physical phenomena

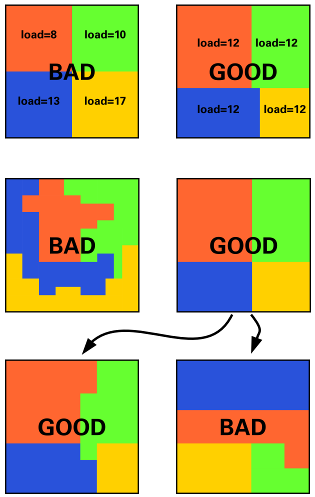
Common solution: dynamic load balancing
- Requires (frequent) repartitioning of domain



Cloud simulation
with COSMO-SPECS

Repartitioning

- Four objectives of repartitioning algorithm
  - Balance workload
  - Reduce communication between partitions (due to data dependencies)
  - Reduce migration, i.e. communication when changing the partitioning
  - Compute partitioning as fast as possible
- Contradictory goals
- Existing methods (heuristics) provide different trade-offs between the four objectives
  - Bisection methods, space-filling curves, graph methods, diffusion methods, ...

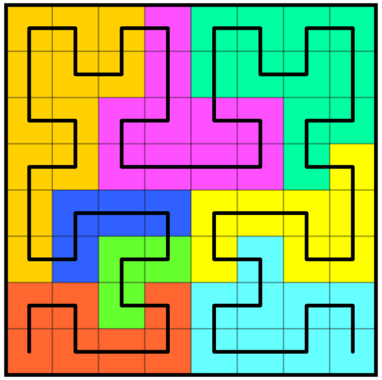


Teresco, Devine, Flaherty, *Partitioning and Dynamic Load Balancing for the Numerical Solution of Partial Differential Equations*, LNCSE, vol. 51, pp. 55-88, 2006.

From SFC Partitioning to 1D Partitioning

- Space-filling curve (SFC) partitioning widely used
  - nD space is mapped to 1D by SFC
  - Mapping is fast and has high locality
  - Migration typically between neighbor ranks
- 1D partitioning is core problem of SFC partitioning
  - Decomposes task chain into consecutive parts
- Two classes of existing 1D partitioning algorithms:
  - Heuristics: fast, parallel, no optimal solution
  - Exact methods: slow, serial, but optimal

Dynamic applications need fast, parallel, and high-quality methods to master Exascale!



Hilbert SFC

Pilkington, Baden, *Dynamic partitioning of non-uniform structured workloads with spacefilling curves*, IEEE T. Parall. Distr., vol. 7, no. 3, pp. 288-300, 1996.

Pinar, Aykanat, *Fast optimal load balancing algorithms for 1D partitioning*, J. Parallel Distr. Com., vol. 64, no. 8, pp. 974-996, 2004.

Overview

- 1D Partitioning Problem Definition
- State of the Art 1D Partitioning
- Improving an Exact Method
- Scalable High-Quality 1D Partitioning
- Conclusion

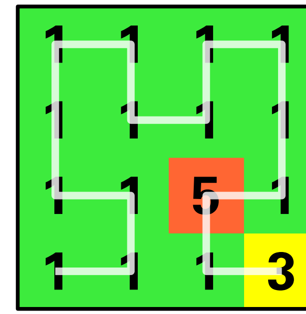
1D Partitioning Problem Definition

Decompose a vector w_i of N positive task weights into P consecutive partitions while minimizing the maximum load (i.e. bottleneck B) among the partitions.

Example for N=16 tasks and P=4 partitions:

- Task weight vector w_i ($i=1,2,\dots,N$):

1	1	1	1	1	1	1	1	1	1	1	1	1	5	1	3



- Optimal solution:

1	1	1	1	1	1	1	1	1	1	1	1	1	5	1	3

- Load L_p of the partitions:

$L_0 = 6$	$L_1 = 6$	$L_2=6$	$L_3=4$

  – Maximum load / Bottleneck $B = \max(L_p) = 6$

  – Load balance $\Lambda_{opt} = (\sum w_i / P) / B_{opt} = 0.92$ ($\Lambda = 1$ would be perfect)

State of the Art 1D Partitioning: Heuristics

- Recursive bisection commonly used
- Heuristic H2 by Miguet and Pierson better to parallelize
- Example for H2 with N=16, P=4, task weights w_i:

1	1	1	1	1	1	1	1	1	1	1	1	1	5	1	3

(1) Prefix sum $W_j = \sum_{i=1}^{j} w_i$

1	2	3	4	5	6	7	8	9	10	11	12	13	18	19	22

(2) First task of partition p: min s with $W_s > p\,(W_N / P)$

$L_0 = 5$	$L_1 = 6$	$L_2 = 2$	$L_3 = 9$

(3) Increment s if W_s is closer to $p\,(W_N / P)$ than $W_{(s-1)}$

$L_0 = 5$	$L_1 = 6$	$L_2 = 7$	$L_3 = 4$

- Bottleneck $B = \max(L_p) = 7$
- Load balance $\Lambda = (W_N / P) / B = 5.5 / 7 = 0.79$

Recursive Bisection Heuristic:
Oden, Patra, Feng, *Domain Decomposition for Adaptive hp Finite Element Methods*, Contemp. Math., vol. 180, 1994.

Method described here:
Miguet, Pierson, *Heuristics for 1D rectilinear partitioning as a low cost and high quality answer to dynamic load balancing*, LNCS, vol. 1225, 1997, pp. 550-564.

State of the Art 1D Partitioning: Exact Methods

- Various exact methods have been proposed
- Fastest method by Pinar and Aykanat: ExactBS
- Based on binary search for the optimal bottleneck B_{opt}
- Search Interval: $W_N / P \leq B_{opt} \leq B_{Heuristic}$
- Requires probing whether a partition exists for given B
  - Binary search on W_j for each P: O(P log N)
  - Han et al.: O(P log (N/P))
  - Pinar and Aykanat: O(P log P + P log(w_{max}/w_{avg}))
- Problems
  - Slower than heuristics
  - More fatal: serial only, one process needs to collect task weights from all other processes

Extensive Overview: Pinar, Aykanat, *Fast optimal load balancing algorithms for 1D partitioning*, J. Parallel Distr. Com., vol. 64, no. 8, pp. 974-996, 2004.

Han, Narahari, Choi, *Mapping a chain task to chained processors*, Inform. Process. Lett., vol. 44, no. 3, pp. 141-148, 1992.

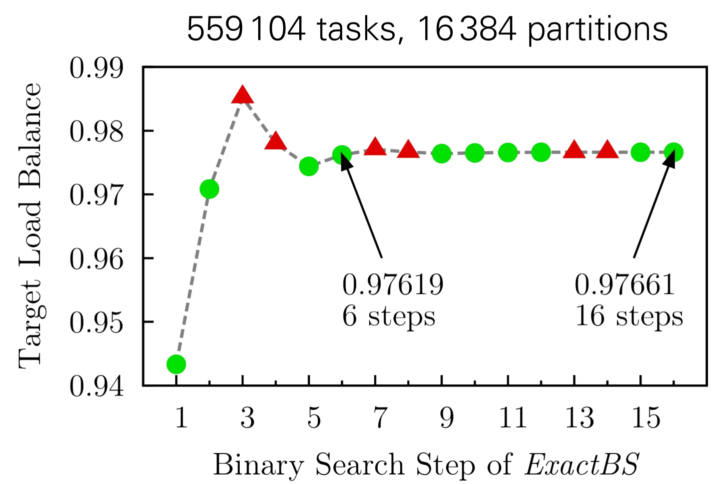
Improving an Exact Method: ExactBS → QBS → QBS*

(1) New probe algorithm, tuned for small N / P

- Guess that consecutive partitions have same number of tasks, if not, do linear (!) search on W_j starting from guessed position

(2) QBS: Quality-Assuring Bisection Algorithm

- Stop binary search at given quality q
- Guarantees load balance $\Lambda = q\ \Lambda_{opt}$
- Reduces number of search steps
- Exact method for q = 1

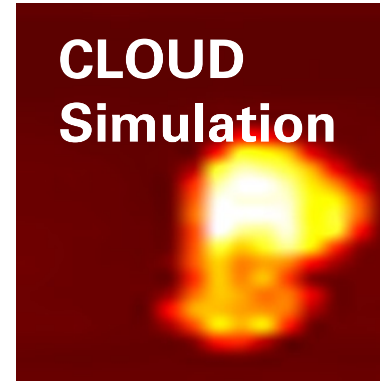


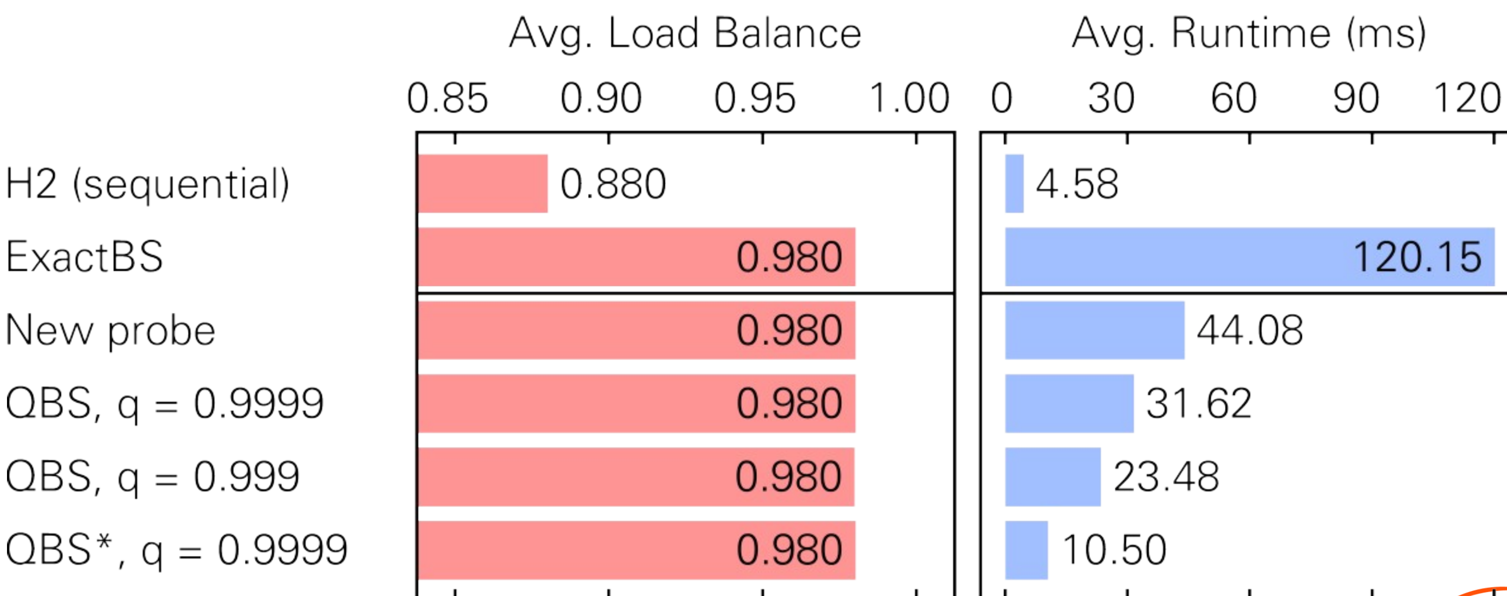
(3) QBS*: Parallelization of binary search

- Search interval for Bopt is split between processes
- Reduces number of search steps
- Downside: all processes need task weights of all processes

Improving an Exact Method: Comparison Benchmark

- Comparison to existing methods H2 and ExactBS
- Averages over 100 successive task weight vectors from the cloud simulation
- System: JUQUEEN, IBM Blue Gene/Q
- 559 104 tasks, 16 384 partitions / MPI ranks





Runtime includes only partitioning calculation, i.e. no collection of task weights and no prefix sum

Scalable High-Quality 1D Partitioning: Algorithm HIER*

Large scale applications require a fully parallel method, i.e. without gathering all task weights

- Run parallel H2 to create G < P coarse partitions:

Orig part. | P0 | P1 | P2 | P3 | P4 | P5 | P6 | P7

↯Parallel Heuristic H2

Coarse part. | P0 / P1 | P2 / P3 | P4 / P5 | P6 / P7

- Run G independent instances of exact QBS* (q=1.0) to create final partitions within each group:

↯QBS* | ↯QBS* | ↯QBS* | ↯QBS*

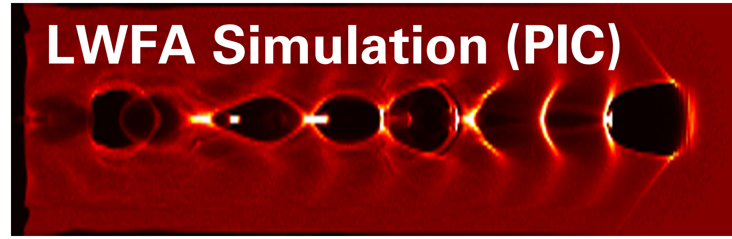
Final part. | P0 | P1 | P2 | P3 | P4 | P5 | P6 | P7

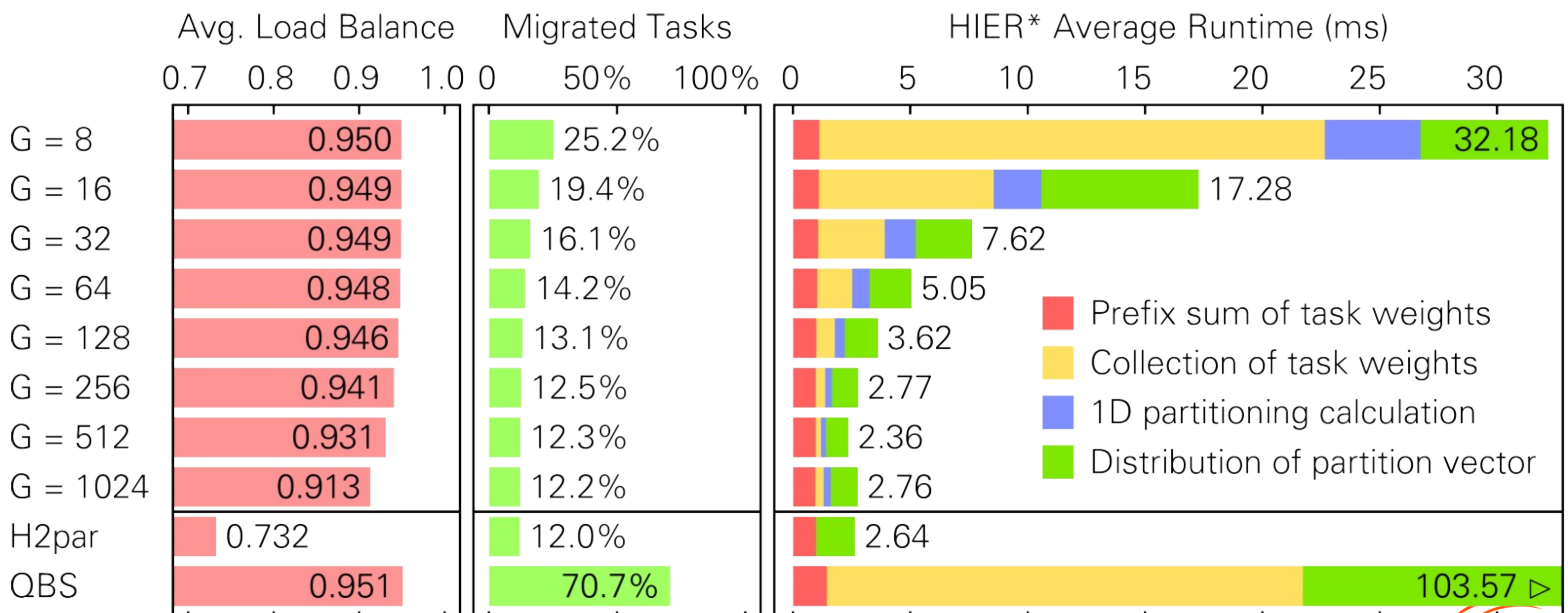
- Parameter G allows trade-off between scalability (high G → heuristic dominates) and load balance (small G → exact method dominates)

H2 nearly optimal if $w_{max} << W_N / P$: Miguet, Pierson, *Heuristics for 1D rectilinear partitioning as a low cost and high quality answer to dynamic load balancing*, LNCS, vol. 1225, 1997, pp. 550-564.

Scalable High-Quality 1D Partitioning: Group Count G

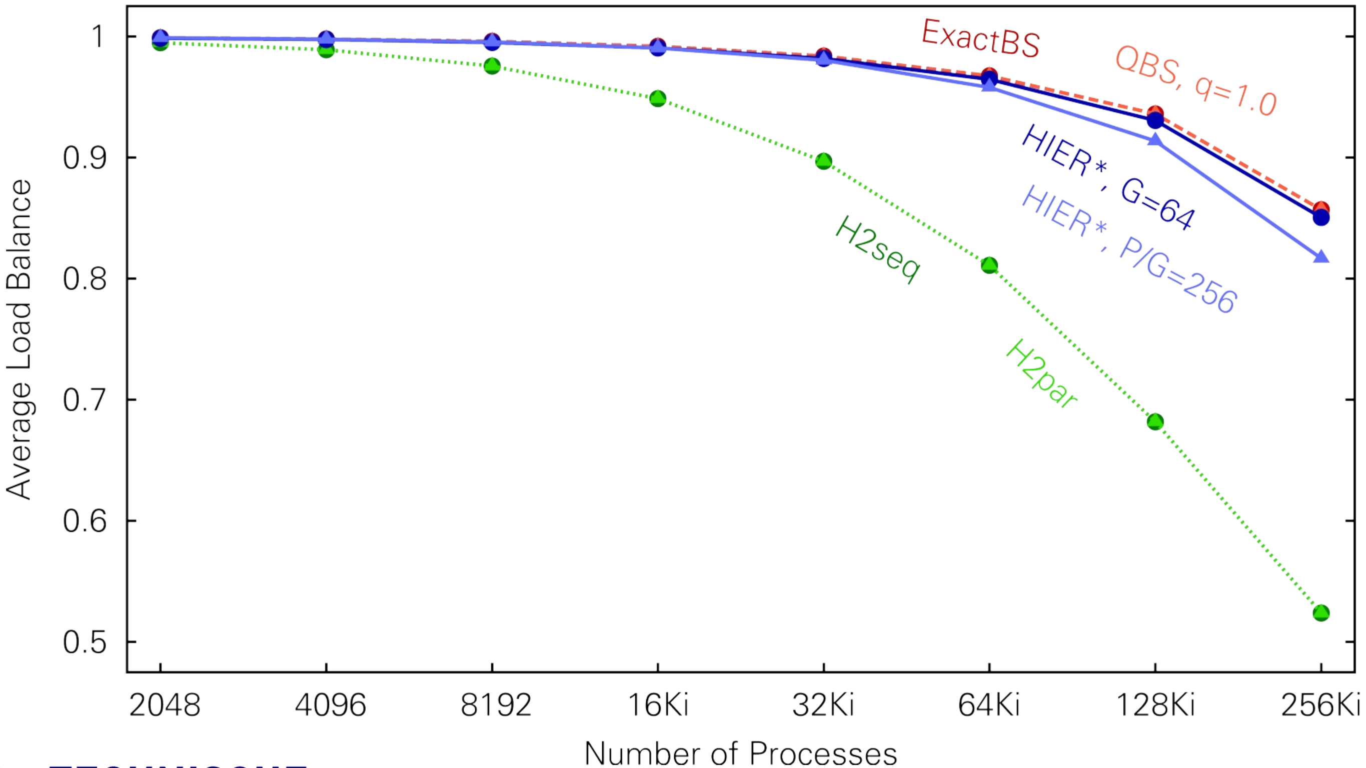
- Comparison of HIER* with parallel heuristic H2 and QBS
- Averages over 2000 successive task weight vectors of the LWFA simulation
- System: JUQUEEN, IBM Blue Gene/Q
- 1 048 576 tasks, 16 384 partitions / MPI ranks





Scalable High-Quality 1D Partitioning: Load Balance

- Cloud simulation, 1 357 824 tasks
- System: JUQUEEN, IBM Blue Gene/Q
- HIER*, G=64 achieves 99.2 % of the optimal load balance at 262 144 processes



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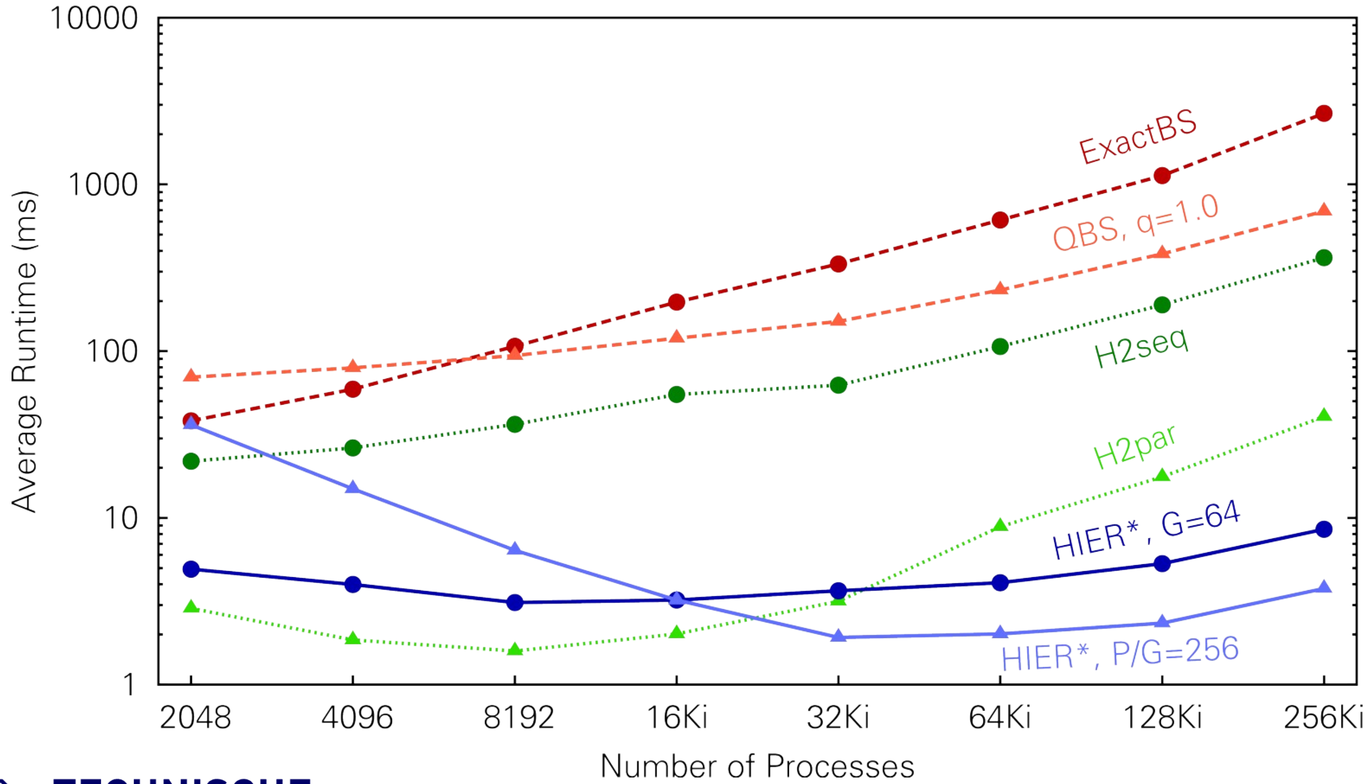
Scalable High-Quality 1D Partitioning: BG/Q Scalability

- Cloud simulation, 1 357 824 tasks
- System: JUQUEEN, IBM Blue Gene/Q
- HIER*, G=64 runs at 262 144 processes ~300x faster than ExactBS



ExactBS: 2668 ms

QBS: 692 ms

H2seq: 363 ms

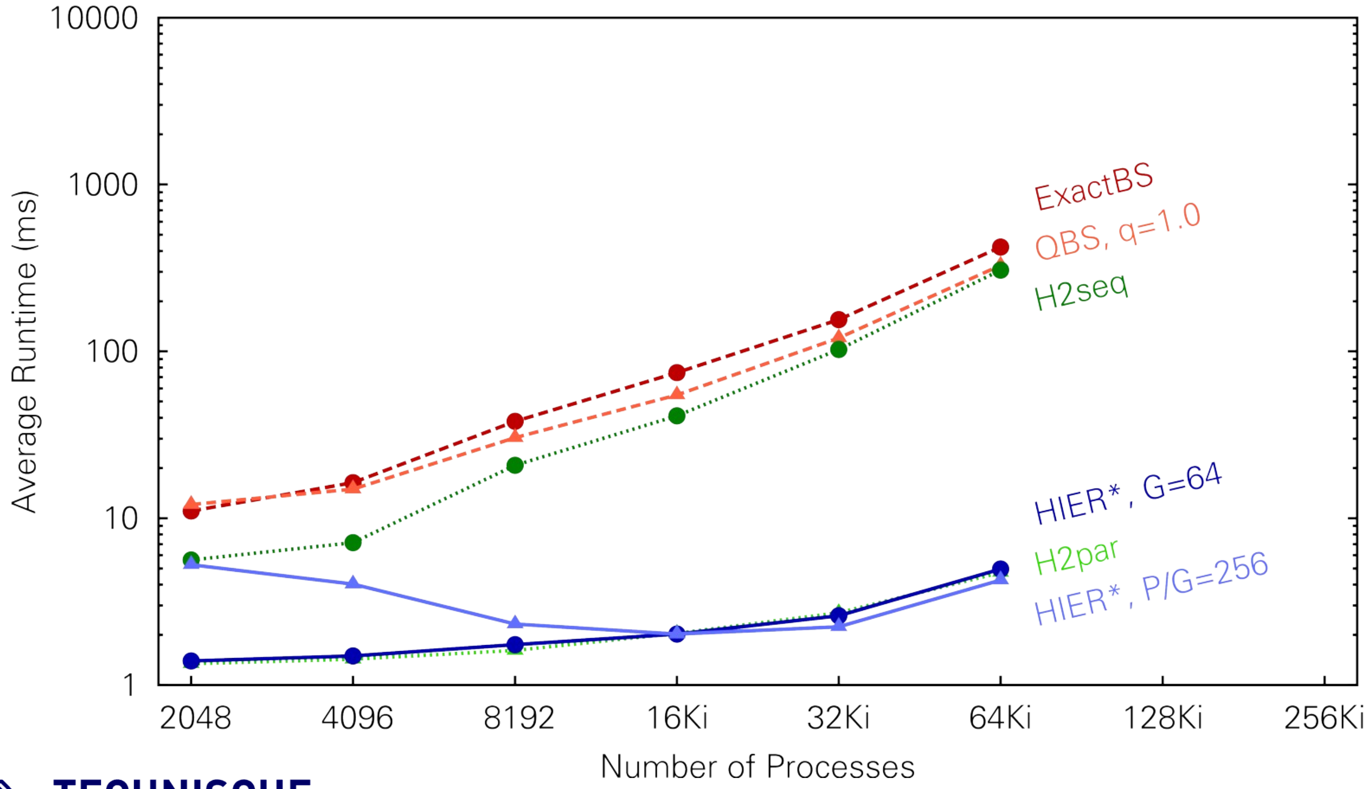
H2par: 40.5 ms

$\text{HIER*}_{G=64}$: 8.55 ms

$\text{HIER*}_{P/G=256}$: 3.77 ms

Scalable High-Quality 1D Partitioning: iDataPlex Scalability

- Cloud simulation, 1 357 824 tasks
- System: SuperMUC, IBM iDataPlex (E5-2680, IB FDR10)
- HIER*, G=64 runs at 65 536 processes ~85x faster than ExactBS



ExactBS: 421 ms

QBS: 328 ms

H2seq: 307 ms

$\text{HIER}^*_{G=64}$: 4.96 ms

H2par: 4.73 ms

$\text{HIER}^*_{P/G=256}$: 4.26 ms

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Conclusions

- Optimized published exact 1D partitioning algorithm
- Developed scalable, hierarchical algorithm
- Implemented in the open source dynamic load balancing and model coupling framework FD4
  - Benchmark program, and cloud dataset available to reproduce results
  - Enables dynamic load balancing up to 262 144 processes for COSMO-SPECS+FD4
- Future work
  - Comparison using other applications workload data
  - 1D partitioning algorithms tuned for low migration
  - Avoid replication of full partition vector on all ranks

FD4 website and benchmark download: http://wwwpub.zih.tu-dresden.de/~mlieber/fd4

Lieber, Nagel, Mix, *Scalability Tuning of the Load Balancing and Coupling Framework FD4*, NIC Symposium 2014, pp. 363-370.

Thank you very much for your attention!

Acknowledgments

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of the Bavarian Academy of Sciences and Humanities

VAMPIR www.vampir.eu

TROPOS
Leibniz Institute for Tropospheric Research

DWD COSMO CONSORTIUM FOR SMALL SCALE MODELING

PIConGPU

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

www.tropos.de

www.cosmo-model.org

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Funding

DFG Deutsche Forschungsgemeinschaft

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Europa fördert Sachsen.
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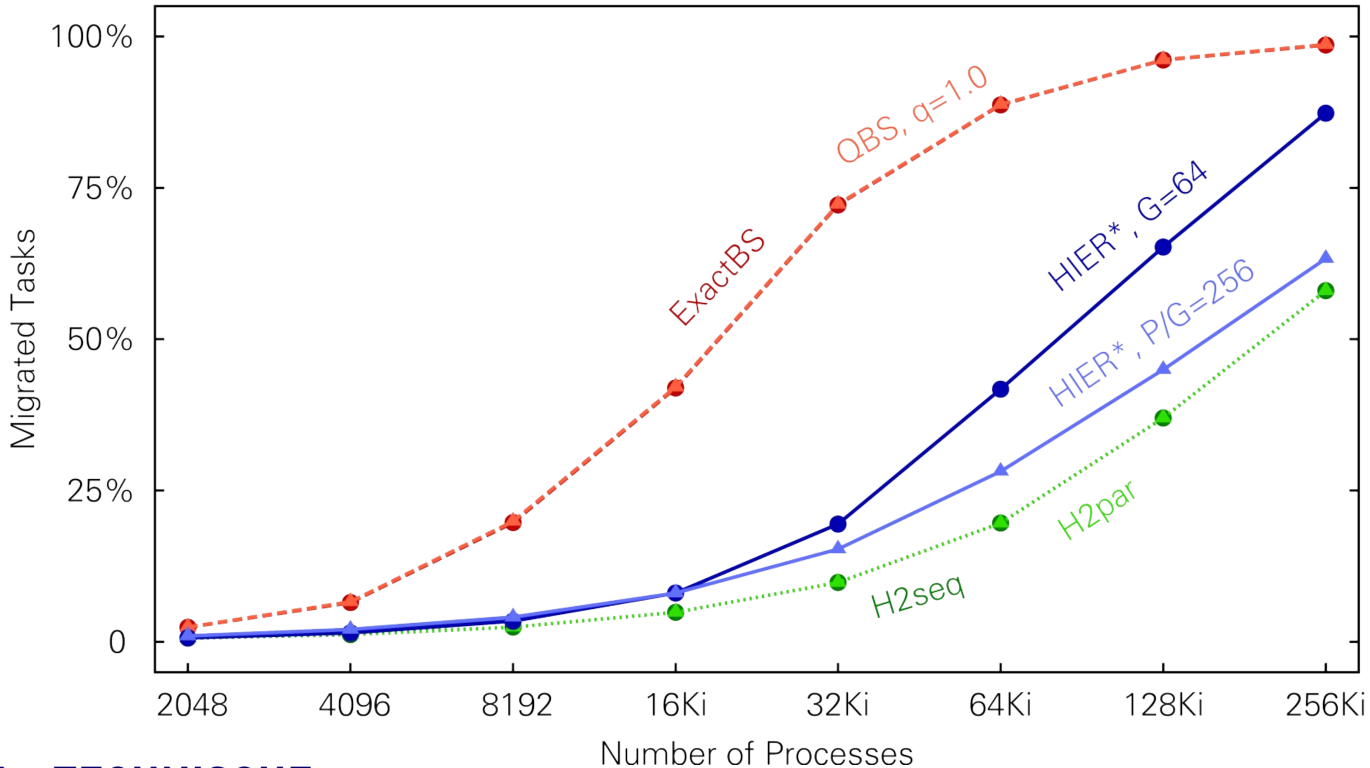
Backup Slides

Scalable High-Quality 1D Partitioning: Migration

- Cloud simulation, 1 357 824 tasks
- System: JUQUEEN, IBM Blue Gene/Q
- Hierarchical method lies between exact and heuristic



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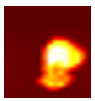
QBS and QBS* Performance (16 384 processes)



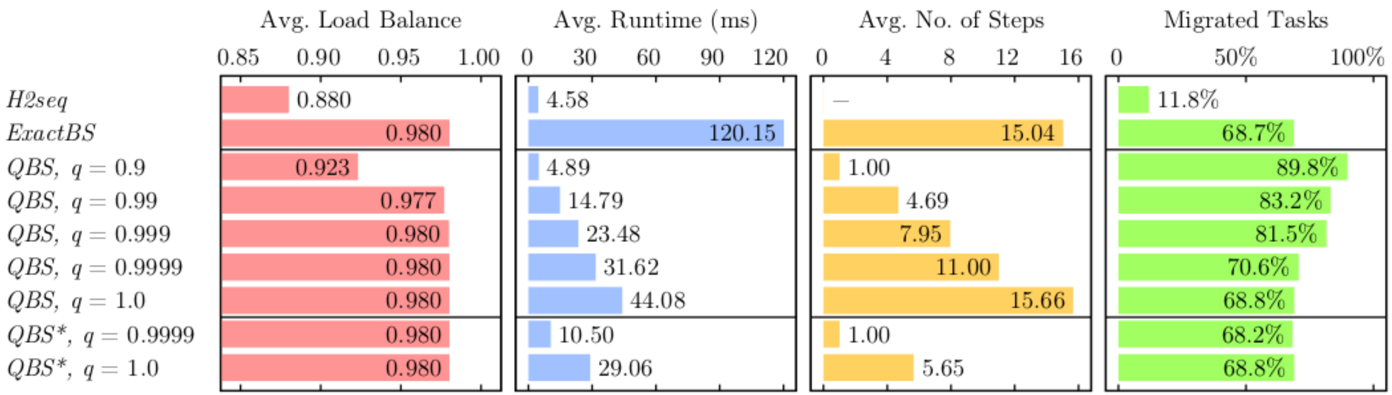


Fig. 5. 1D partitioning benchmark results for the sequential algorithms *H2seq*, *ExactBS*, and *QBS* with the CLOUD dataset (559 104 tasks) for 16 384 processes on JUQUEEN. *QBS** is a version with parallelized search for the optimal bottleneck. The runtime includes the 1D partitioning calculation only.

HIER* Algorithm as seen from MPI

- Prefix sum of task weights + broadcast of total load
  - *MPI_Exscan* (parallel prefix sum)
  - MPI_Bsend + MPI_Recv (consistency at partition borders)
  - *MPI_Bcast* (last rank broadcasts total load to all)
- Compute coarse partitioning with parallel H2
  - MPI_Isend + MPI_Recv + MPI_Waitall (send partition borders to group master)
  - MPI_Bcast (group master broadcasts borders within group)
- Collection of task weights within groups
  - MPI_Isend + MPI_Irevc + MPI_Waitall (send weights from other groups ranks to the nearest ranks in the group these tasks belong to in coarse partitioning)
  - MPI_Allgather (exchange task weights within group)
- Exact partitioning within group with QBS*, q=1
  - MPI_Allreduce
- Distribition of global partition vector
  - MPI_Allgather (between all group masters)
  - MPI_Bcast (within groups)

HIER and HIER* Performance (16 384 processes)

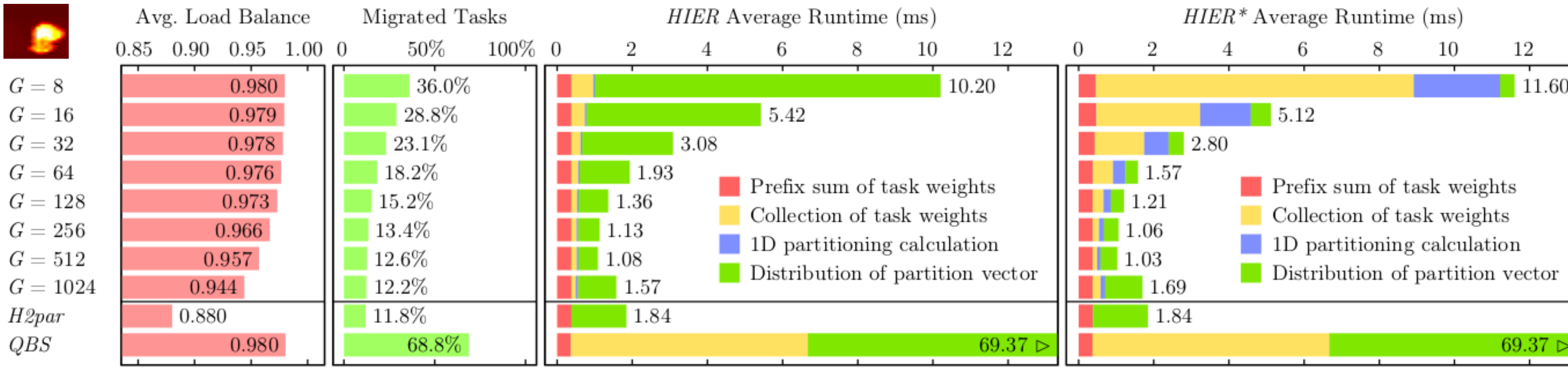


Fig. 6. 1D partitioning benchmark results of the hierarchical methods *HIER* and *HIER** with the CLOUD dataset (559 104 tasks) for 16 384 processes on JUQUEEN. For comparison, the results of the parallel heuristic *H2par* and the sequential exact algorithm *QBS* ($q = 1$) are shown.

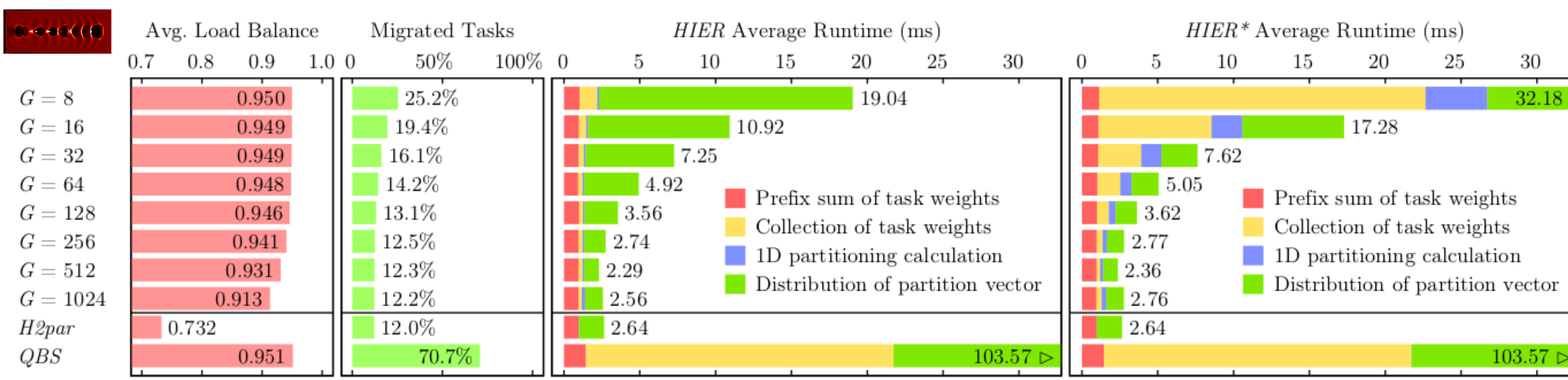
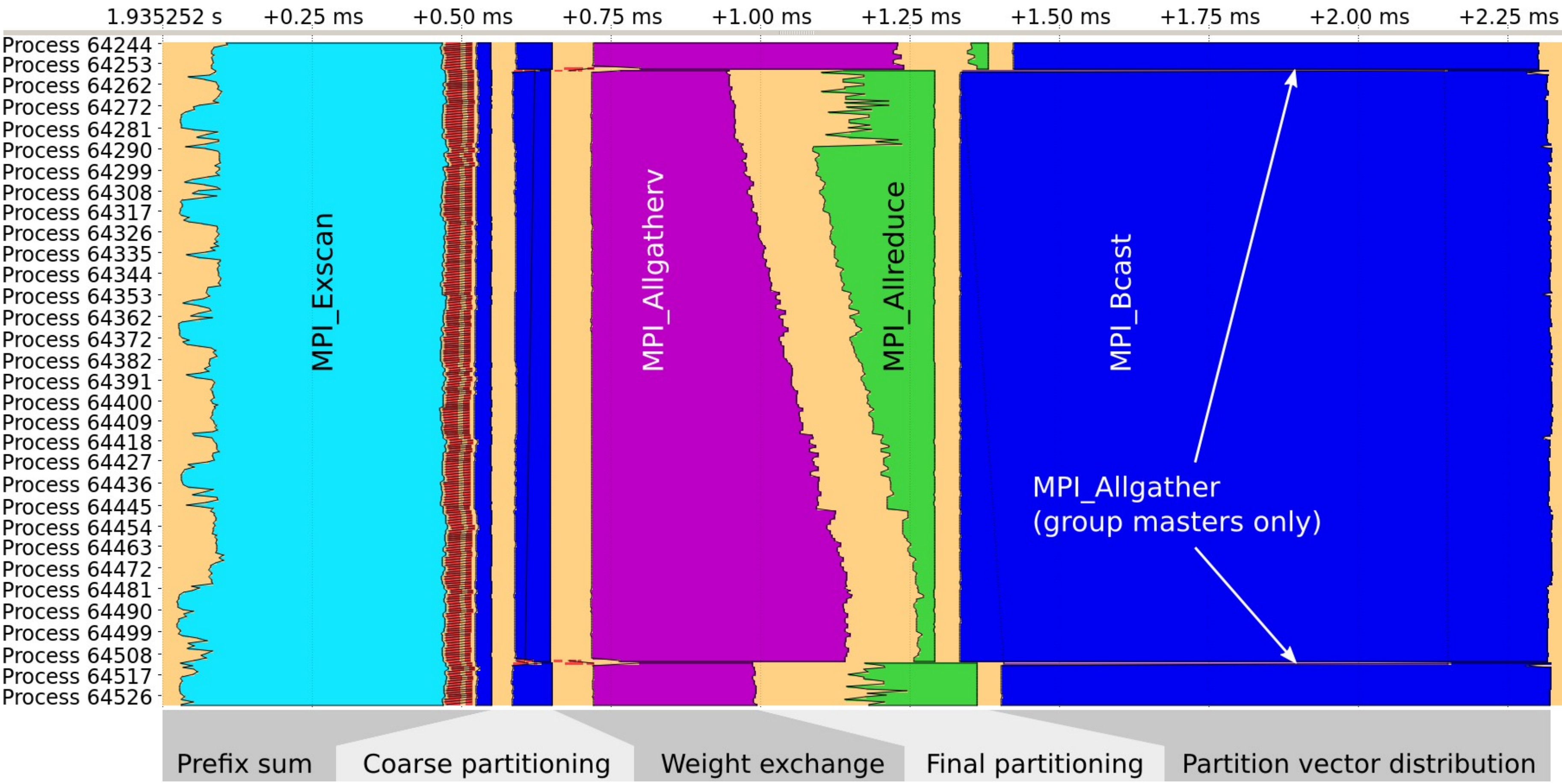


Fig. 7. 1D partitioning benchmark results of the hierarchical methods *HIER* and *HIER** with the LWFA dataset (1 048 576 tasks) for 16 384 processes on JUQUEEN. For comparison, the results of the parallel heuristic *H2par* and the sequential exact algorithm *QBS* ($q = 1$) are shown.

HIER* seen in Vampir (one Group of 256 out of 64Ki)



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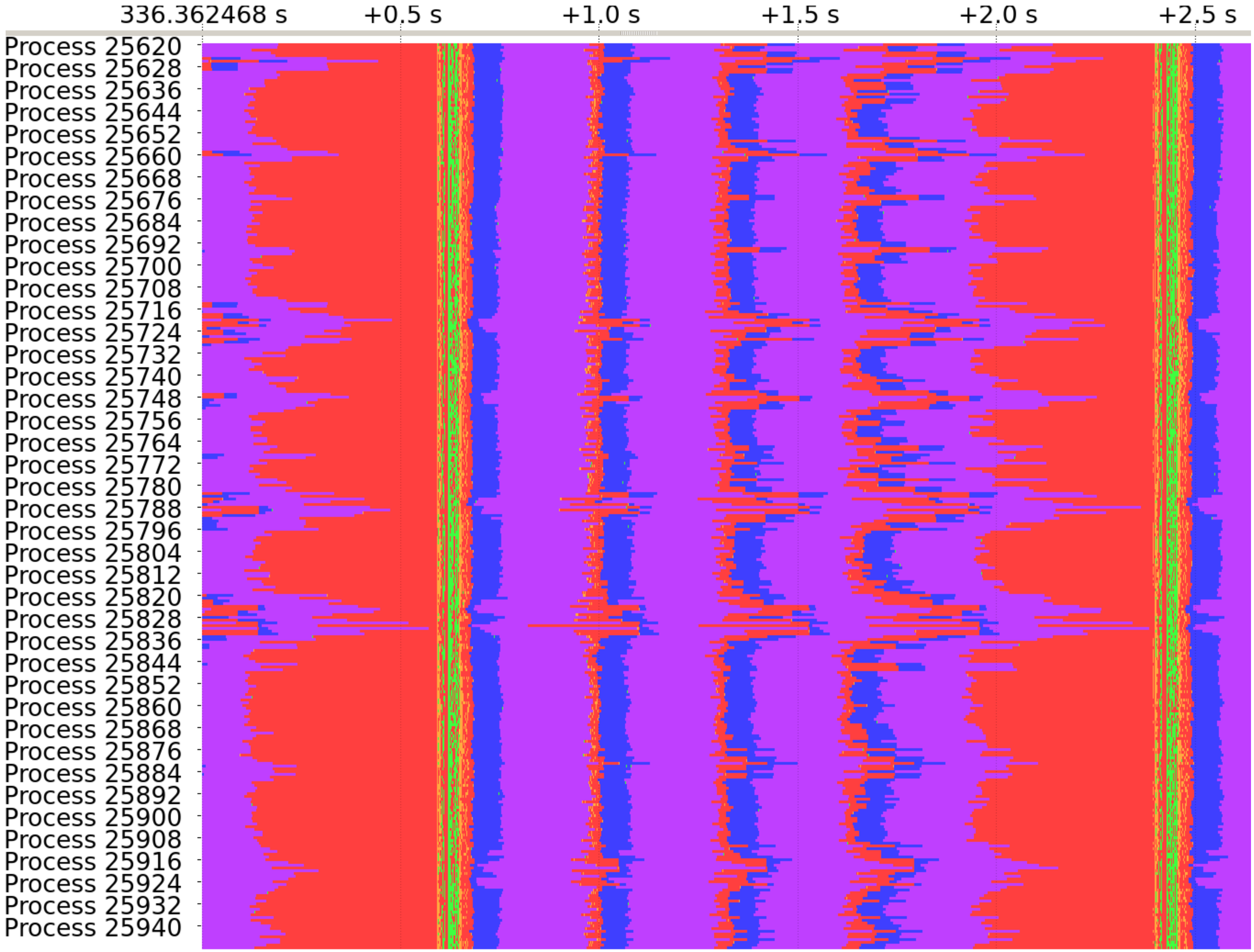
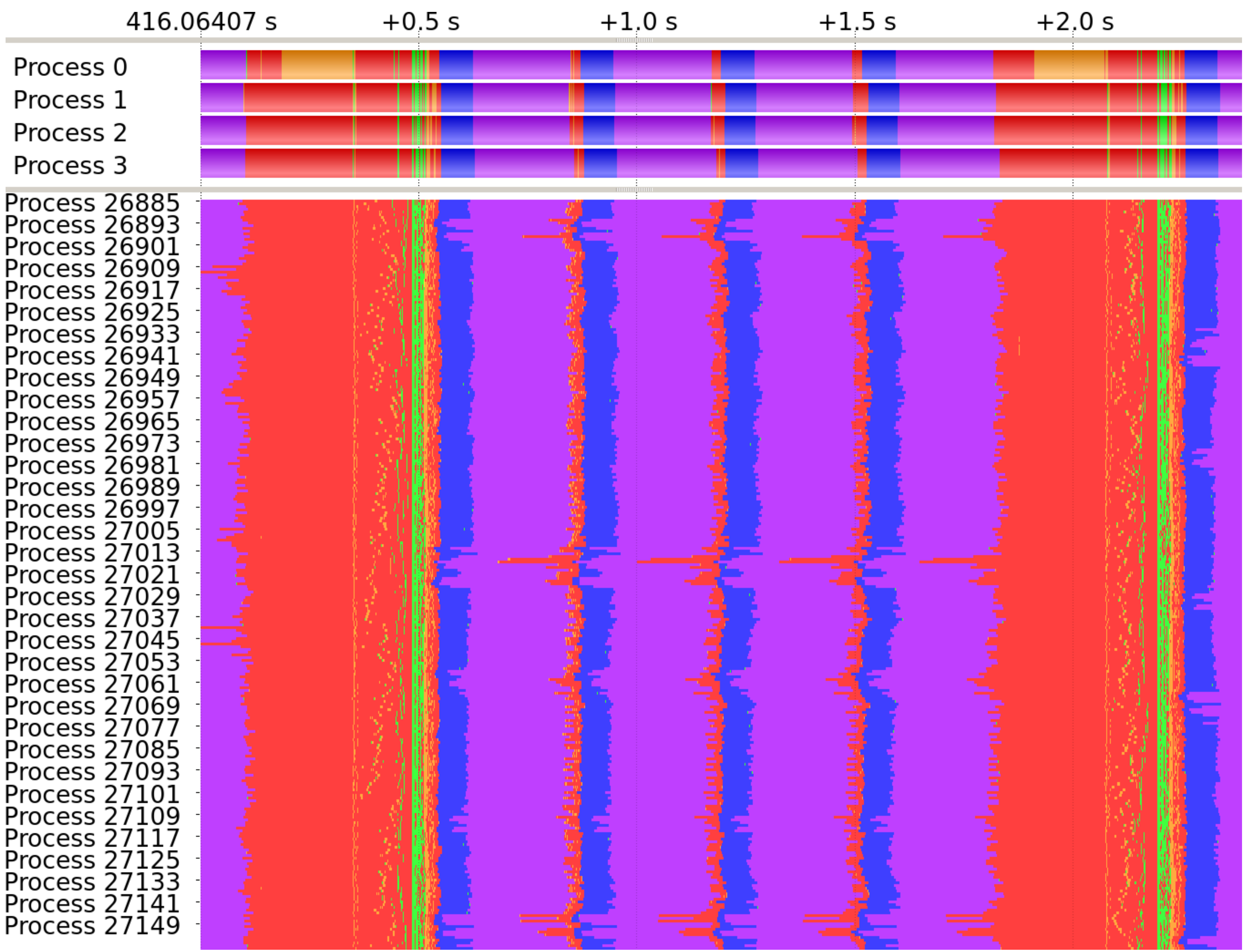
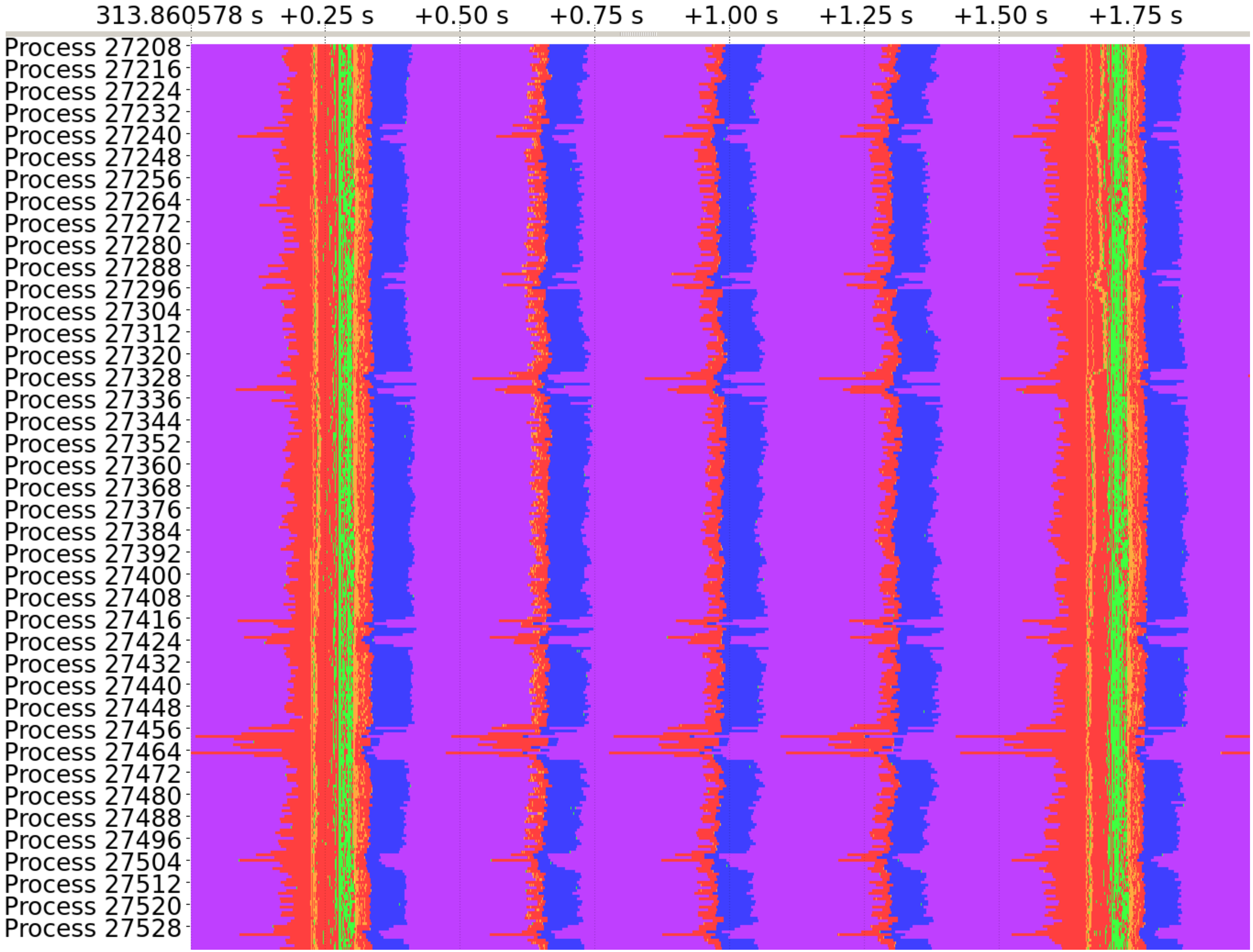
Heuristic H2 in Action (COSMO-SPECS+FD4)



ExactBS in Action (COSMO-SPECS+FD4)



HIER* in Action (COSMO-SPECS+FD4)



COSMO-SPECS+FD4: Comparison of Methods

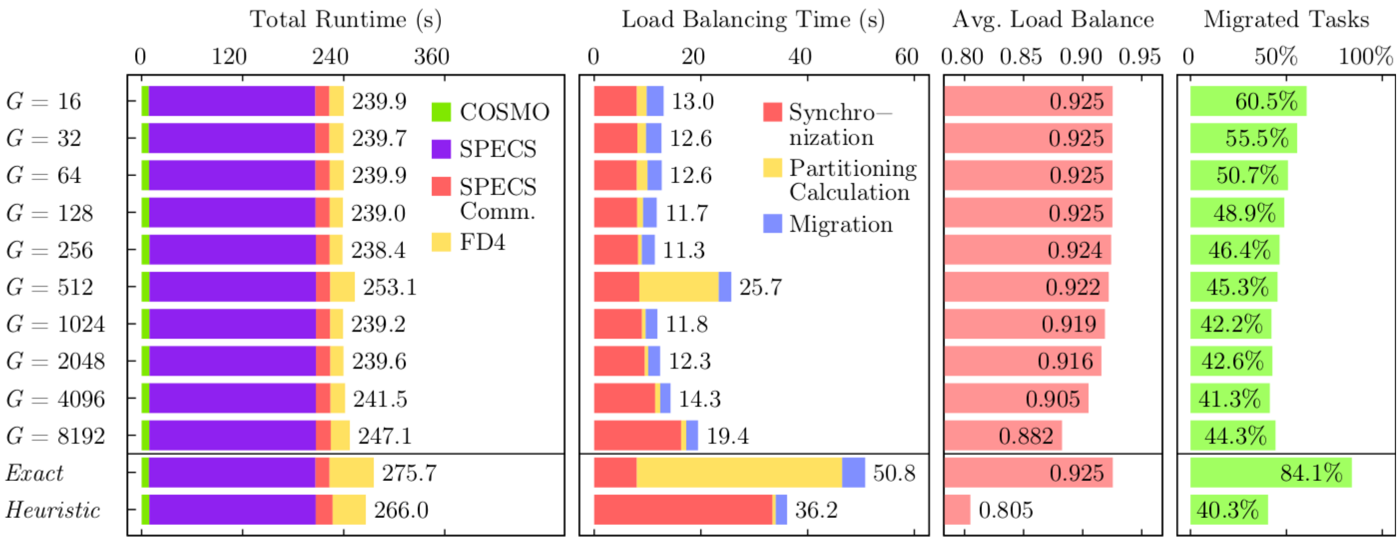


Figure 3. Influence of the group count G on the hierarchical 1D partitioning algorithm in COSMO-SPECS+FD4 with 65 536 processes on BlueGene/Q. The exact method and the heuristic are included as reference.

Lieber, Nagel, Mix, *Scalability Tuning of the Load Balancing and Coupling Framework FD4*, NIC Symposium 2014, pp. 363-370.