BLUE WATERS

SUSTAINED PETASCALE COMPUTING

Characterizing the Influence of System Noise on Large-Scale Parallel Applications

Torsten Hoefler

With contributions fromTimo Schneider and Andrew Lumsdaine

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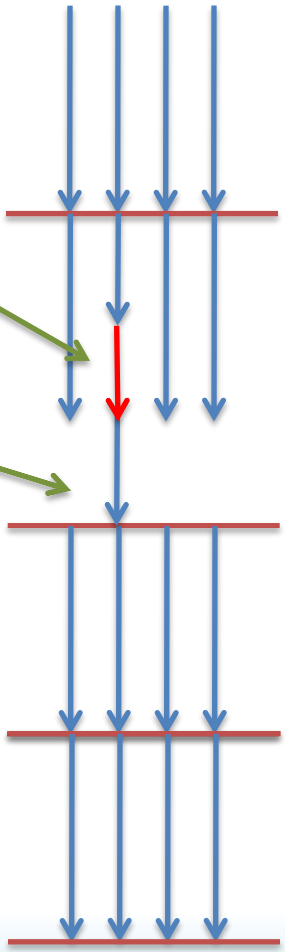
NCSA NSF IBM GREAT LAKES CONSORTIUM FOR PETASCALE COMPUTATION

System Noise – Introduction and History

- CPUs are time-shared
  - Deamons, interrupts, etc. steal cycles
  - No problem for single-core performance
    - Maximum seen: 0.26%, average: 0.05% overhead
  - “Resonance” at large scale (Petrini et al ’03)
- Numerous studies
  - Theoretical (Agarwal’05, Tsafrir’05, Seelam’10)
  - Injection (Beckman’06, Ferreira’08)
  - Simulation (Sottile’04)

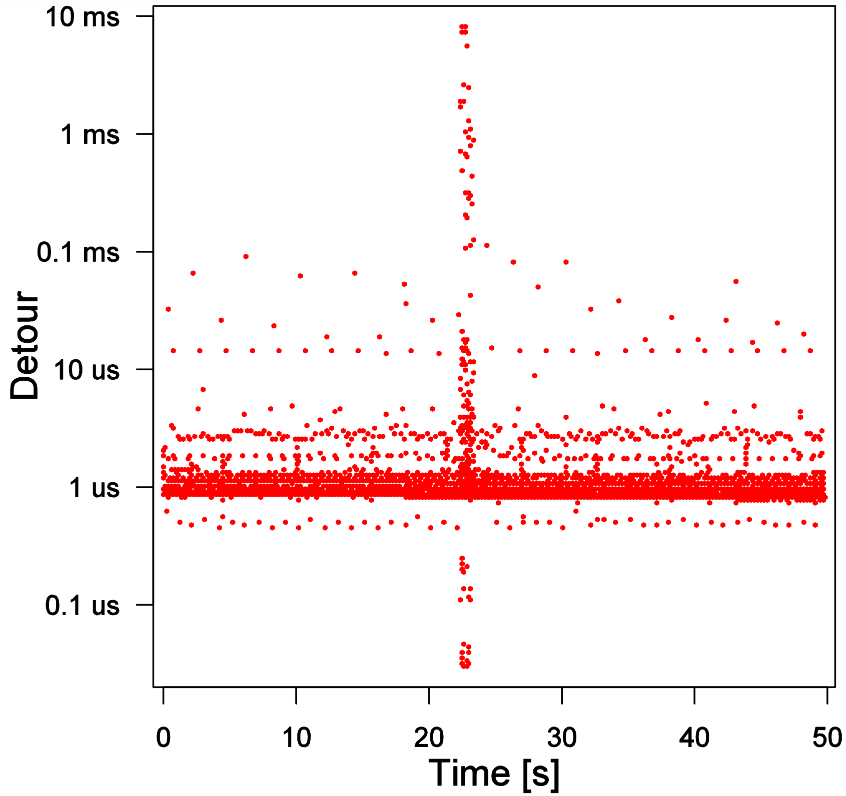


Measuring OS Noise on a Single Core

- Selfish Detour Benchmark (Beckman et al.)
  - Tight execution loop, benchmark iteration time
  - Record each outlier in iteration time
  - Improved detour (~30% better resolution)

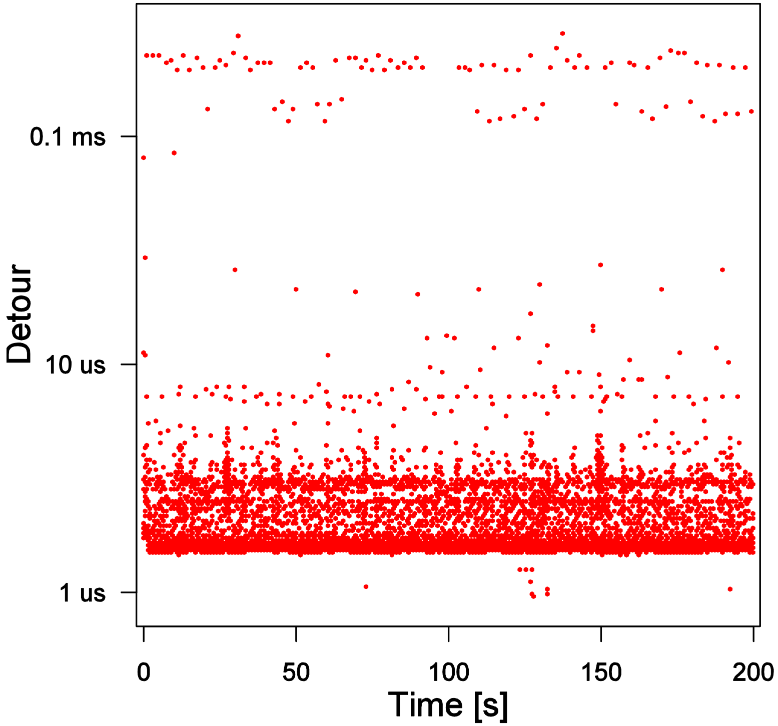
- Detour implemented in Netgauge benchmark tool
  - Also FWQ, FTQ (not used in this work)
  - Available at: `http://www.unixer.de/Netgauge`

Measurement Results – CHiC Linux (diskless)



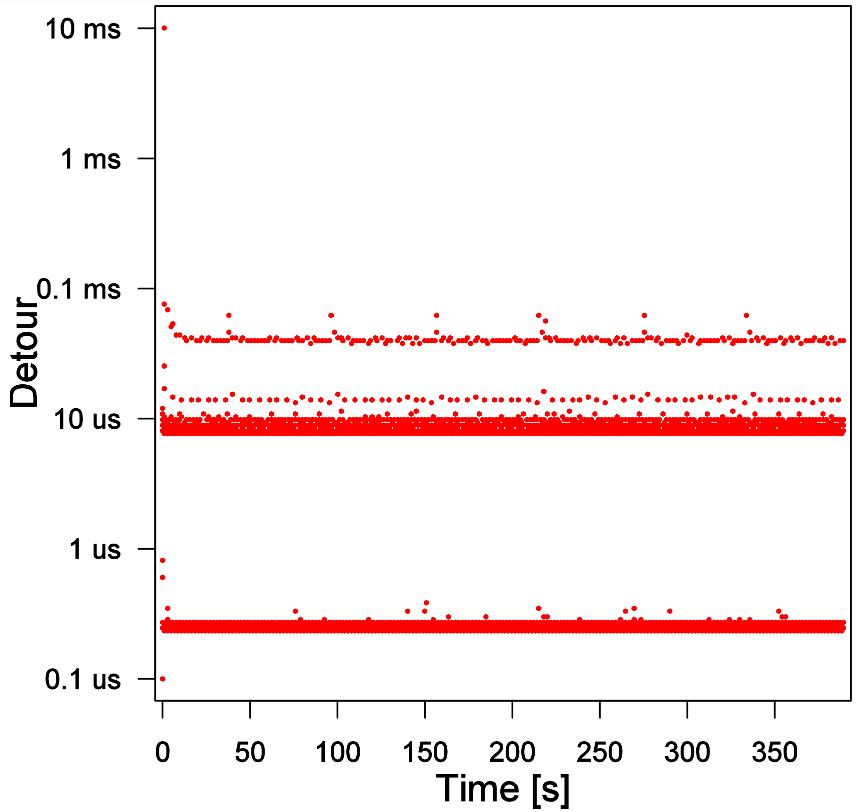
- 2152 Opteron cores, 11.2 Tflop/s Linux 2.6.18
- Resolution: 3.74 ns, noise overhead: 0.21%

Measurement Results – SGI Altix



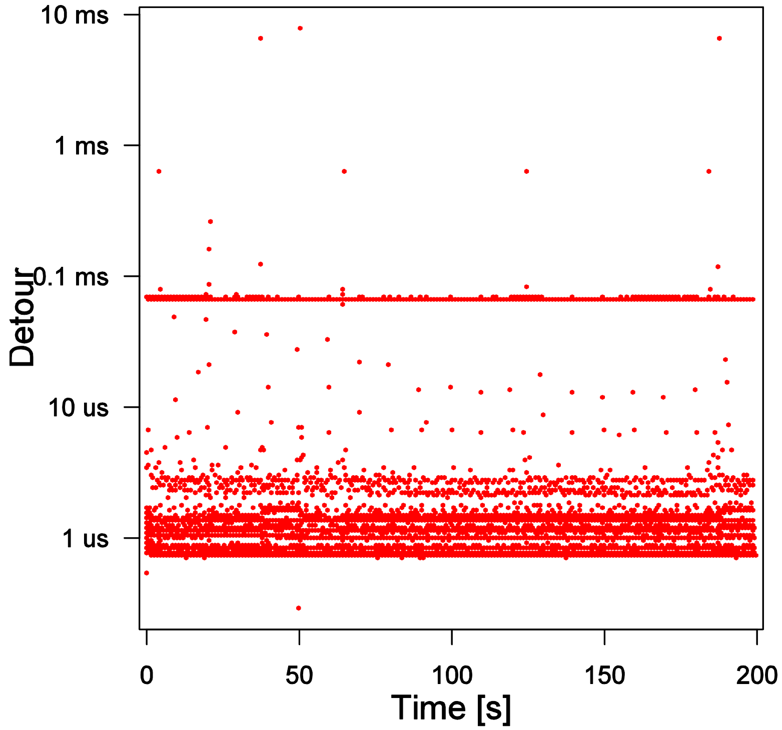
- Altix 4700, 2048 Itanium II cores, 13.1 Tflop/s, Linux 2.6.16
- Resolution: 25.1 ns, noise overhead: 0.05%

Measurement Results – BG/P ZeptoOS



- 164k PPC 450 cores, 485.6 Tflop/s, ZeptoOS 2.6.19.2
- Resolution: 29.1 ns, noise overhead: 0.08%

Measurement Results – Cray XT-4 (Jaguar)



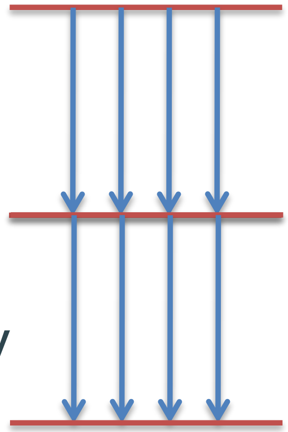
- 150k Opteron cores, 1.38 Pflop/s, Linux 2.6.16 CNL
- Resolution: 32.9 ns, noise overhead: 0.02%

An Analytical Model for Noise Propagation

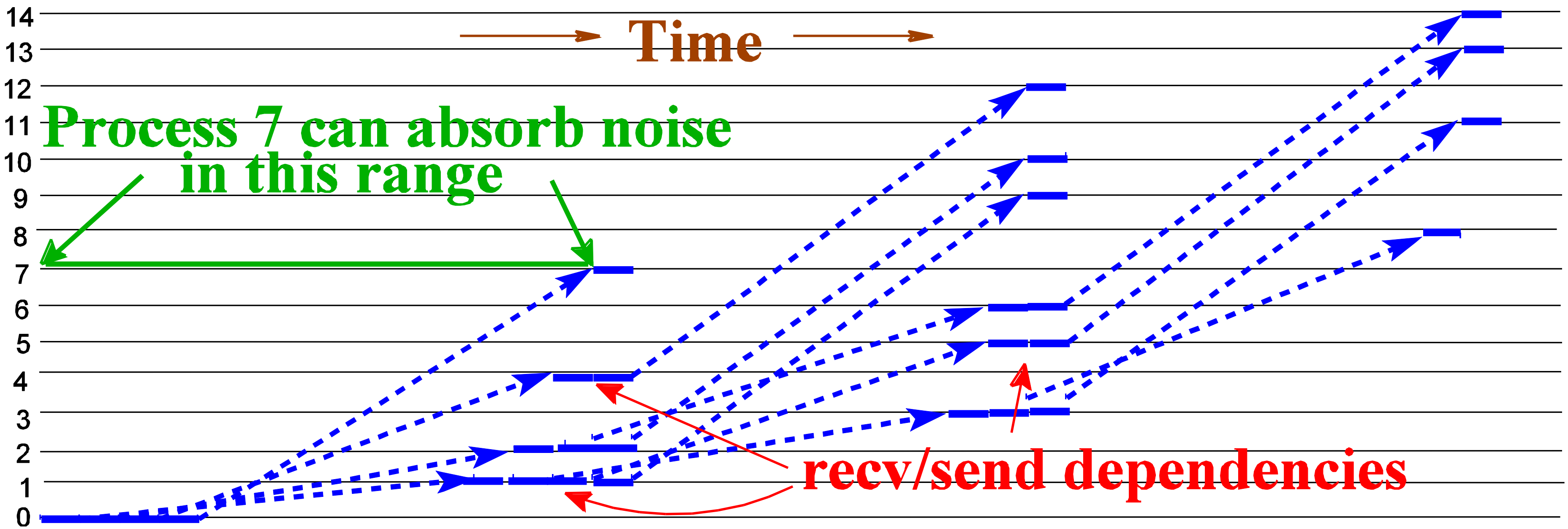
- Synchronization propagates or absorbs noise
  - Lamport's happens-before-relation for messages
  - Depends on relative time of send/recv (or wait)
- Several protocol-specific details
  - Small (eager), large (rendezvous), and nonblocking
- LogP model to express communication
  - Several missing pieces
  - LogGPS model (Ino et al.) captures most effects!
  - We added "O" to capture s/r overhead per byte

Collective Operations

- MPI-2.2: *"[...] a collective communication call may, or may not, have the effect of synchronizing all calling processes. This statement excludes, of course, the barrier function."*
- Main weaknesses in theoretical models:
  - Assumption 1: All collective operations synchronize
    - In fact, many do not (e.g., Bcast, Scan, Reduce, …)
  - Assumption 2: Collectives synchronize instantaneously
    - In fact, they (most likely) communicate with messages
  - Assumption 3: All processes leave collective simultaneously
    - In fact, they leave as early as possible (when data is consistent)

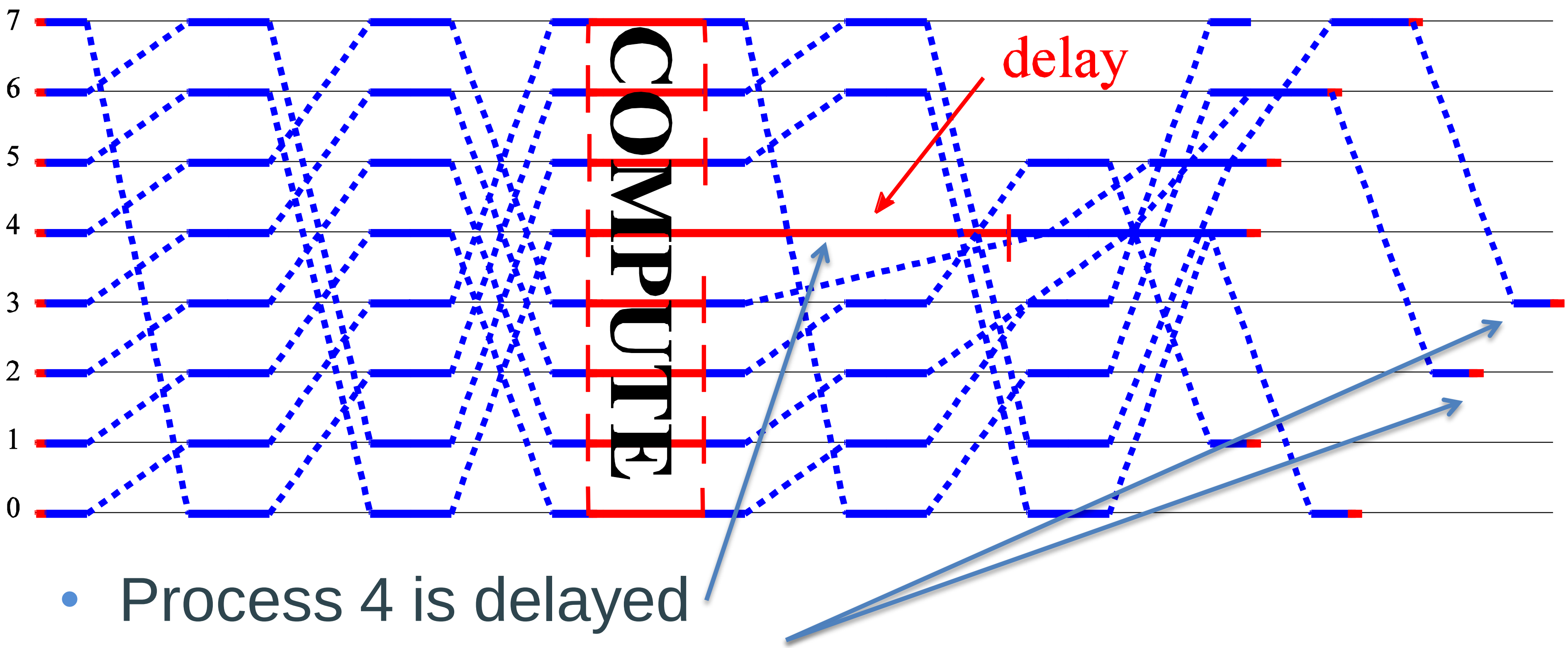


Example: Binomial Broadcast Tree



- Violates all three assumptions:
  - No global or instant synchronization, asynchronous exit

A Noisy Example – Dissemination Barrier



- Process 4 is delayed
  - Noise propagates "*wildly*" (of course deterministic)

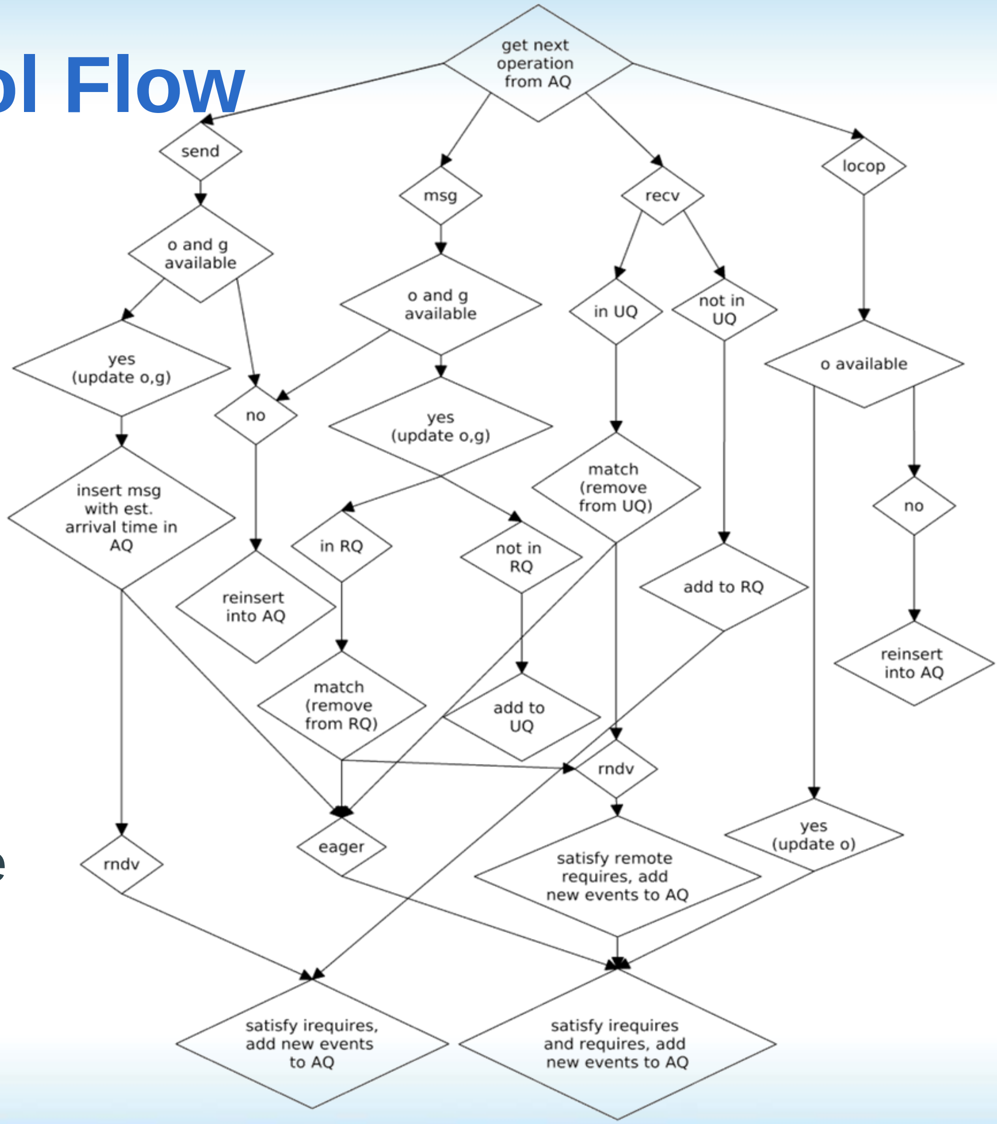
LogGOPS Simulation Framework

- Detailed analytical modeling is hard!
- Model-based (LogGOPS) simulator
  - Available at: `http://www.unixer.de/LogGOPSim`
  - Discrete-event simulation of MPI traces (<2% error) or collective operations (<1% error)
  - > 10^6 events per second!
- Allows for trace-based noise injection
  - In o_s, o_r, O, local reduction, and application time
- Validation
  - Simulations reproduce measurements by Beckman and Ferreira well!

- Details: Hoefler et al. LogGOPSim – Simulating Large-Scale Applications in the LogGOPS Model (Workshop on Large-Scale System and Application Performance, Best Paper)

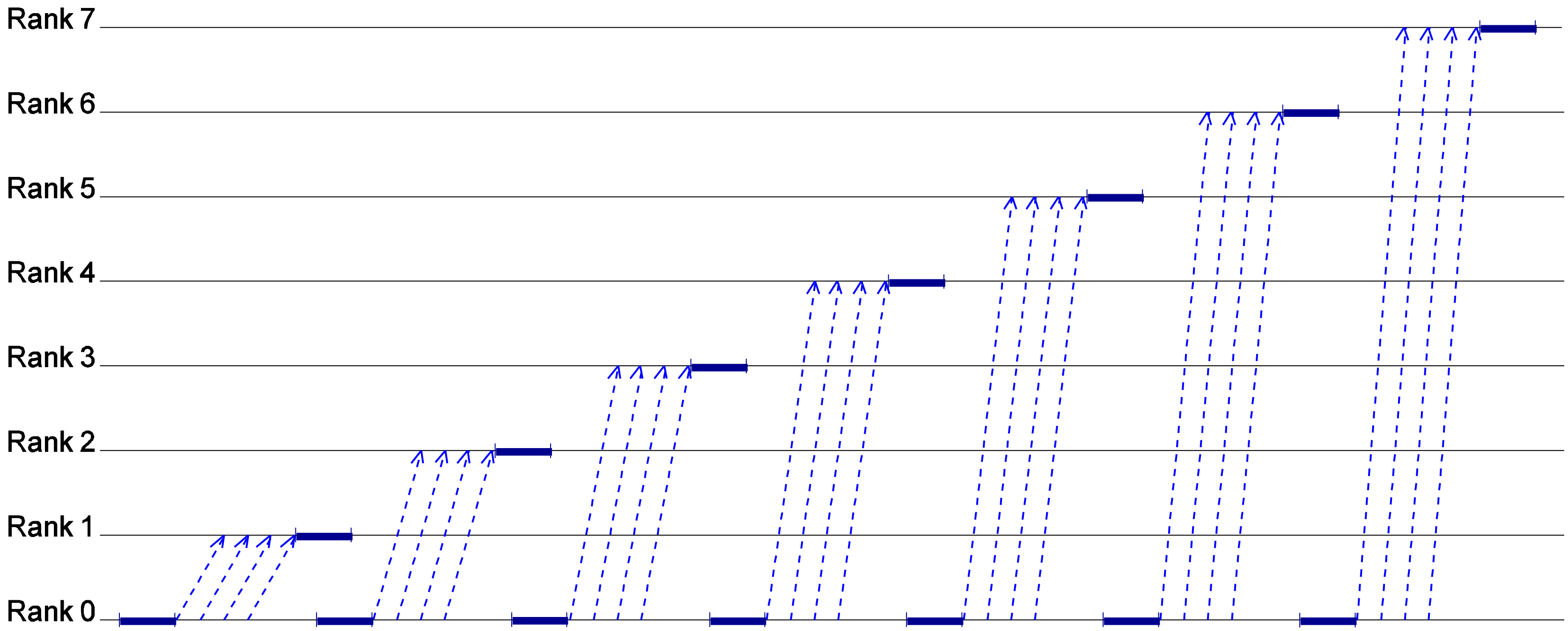
Simulator Core Control Flow

- Single queue design
  - Fast priority queue
1. Find executable ops
   - send, recv, msg, or loclop
2. Insert with current time
3. Fetch (globally) next op
   - check if it can be executed
   - match send/recv
   - re-insert if o, g not available
4. Lather, rinse, repeat



Verification – Linear Scatter

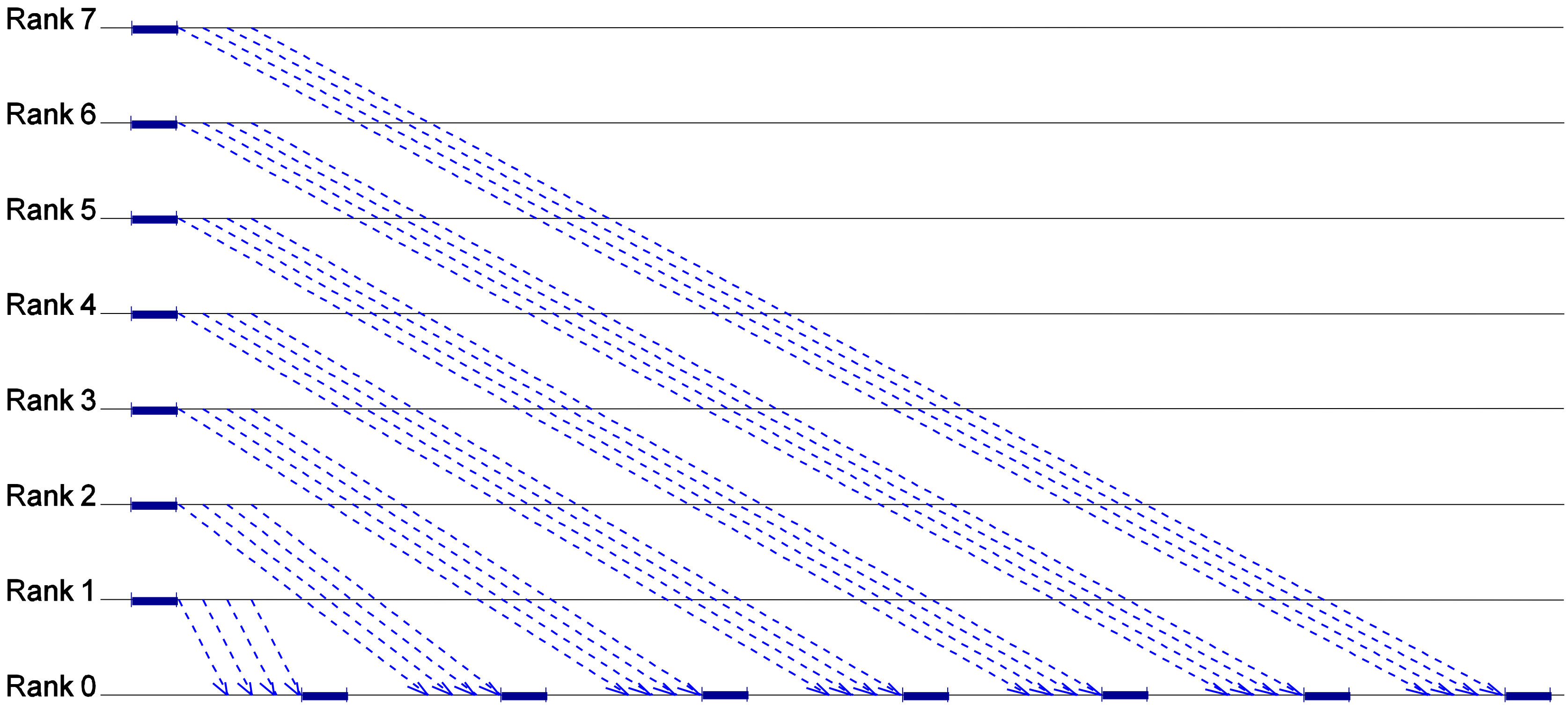
$$T_{scat} = 2o + L + \max\{(P-2)o + (P-1)sO), (P-2)g + (P-1)sG\}$$



- LogGOPS makes verification simple

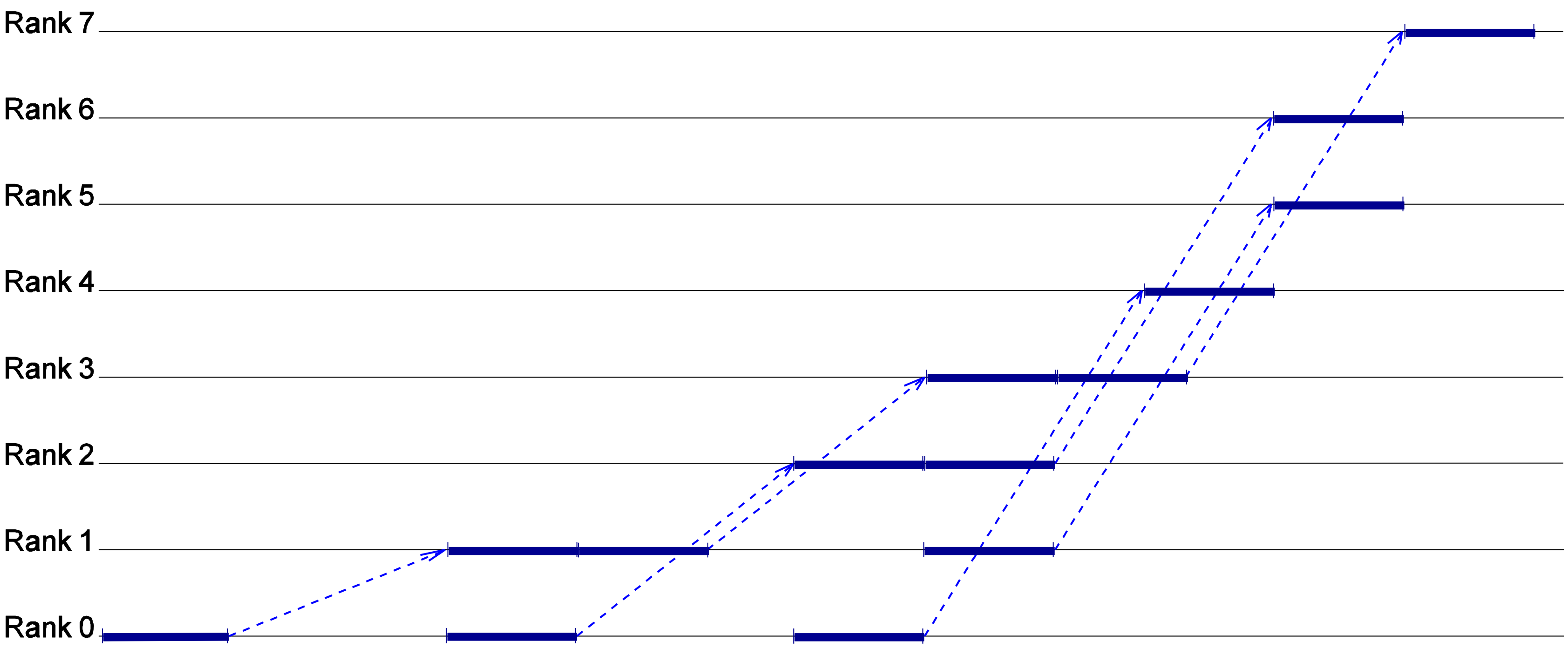
Verification - Gather

$$T_{gat} = 2o + L + \max\{(P-2)o + (P-1)sO), (P-2)g + (P-1)sG\}$$



Verification – Binomial Tree

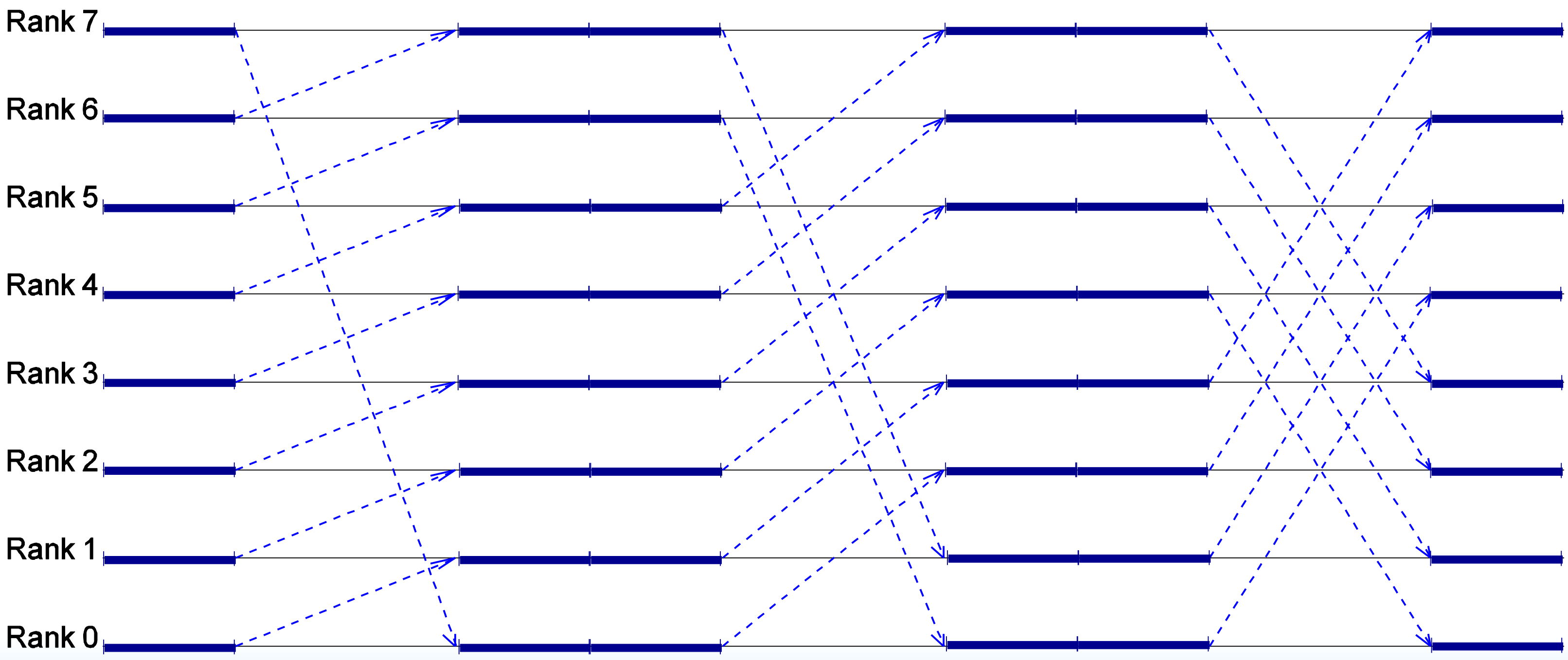
$$T_{bino} = (2o + L + \max\{sO, sG\})\lceil \log_2 P \rceil$$



Verification - Dissemination

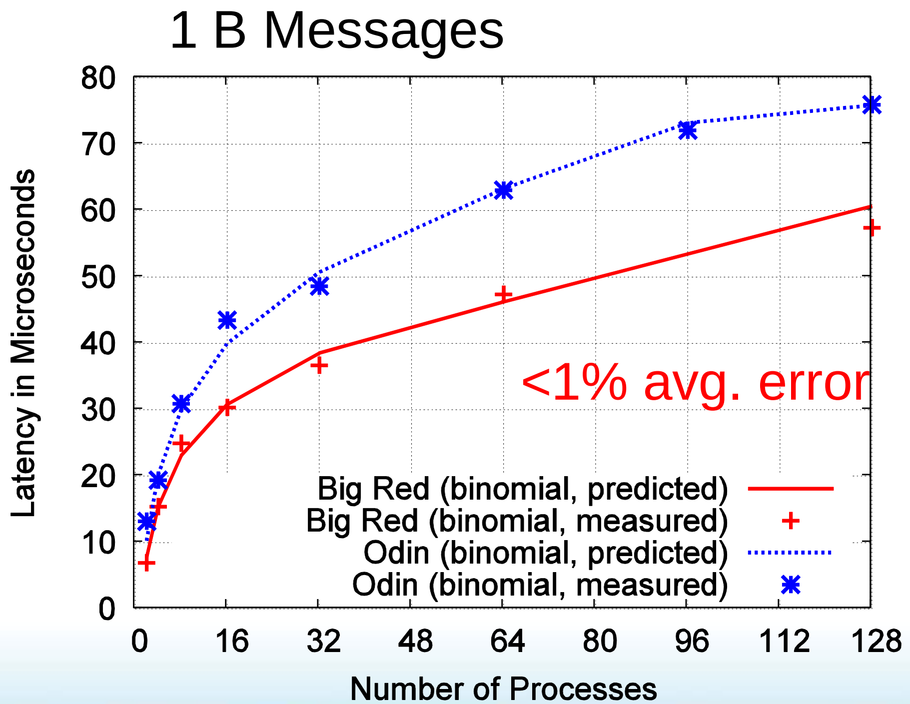
$$\delta = \begin{cases} (s-1)O - L : (s-1)O - L > 0 \\ 0 : \text{otherwise.} \end{cases} \quad (1)$$

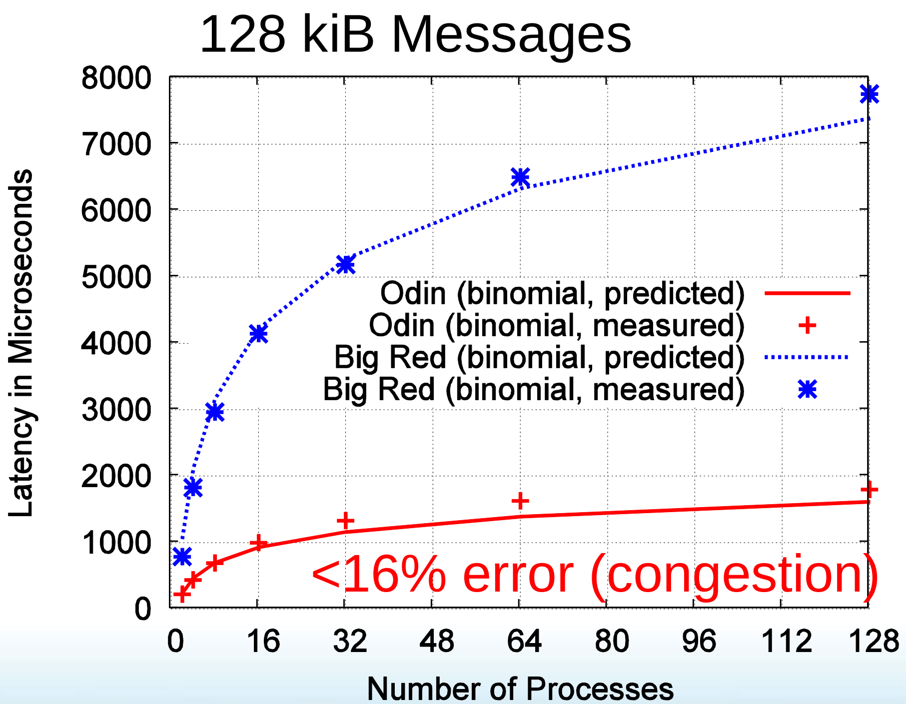
$$T_{diss} = (\delta + 2o + L + \max\{sO, sG\})\lceil \log_2 P \rceil \quad (2)$$



Experimental Evaluation

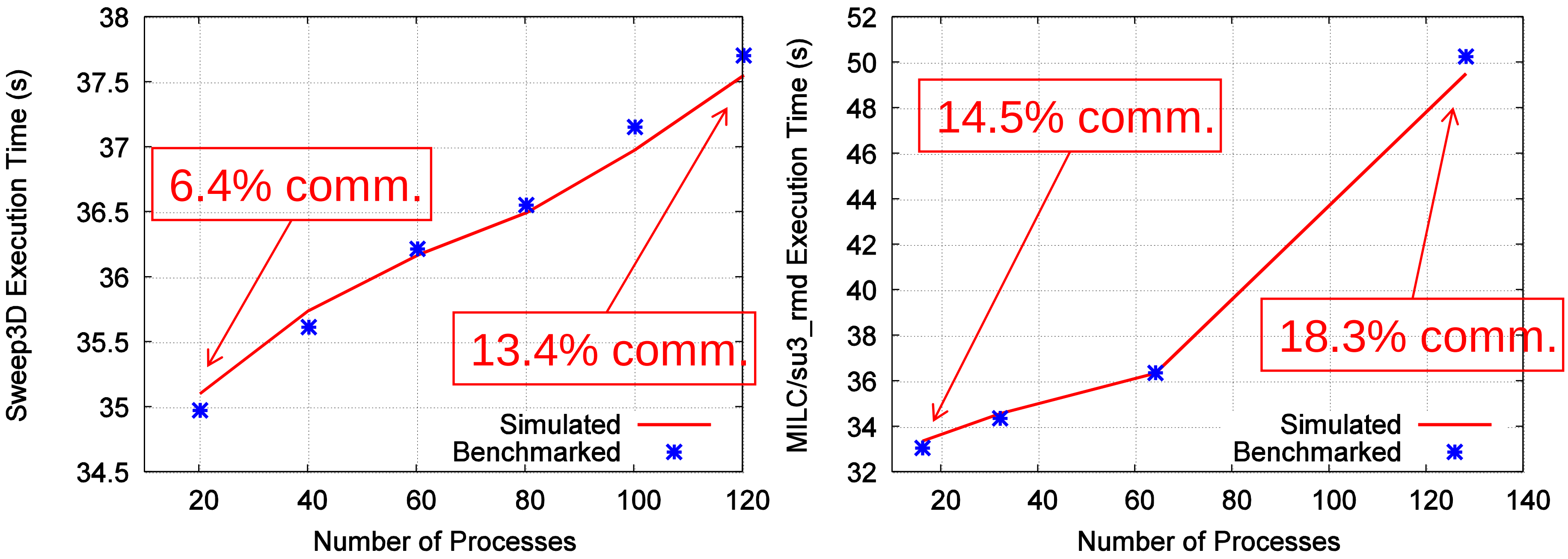
- Odin: $L=5.3\mu s$, $o=2.3\mu s$, $g=2\mu s$, $G=2.5ns$, $O=1ns$
- Big Red: $L=2.9\mu s$, $o=2.4\mu s$, $g=1.7\mu s$, $G=5ns$, $O=2ns$





Application Simulation Accuracy

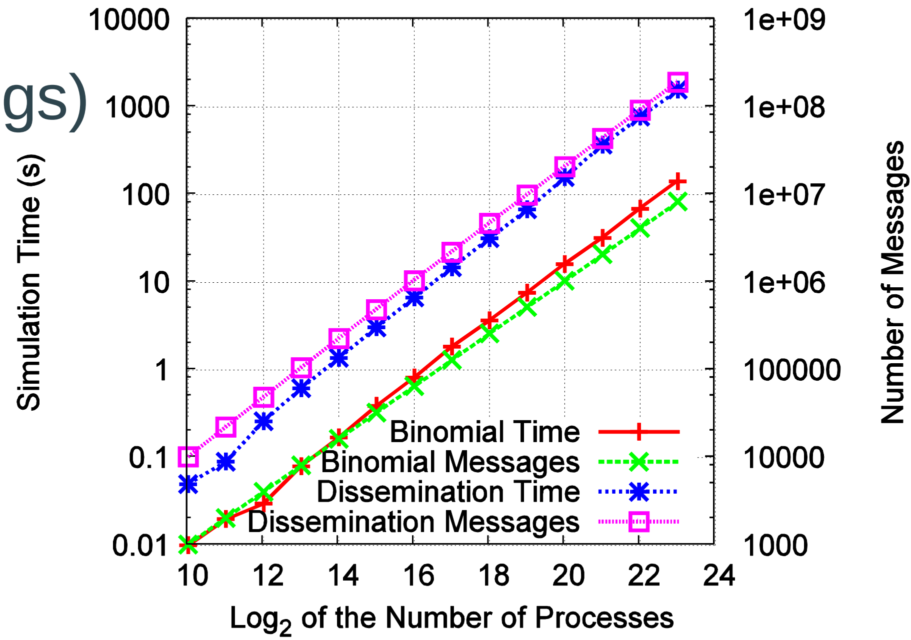
- Sweep3D and MILC weak scaling on Odin



- <2% average error

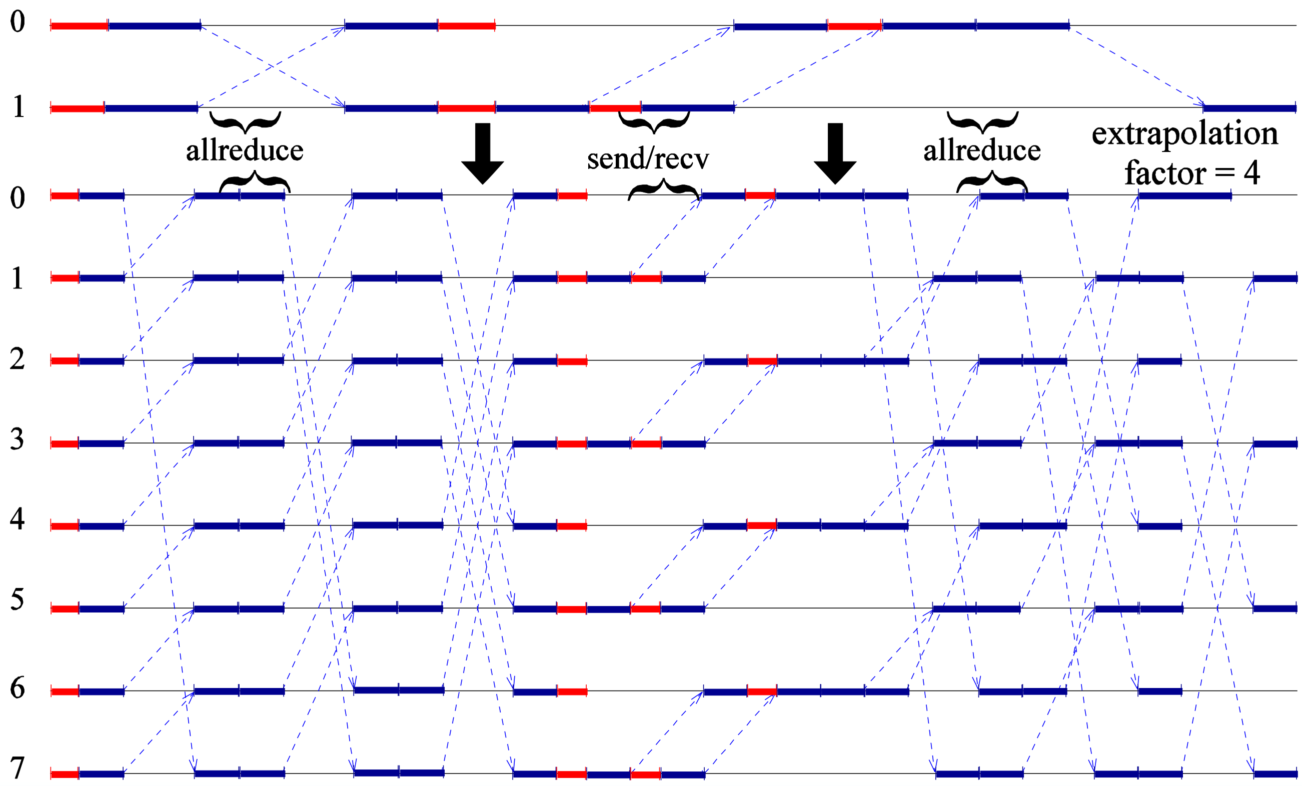
Simulation Speed

- Tested on 1.15 GHz Opteron (slow!)
  - 1024 – 8 million processes
  - Binomial (P msgs)
  - Dissemination ($P\log(P)$ msgs)
- > 1 million events per second
  - Can demo it on my laptop later ☺



Application Trace Extrapolation

- Supports simple extrapolation scheme:



Application Simulation Performance

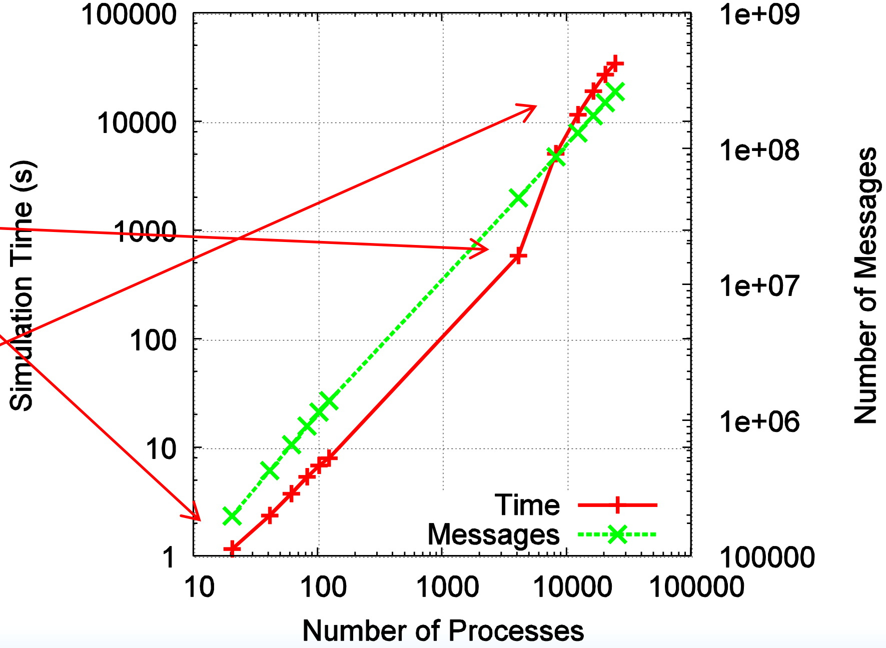
- 37.7 s Sweep3D extrapolated from 40-28k CPUs
  - 0.4 Mio msgs → 313 Mio msgs

40 CPUs – 2.43 s

4k CPUs – 10 min

28k CPUs – 9.7h (swap)

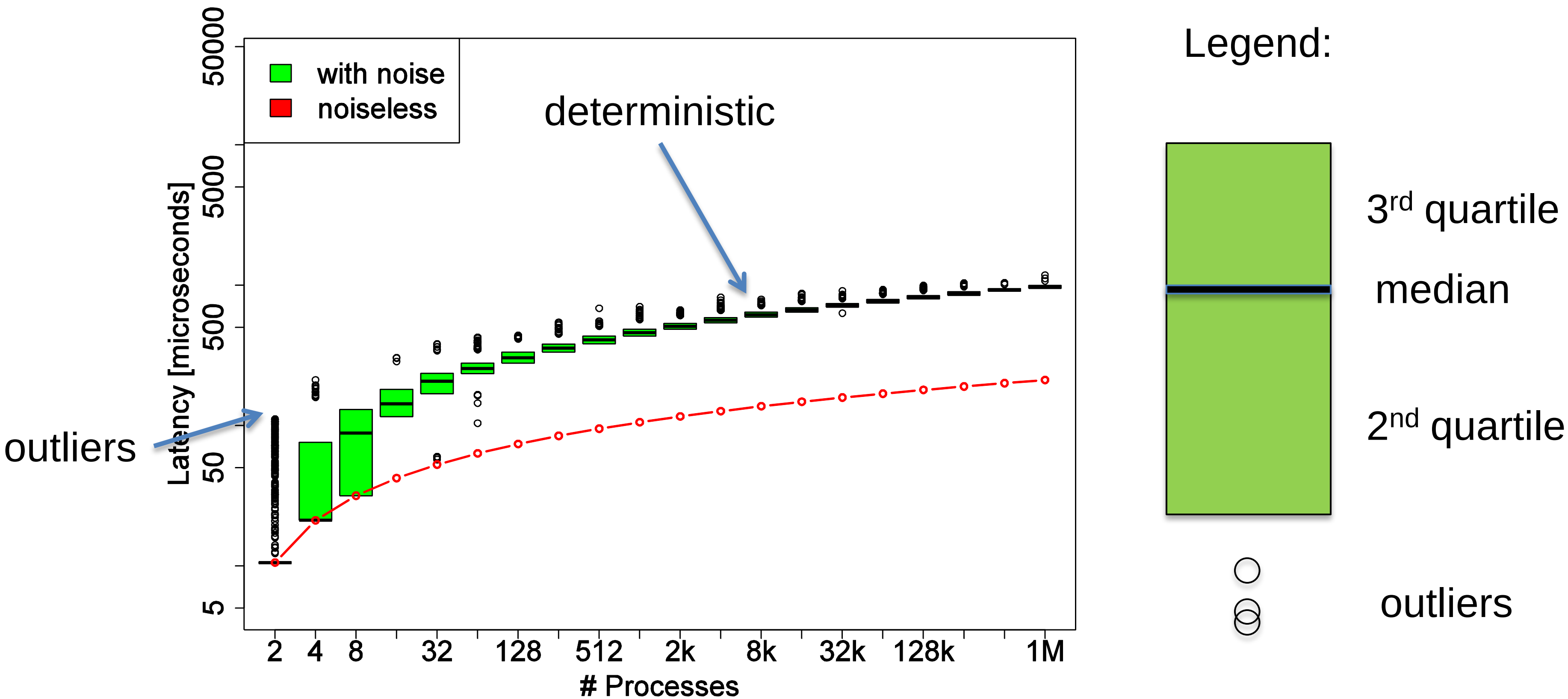
Main memory is an issue! hits swap at 8k CPUs



Some More Use-Cases

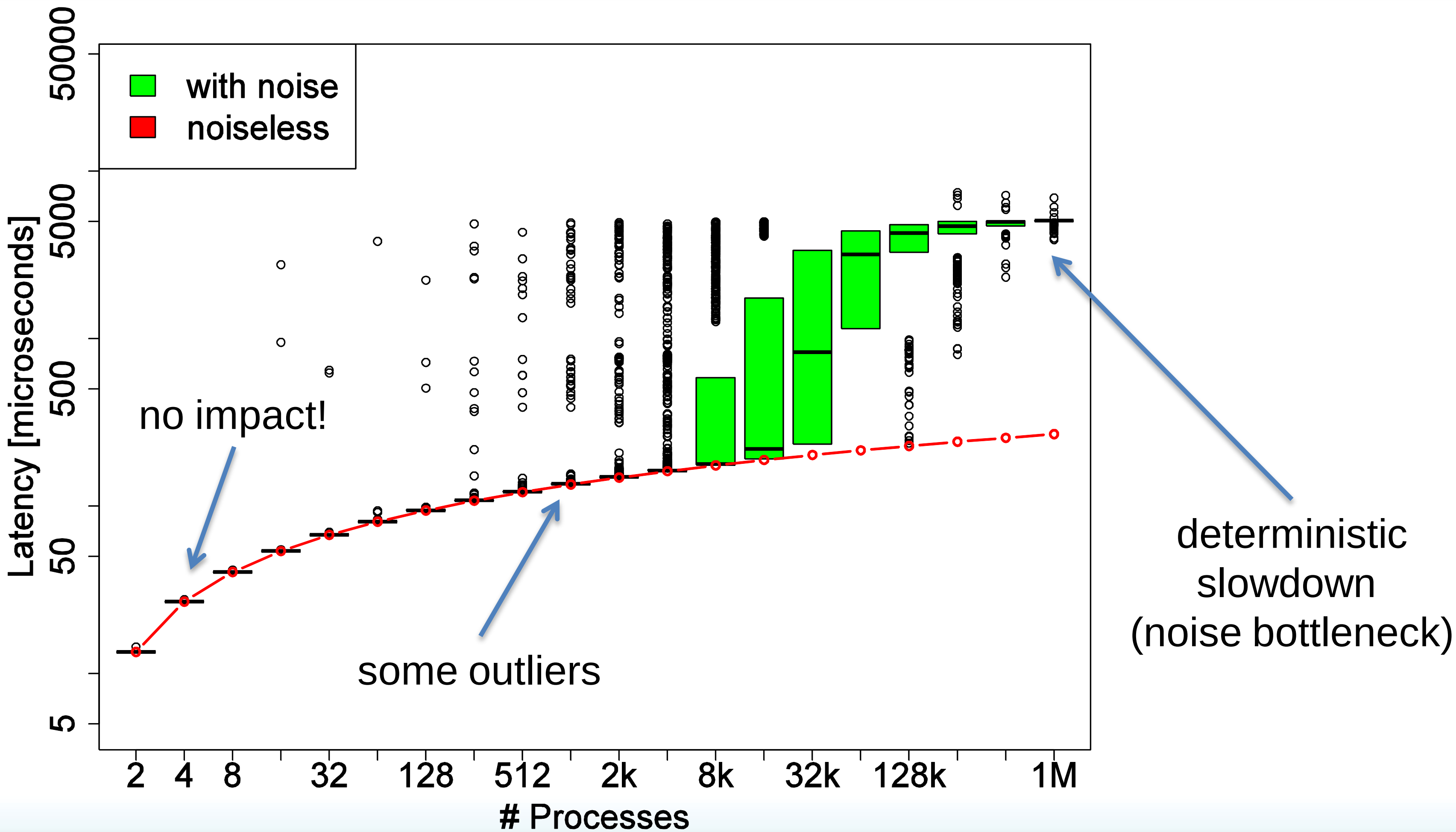
1. Estimating an application's potential for overlapping communication/computation
2. Estimating the effect of a faster/slower network on application performance
3. Demonstrating the effects of pipelining in current benchmarks for collectives
4. **Estimating the effect of Operating System Noise at very large scale**

Single Collective Operations and Noise

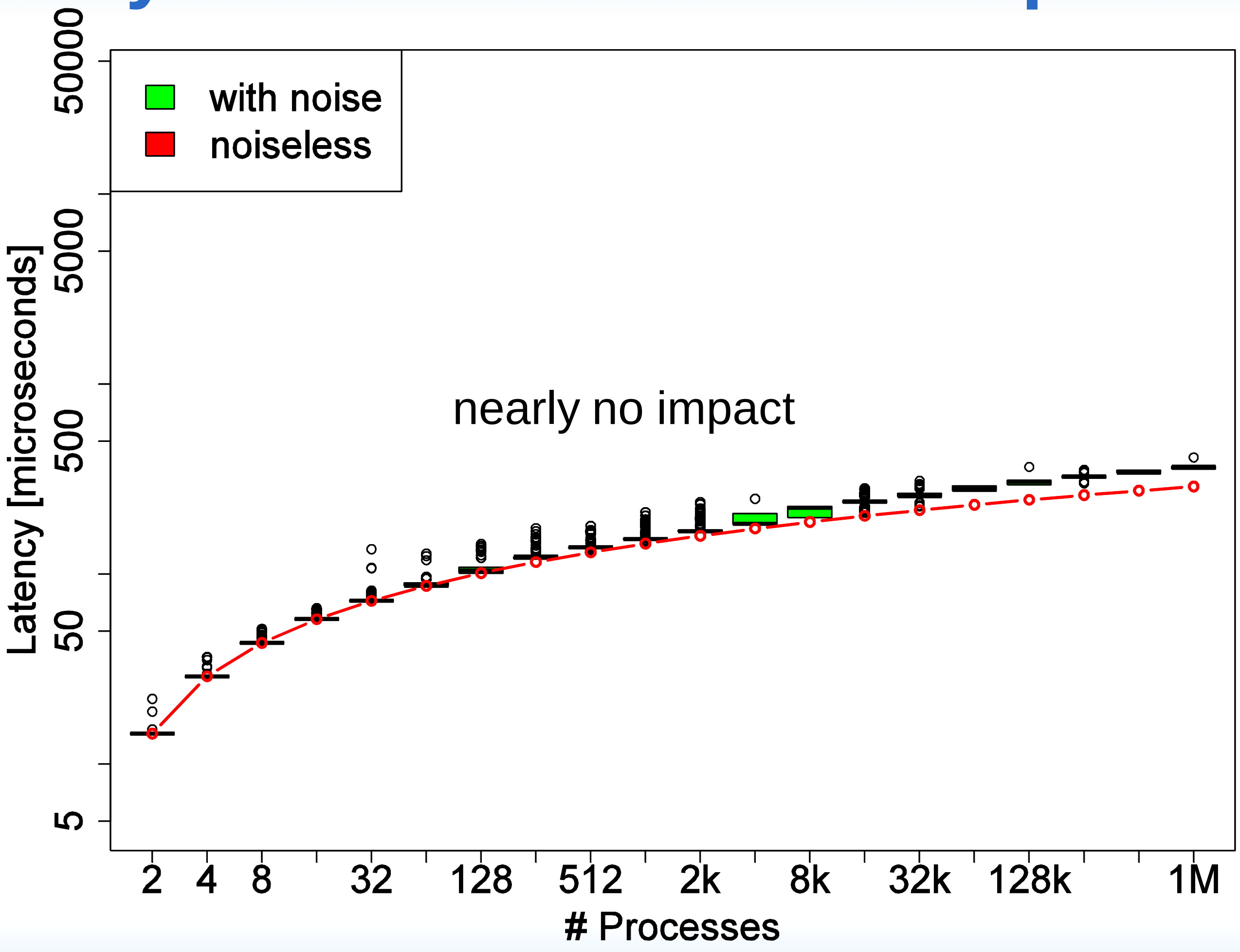


- 1 Byte, Dissemination, regular noise, 1000 Hz, 100 μs

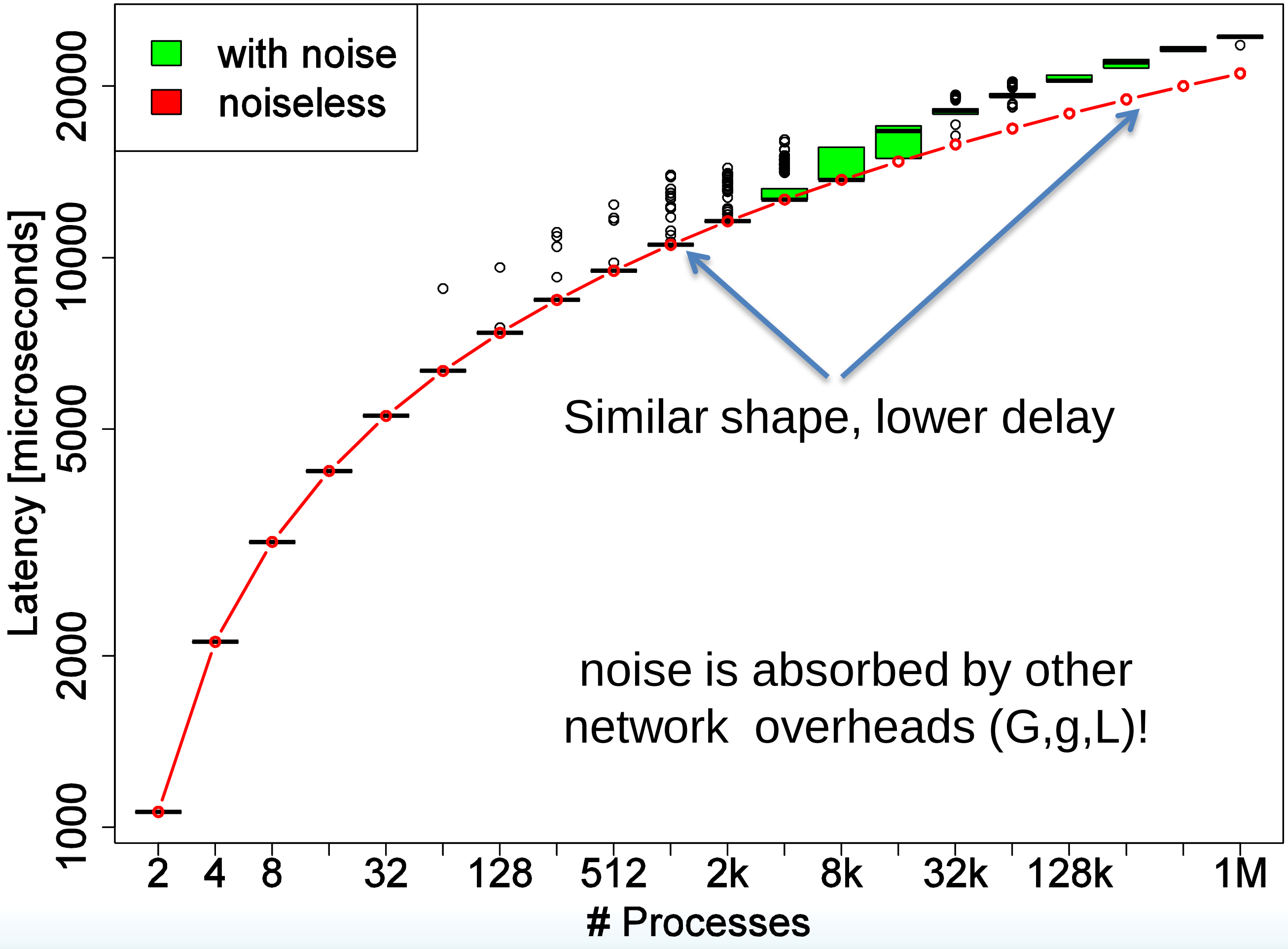
Single Byte Dissemination on Jaguar



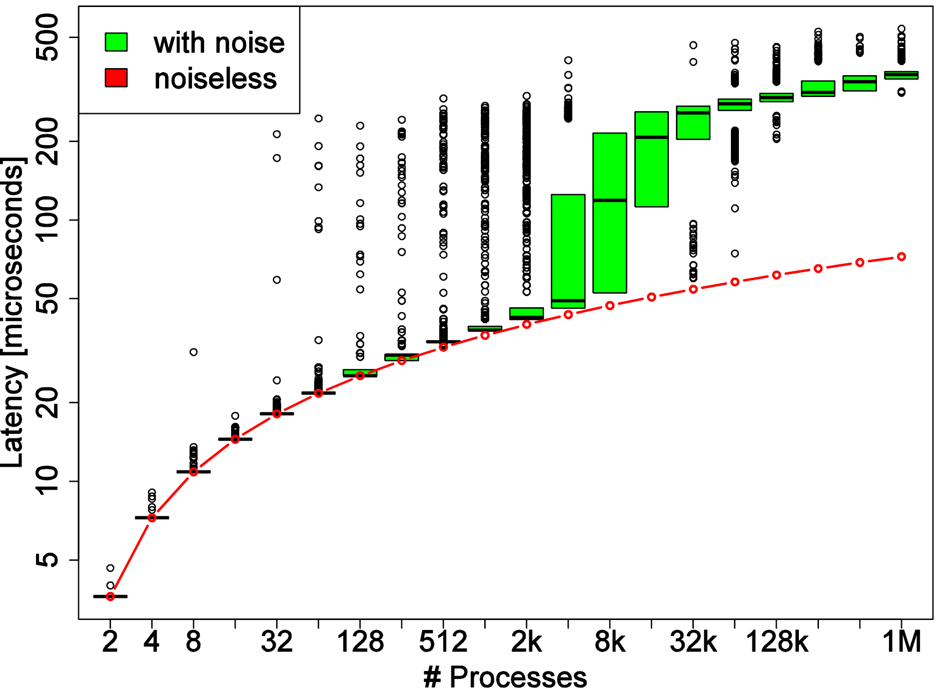
Single Byte Dissemination on ZeptoOS



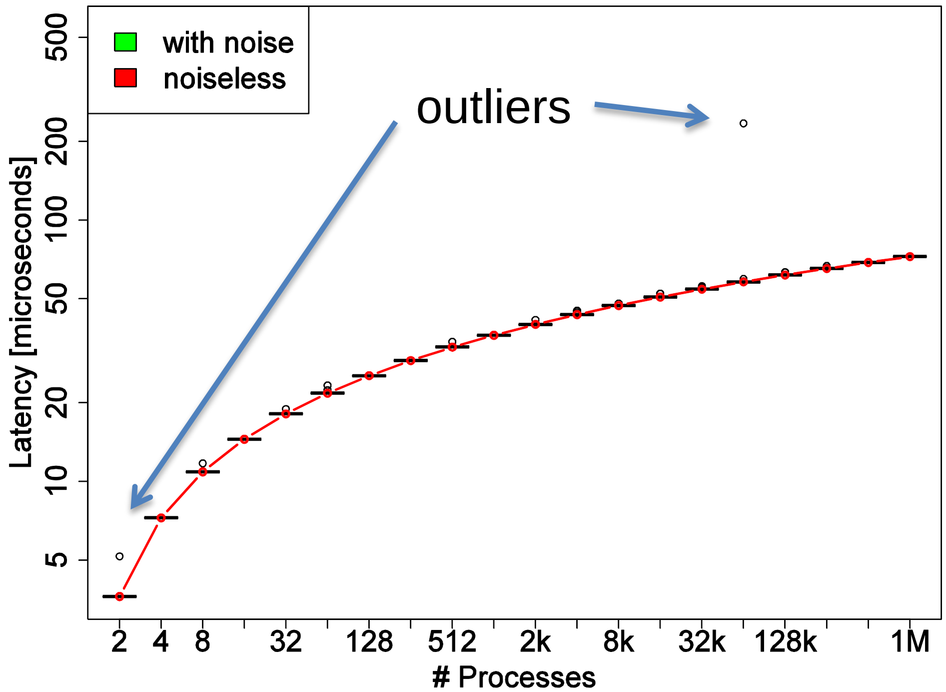
1MiB Messages on Jaguar



Effect of Co-Scheduling Noise (Altix)

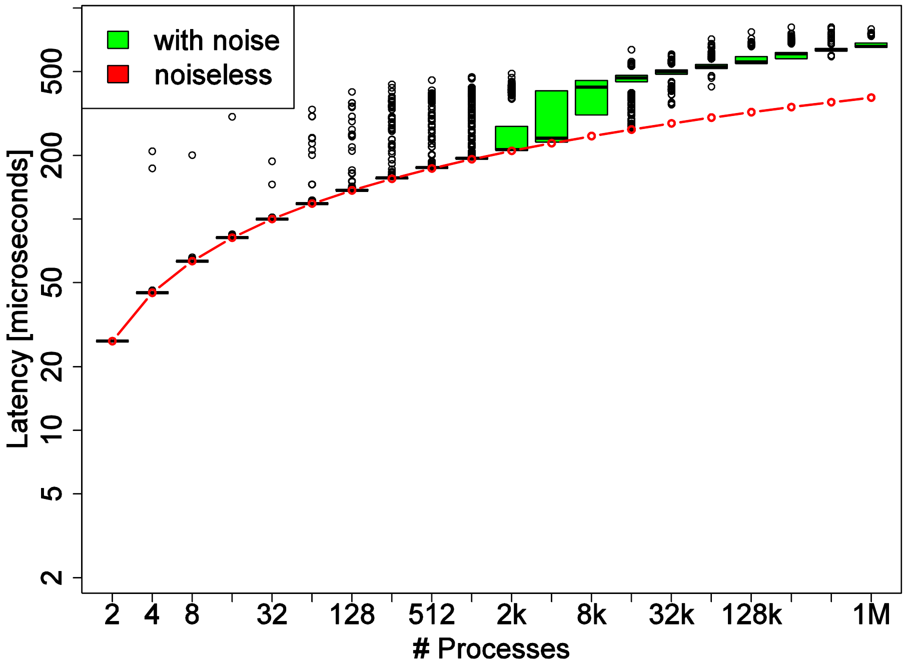


Normal

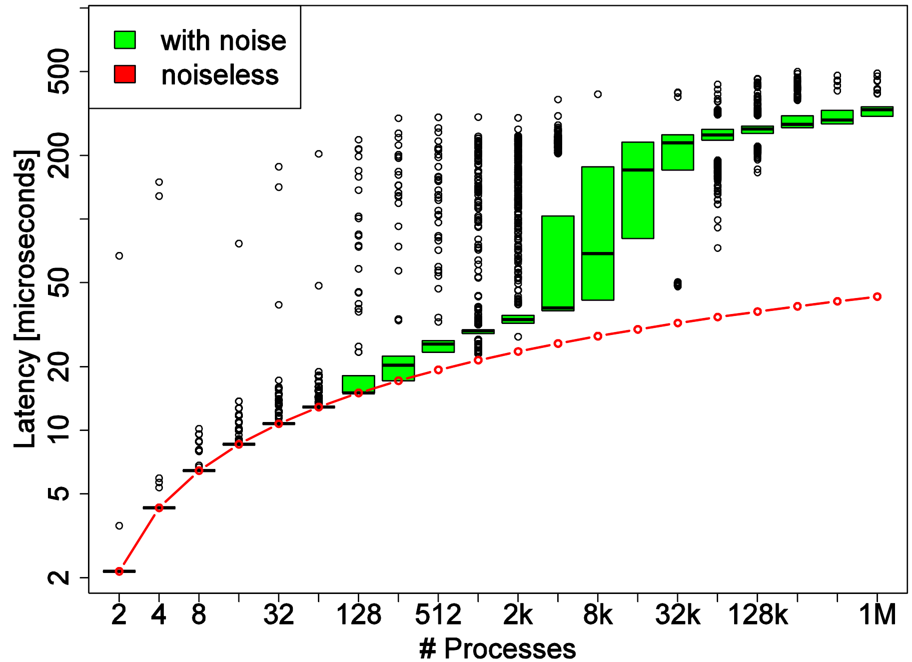


Co-Scheduled

Does the Network Speed Matter?



0.1x network speed

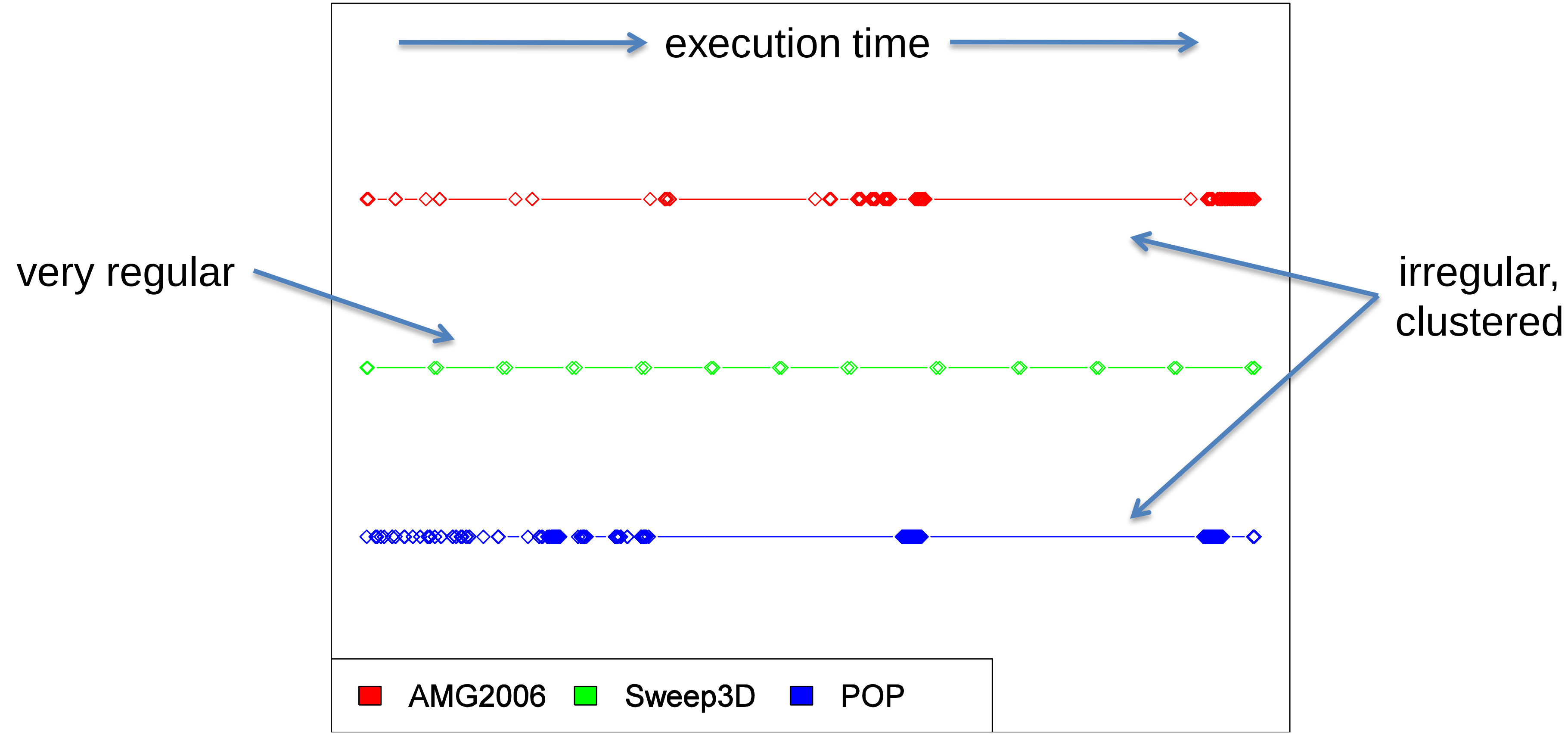


10x network speed

Method: increase/decrease L,G,g

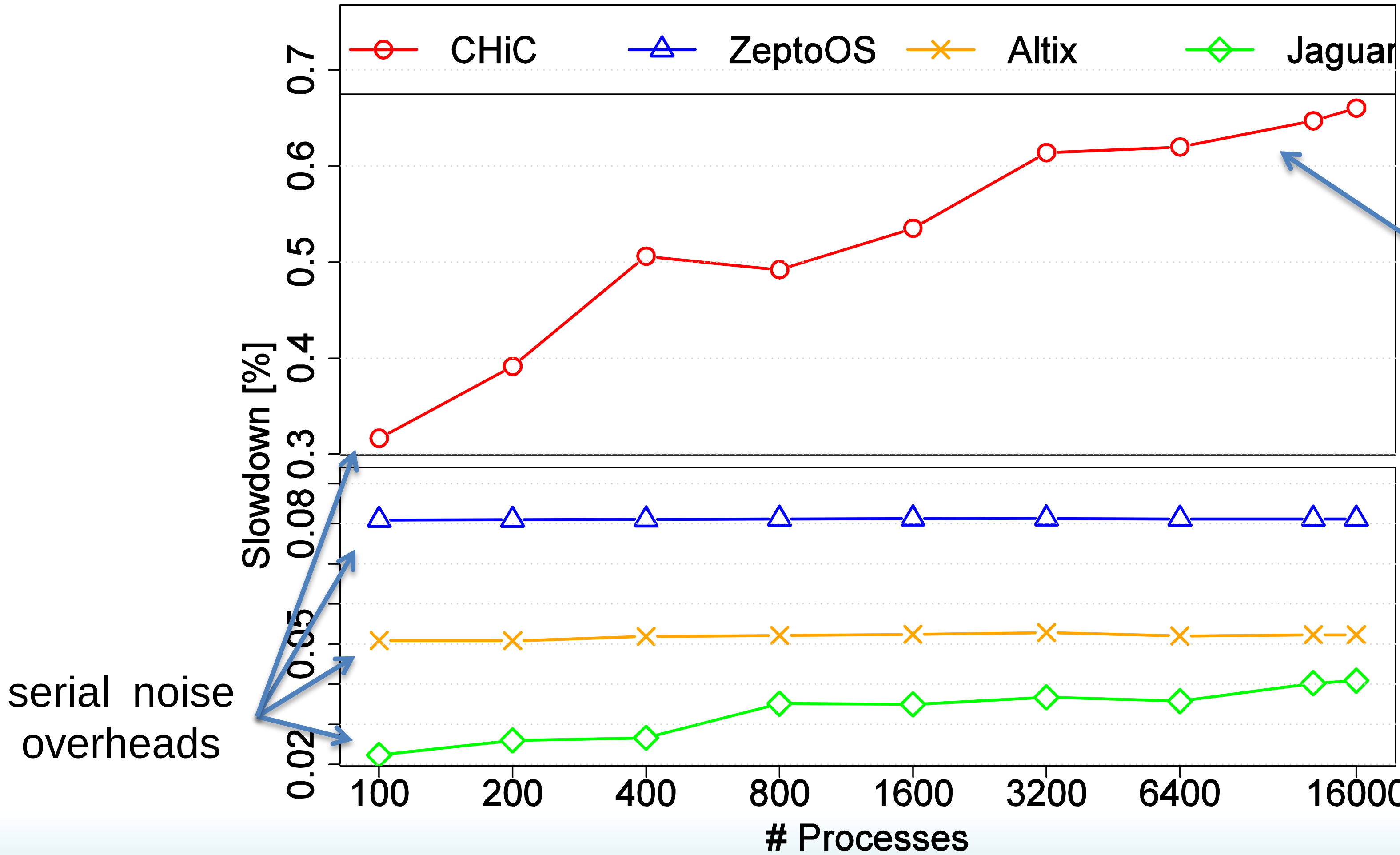
Observation: noise bottleneck independent of network speed

Real Applications



Distribution of Collective Operations

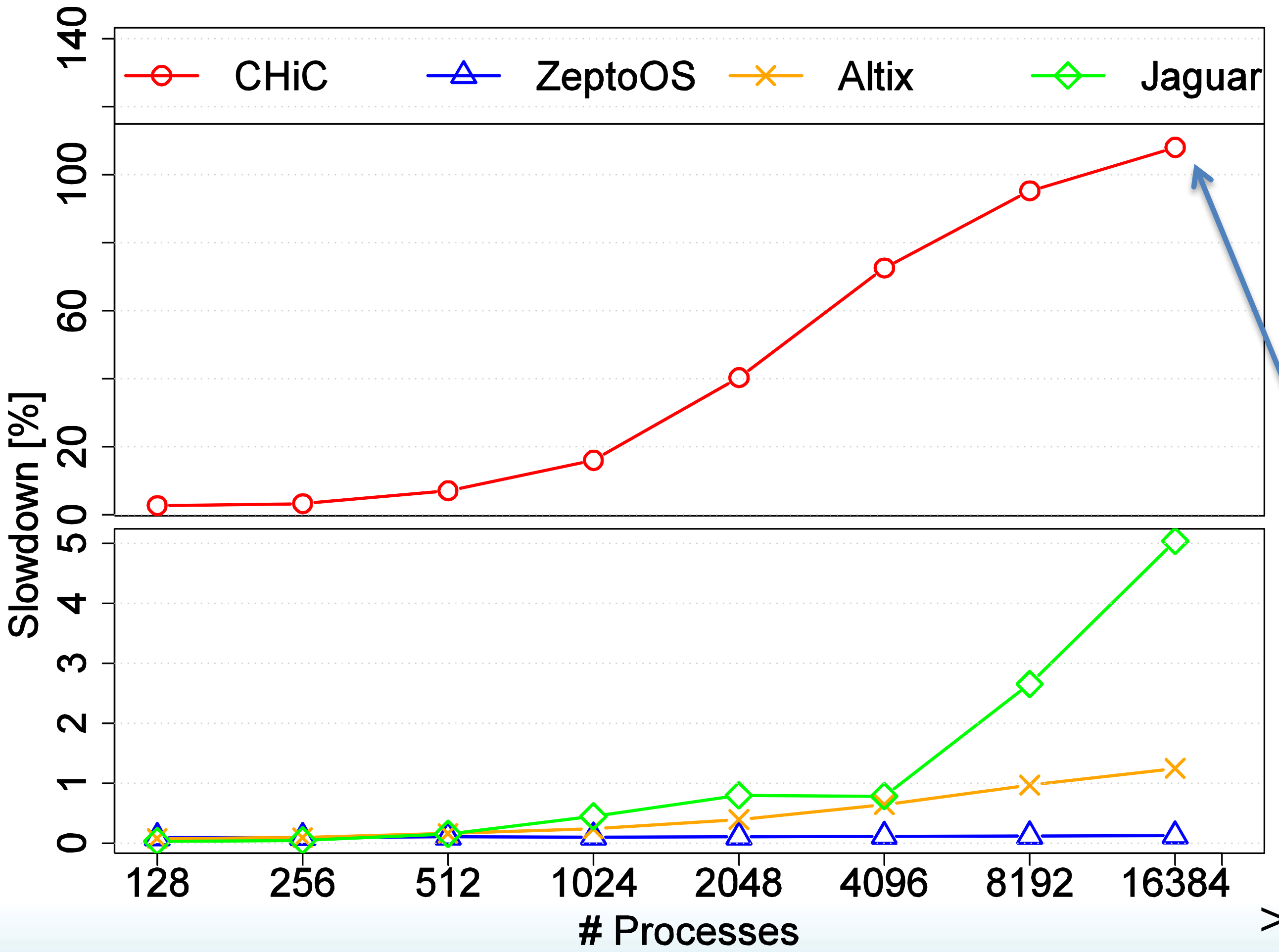
Sweep3D (Collective and Point-to-Point)



92.4% bl p2p
4 bcast
3 barrier
32 allreduce

>289 million messages!

POP (Collective and Point-to-Point)



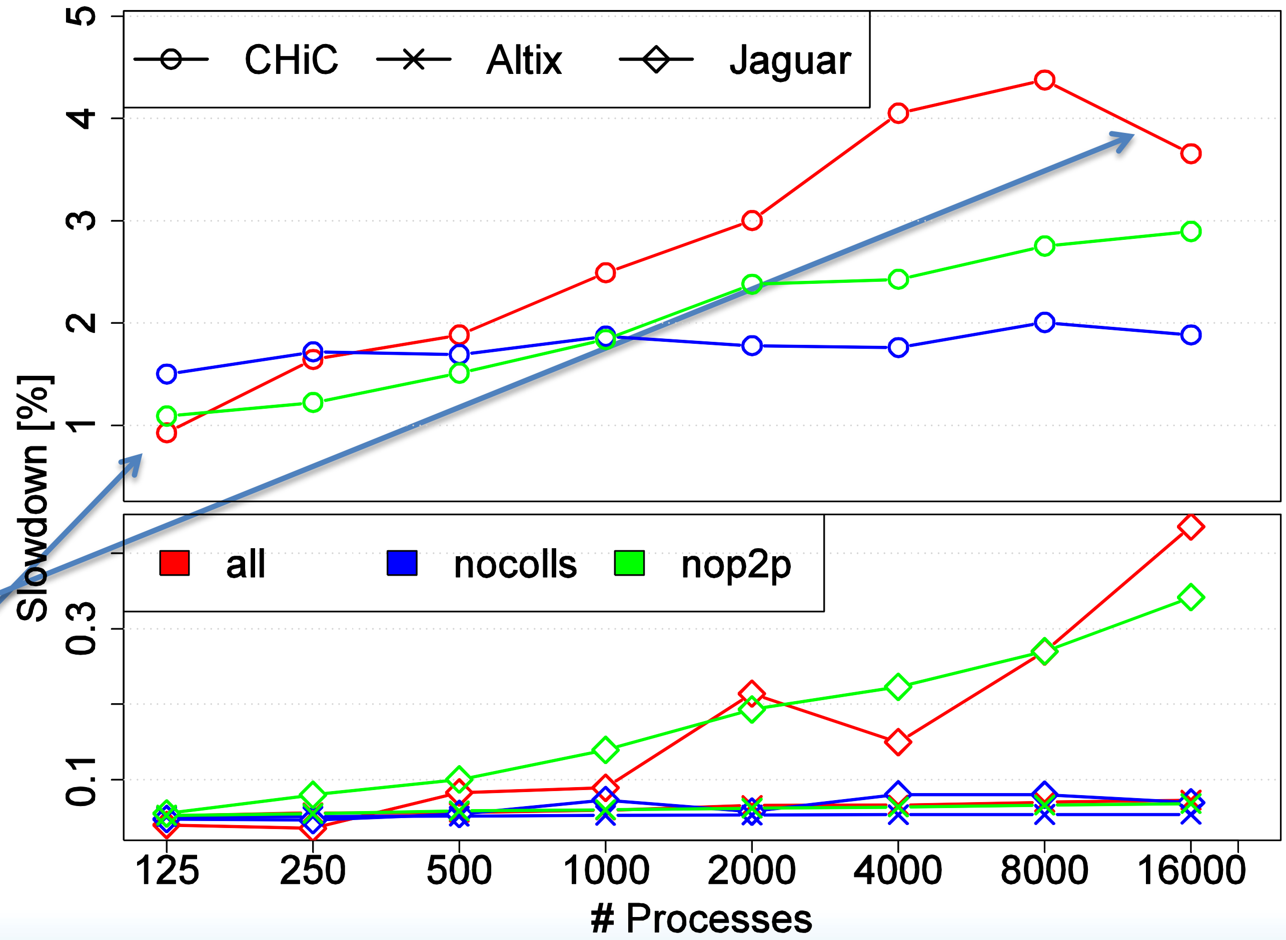
0.2% nb p2p
703 bcast
575 barrier
608 allreduce

>2x slowdown!

>625 million messages!

Does Point-to-Point Communication Matter?

AMG 2006

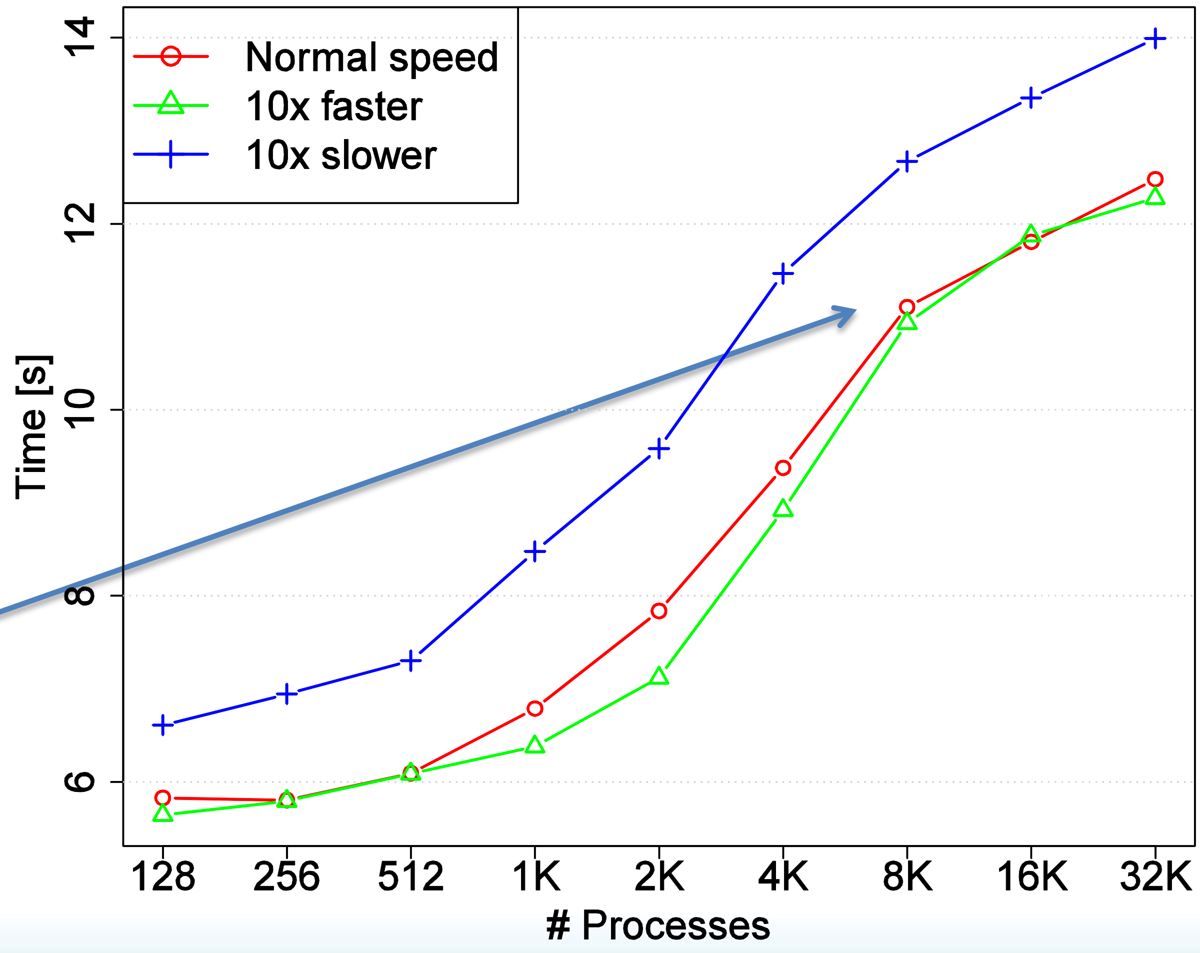


p2p propagates

p2p absorbs

Influence of Network Speed on Applications

POP @ CHiC



Noise bottleneck: faster network does not increase performance

Conclusions & Future Work

- Modeling OS noise is not that simple
  - Will validate used models with simulation
- Model-based simulation approach scales well
  - Results match previous benchmark studies (<6% error)
- Overhead depends on noise *shape* rather than *intensity*
  - ZeptoOS shows nearly no propagation! (0.08% overhead)
  - Cray XT is severely impacted! (0.02% overhead)
- Noise bottleneck is serious at scale!
  - Faster network or CPU cannot help, noise will dominate!
- We developed a tool-chain to adjust the bottleneck
  - Available online: `http://www.unixer.de/LogGOPSim`

Collaborators, Acknowledgments & Support

- Collaborators:
  - Timo Schneider, Andrew Lumsdaine — INDIANA UNIVERSITY PERVASIVE TECHNOLOGY INSTITUTE
- Thanks to (alphabetically)
  - Franck Cappello, Steven Gottlieb, William Gropp, William Kramer, and Marc Snir
- Sponsored by

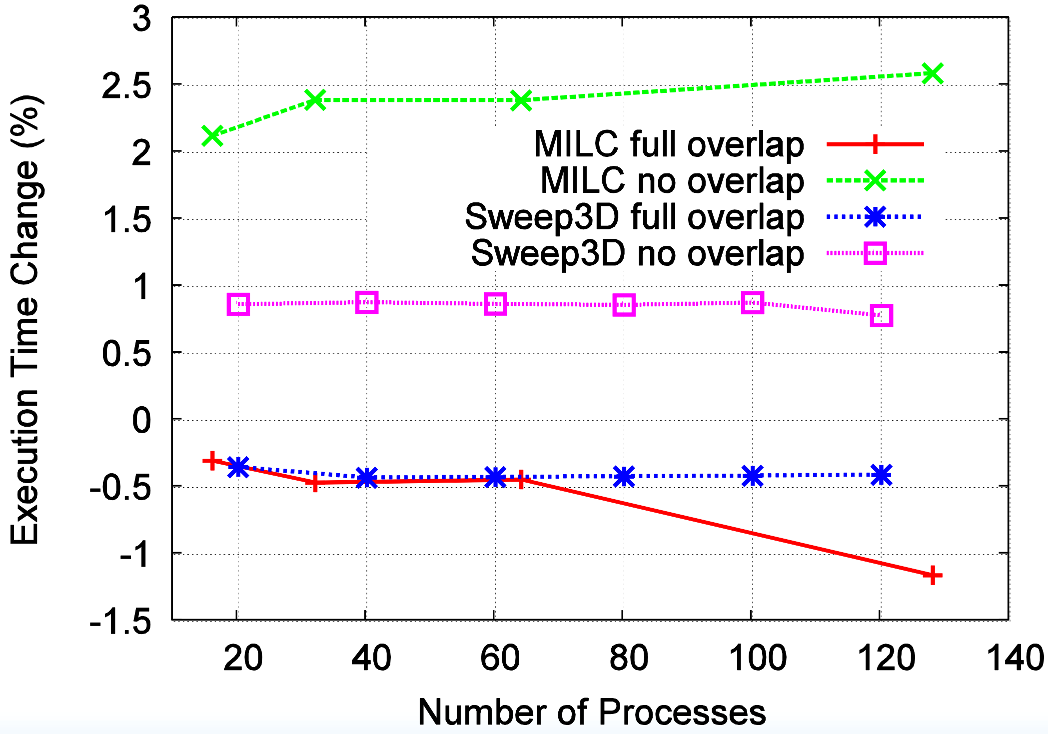
Thanks and try it at Home!

- LogGOPSim (the simulation framework)
  http://www.unixer.de/LogGOPSim
- Netgauge (measure LogGP parameters + OS Noise)
  http://www.unixer.de/Netgauge
- References:
  - Hoefler et al.: “Characterizing the Influence of System Noise on Large-Scale Applications by Simulation” (Best Paper at SC10)
  - Hoefler et al.: “LogGOPSim - Simulating Large-Scale Applications in the LogGOPS Model” (Best Paper at LSAP’10)

Backup

Application Overlap Potential

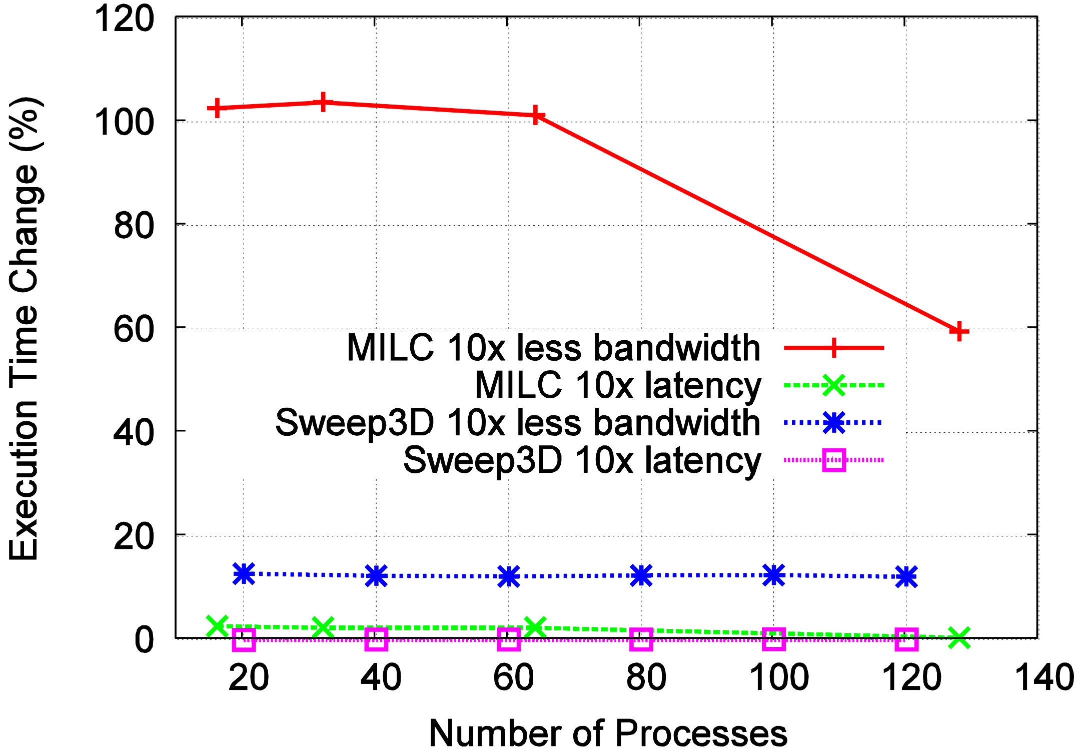
- Choose overhead appropriately:
  - full overlap:
    - o=0
    - O=0
  - no overlap:
    - o=g
    - O=G



Influence of Network Parameters

- Adjust L (latency) and G (bandwidth)

Both are much more sensitive to bandwidth than to latency!



Explaining Benchmark Problems

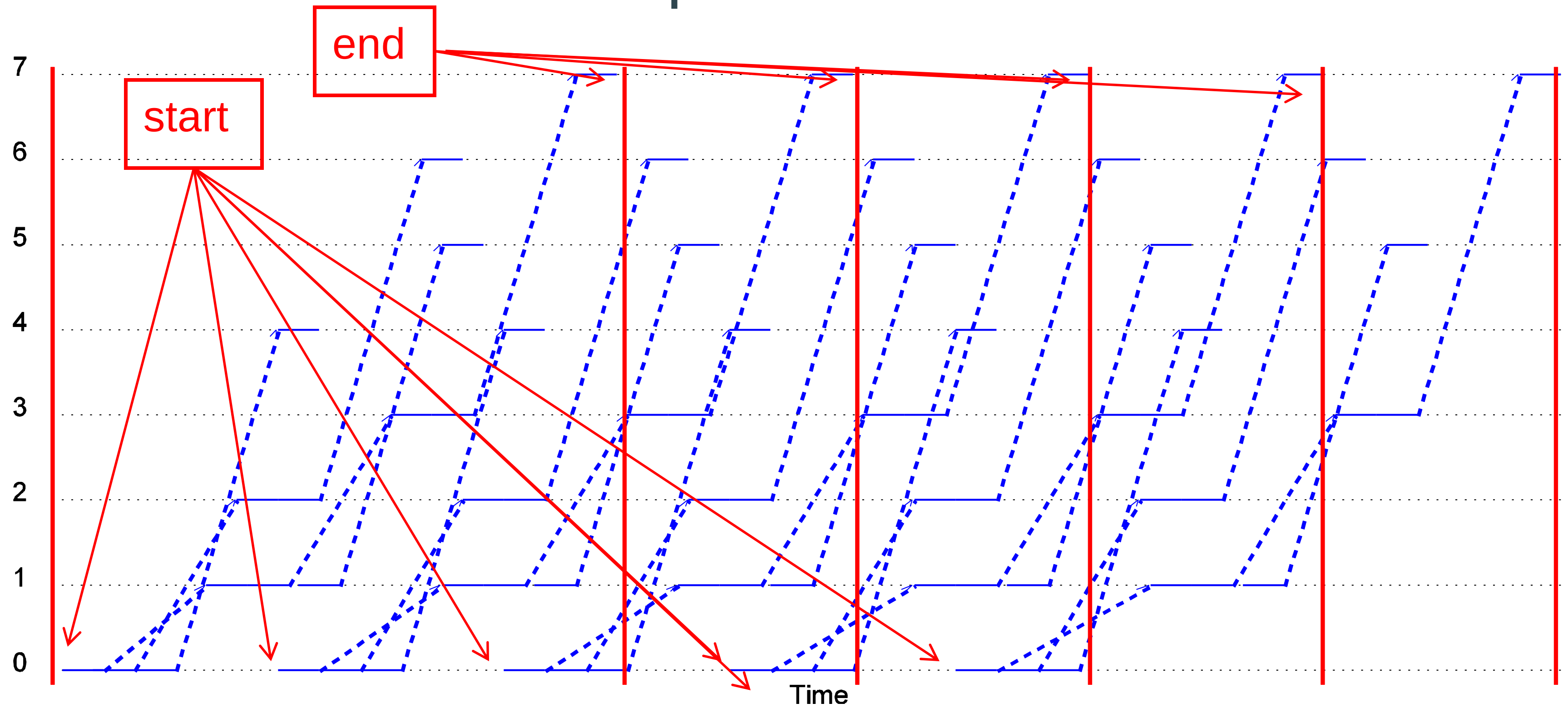
- Collective operations are often benchmarked in loops:

```
start= time();
for(int i=0; i<samples; ++i) MPI_Bcast(…);
end=time();
return (end-start)/samples
```

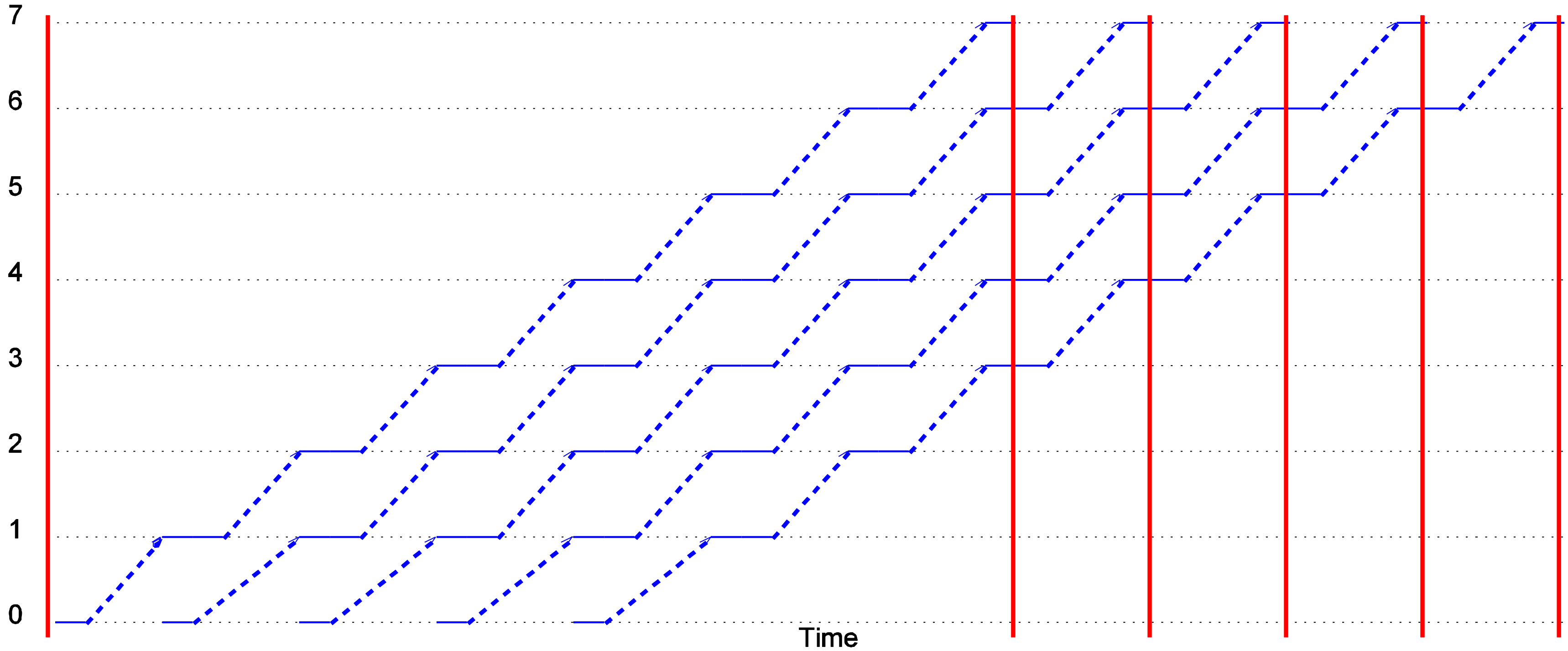
- This leads to pipelining and thus wrong benchmark results!

Pipelining? What?

Binomial tree with 8 processes and 5 bcasts:



Linear broadcast algorithm!



This bcast must be really fast, our benchmark says so!

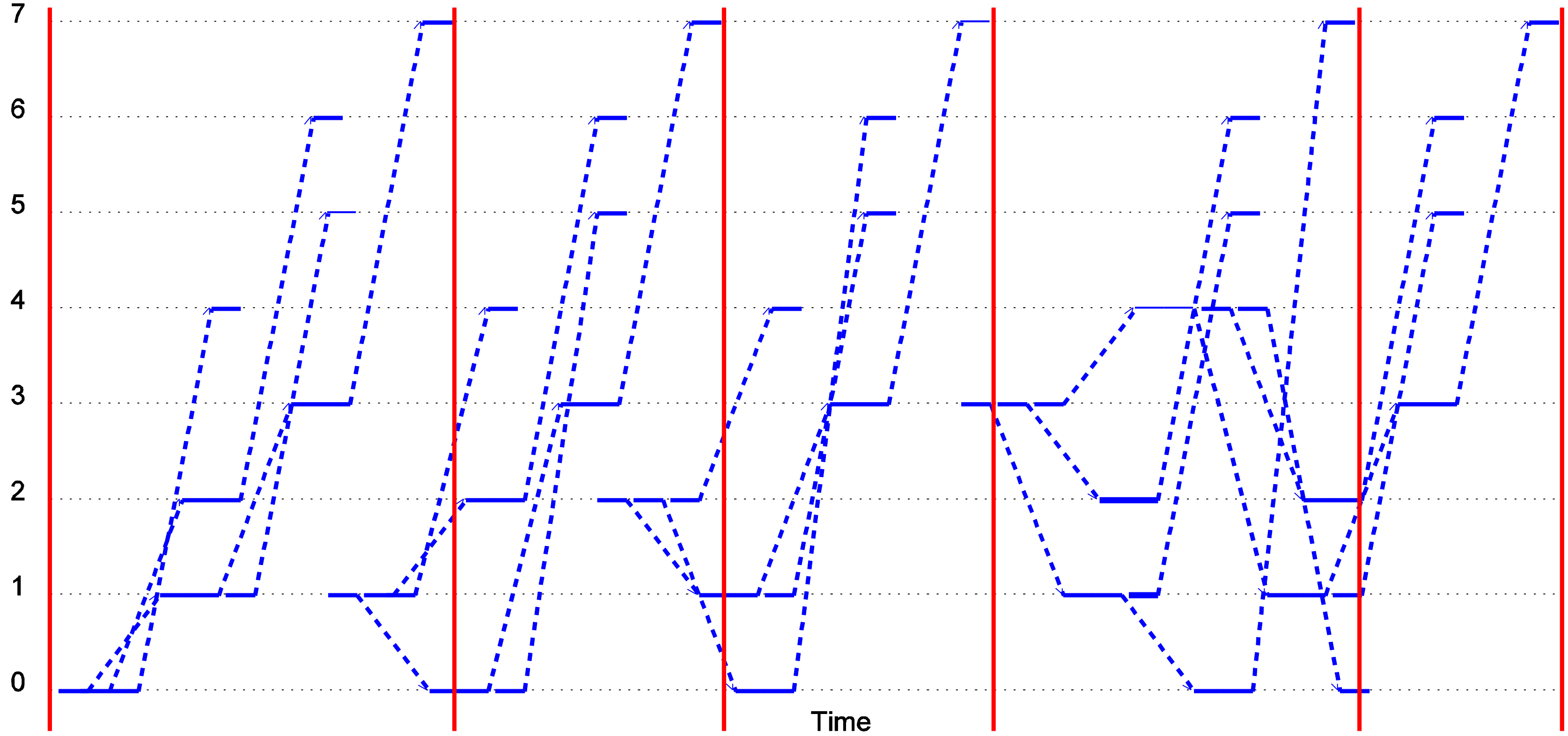
Root-rotation! The solution!

- Do the following (e.g., IMB)

```
start= time();
for(int i=0; i<samples; ++i)
  MPI_Bcast(…,root= i % np, …);
end=time();
return (end-start)/samples
```

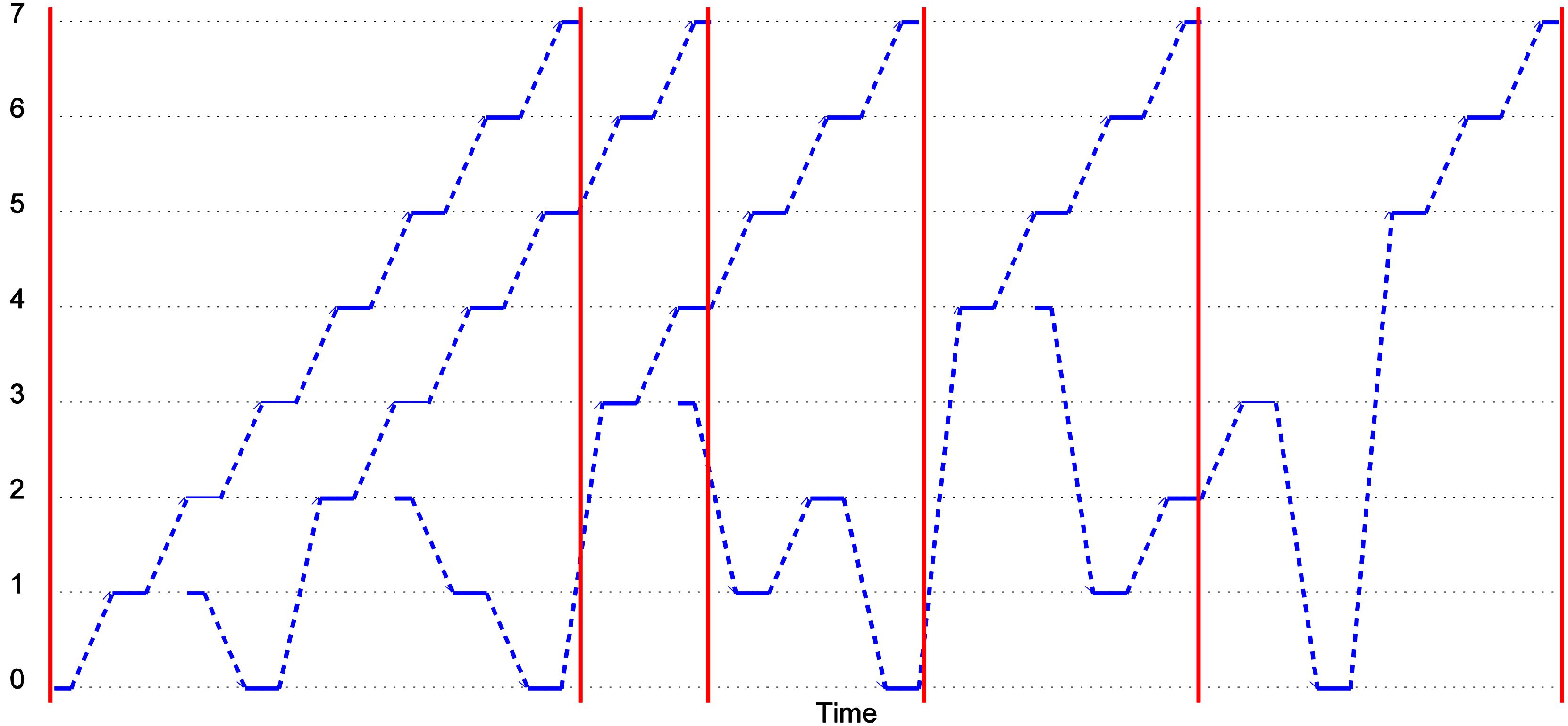
- Let’s simulate …

D’oh!



- But the linear bcast will work for sure!

Well … not so much.



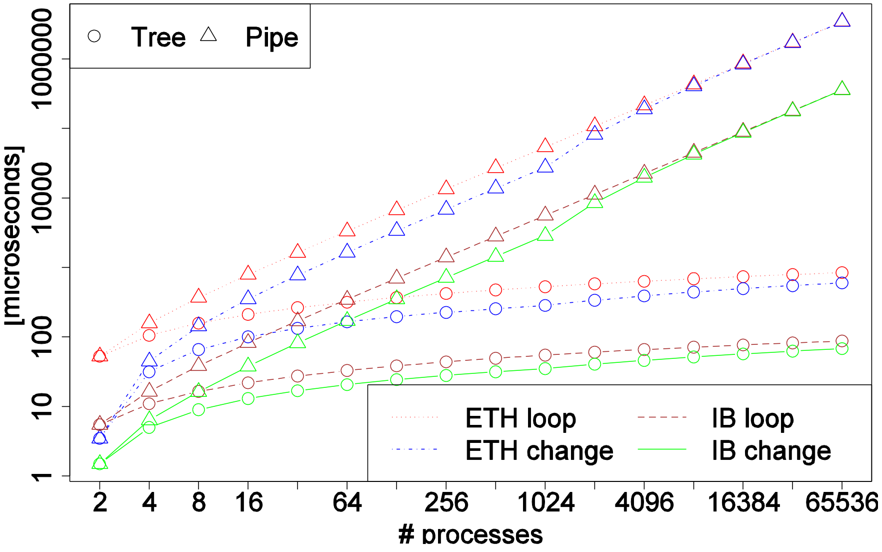
But how bad is it really? Simulation can show it!

Absolute Pipelining Error

- Error grows with the number of processes!
- Details in:

Hoefler et al.: “*LogGP in Theory and Practice*”

In: Journal of Simulation Modelling Practice and Theory (SIMPAT). Vol 17, Nr. 9

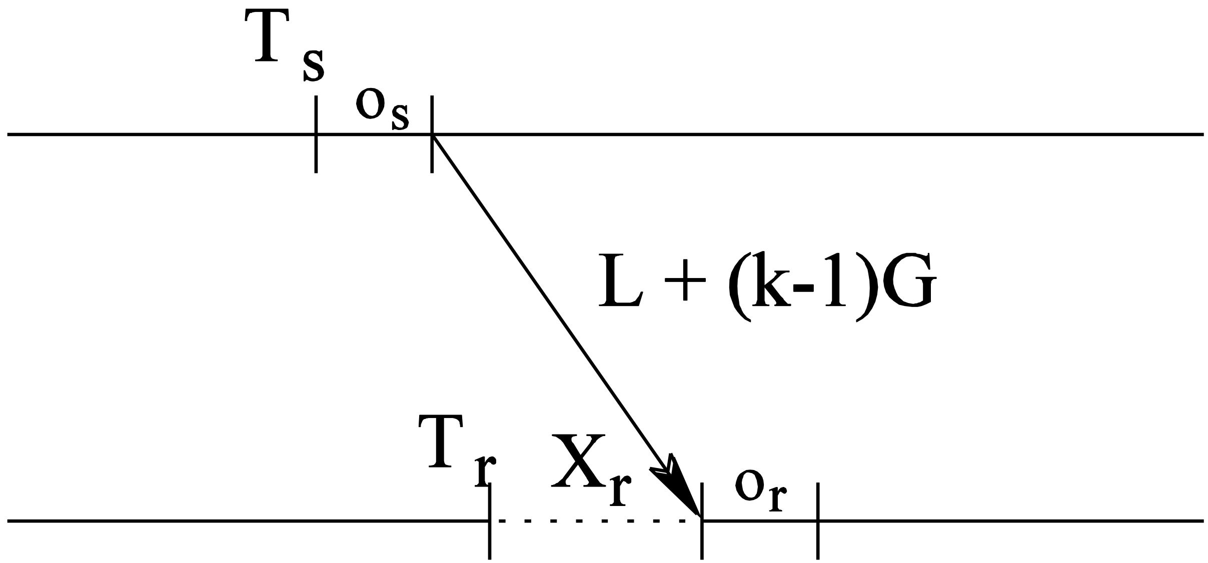


Comparison of Simulations and Experiments

- Beckman et al. - Allreduce on BG/L
  - 1000, 100, 10 Hz detours of 16, 50, 100, 200 μs
  - Reproduced linear scaling with noise
  - 16x slowdown in 32k processes, simulation: 13x
    - We used (better) LogGOPS parameters from BG/P

- Ferreira et al. Allreduce on Cray XT
  - 10 Hz, 2.5 μs detours
  - Experiment: 32x slowdown, simulation: 30x

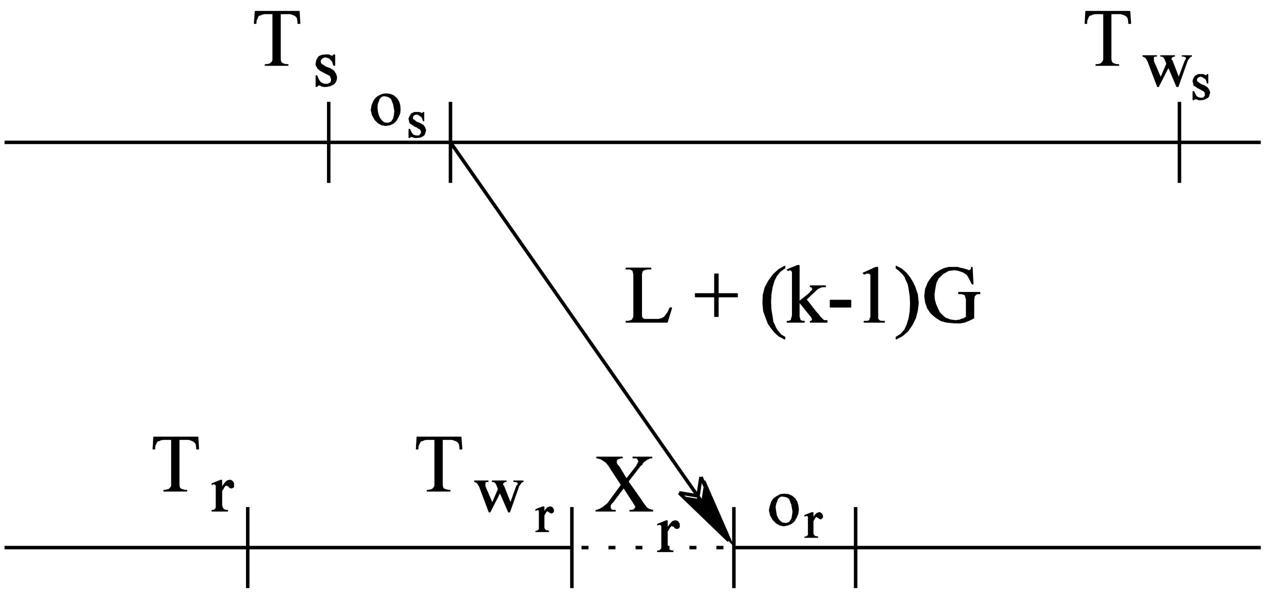
Blocking Point-to-Point Communication



- Synchronization overhead X_r can absorb noise at receiver
  - Sender noise can be absorbed if receive is posted late
- X_r and X_s (rendezvous) can be amplified by noise
- Synchronization overheads can only be avoided if

$$T_r = T_s + o_s + L + (k-1)G + o_r$$

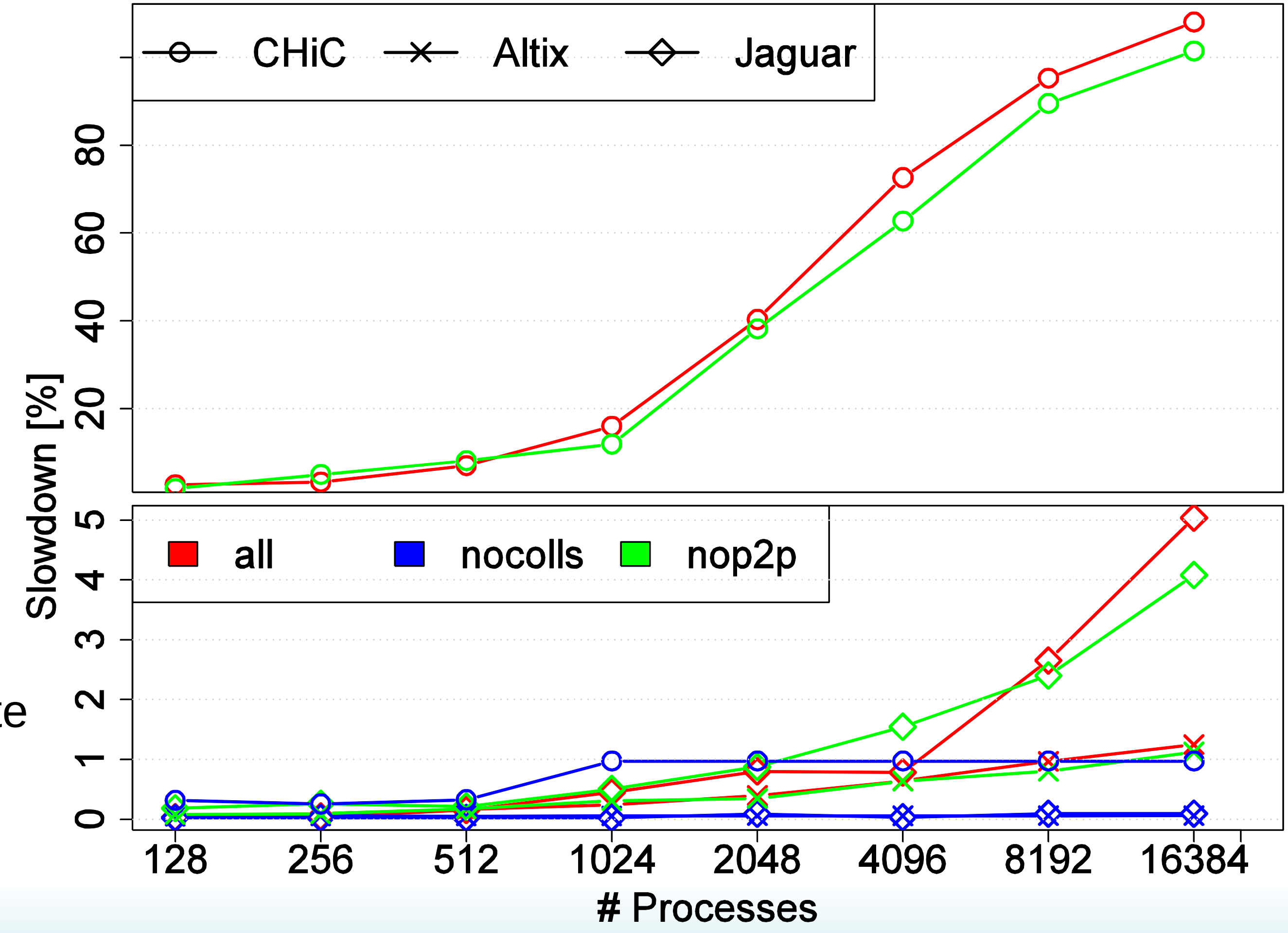
Nonblocking Point-to-Point Communication



- Time between Wait and Send/Recv Init acts as “buffer”
- Can absorb OS noise and synchronization overheads
  - Exact details are discussed in the full paper

Does Point-to-Point Communication Matter?

POP



collectives dominate noise overhead

AMG 2006 (Collective and Point-to-Point)