

Predicting the Energy Consumption of MPI Applications at Scale Using a Single Node

Franz C. Heinrich, Tom Cornebize,
Augustin Degomme, Arnaud Legrand
CNRS/Inria/Univ. Grenoble Alpes, France
firstname.lastname@imag.fr

Alexandra Carpen-Amarie
Sascha Hunold
TU Wien, Austria
TU Wien, Austria
{carpenamarie,hunold}@par.tuwien.ac.at

Anne-Cécile Orgerie
Martin Quinson
CNRS/Inria/ENS Rennes, France
firstname.lastname@irisa.fr

Abstract—Monitoring and assessing the energy efficiency of supercomputers and data centers is crucial in order to limit their energy consumption. Applications from the domain of High Performance Computing (HPC) consume a significant fraction of the overall energy consumed by HPC centers. Simulation is a popular approach for studying the behavior of HPC applications in a variety of scenarios, and it would therefore be advantageous to study the energy consumption of HPC applications in a cost-efficient, controllable, and also reproducible simulation environment. Unfortunately, simulators of HPC applications (e.g., MPI applications) typically lack the capability of predicting the energy consumption, in particular when platforms consist of multi-core nodes. In this work, we aim to accurately predict the energy consumption of MPI applications via simulation. First, we introduce the models required for meaningful simulations, which are the computation model, the communication model, and the energy model of the target platform. Second, we show that by carefully calibrating these models on a single node, the predicted energy consumption of HPC applications at a larger scale is very close (within a few percents) to real experiments. We show how to integrate such models into the SimGrid simulation toolkit. In order to obtain good execution time predictions on multi-core architectures, we show it is essential to correctly account for memory effects in simulation. The proposed simulator is validated through an extensive set of experiments with common HPC benchmarks. Finally, we show the simulator can be used for studying applications at scale, which allows to save both experimental time and resources compared to real experiments.

I. INTRODUCTION

Current supercomputers consume several megawatts of electrical energy. Cutting energy consumption by finding the sweet spot between performance and energy consumption of HPC applications is therefore an important goal. Multi-core processors consume a large fraction of the energy used by these supercomputers and hence, exploiting power-saving techniques of these processors (e.g., Dynamic Frequency and Voltage Scaling (DVFS)) plays a crucial role.

When attempting to find trade-offs between performance and energy consumption on large-scale machines through experimentation, one faces a vast amount of configuration possibilities, e.g., number of nodes, number of cores per node, or DVFS levels. For that reason, a thorough experimental evaluation of the energy usage of HPC applications requires a large amount of resources and a lot of compute time. Simulation may help to answer the question of energy-efficiency, and it has already been applied for analyzing HPC applications in

a variety of scenarios. However, HPC simulators usually lack the capability to predict energy although being able to study the effects of different DVFS policies may contribute to the understanding and the design of energy saving policy.

In the present article, we address the problem of predicting the energy consumption of HPC applications through simulation. In particular, we show how to obtain energy predictions of MPI applications using SimGrid. Energy usage in this context is modeled as the energy consumed by multi-core processors over the whole execution of the application. Thus, an accurate prediction of the execution time of MPI applications is necessary for a faithful prediction of their energy usage. Such accurate predictions of performance and energy consumption of MPI applications could be highly beneficial for capacity planning, from both HPC platform designers and users' perspectives, in order for them to adequately dimension their infrastructure.

The paper makes the following main contributions:

- 1) We first show how to predict (emulate) the execution time of MPI applications running on a cluster of multi-core machines, by using only a single node of the target cluster for the emulation. More specifically, compared to our previous work in the context of SimGrid, our contribution addresses additional difficulties raised by the multi-core architecture of the nodes. In particular, we show that it is important to both correctly model the two types of communications on such multi-core nodes, i.e., intranode (shared-memory) and internode (MPI) communications and to account for the impact of memory/cache effects on computation time estimations to obtain reliable predictions of the energy.

- 2) We propose and implement an energy model and explain how to instantiate it by using *only* a single node of a cluster. This model can later be used to predict energy consumption of the entire cluster.

- 3) We demonstrate the validity of our model by showing that it can accurately predict both the performance and the energy of three MPI applications, which are NAS-LU, NAS-EP, and HPL.

- 4) We report pitfalls that one can easily stumble upon when modeling and calibrating the platform and which would lead to erroneous predictions when being overlooked.

- 5) Finally, we illustrate the scalability of our approach by providing evaluations of the amount of time (and energy) that

can be saved by using simulations rather than real experiments to evaluate the performance of MPI applications.

The remainder of this article is organized as follows. Section II discusses related work, and Section III introduces our experimental setup. In Section IV, we explain the models used within the SimGrid framework for predicting the computation and communication times, as well as the energy consumption of MPI applications. Section V presents how each of the involved models should be calibrated and instantiated to obtain faithful predictions. We evaluate the effectiveness of our approach in Section VI before concluding in Section VII.

II. RELATED WORK

A. Energy Models for Compute Servers

In contemporary HPC nodes, processors are responsible for the lion's share of the energy consumption [1]. The activity and the frequency of a CPU have a significant impact on its power consumption [2], and thus, the lower the frequency of a processor, the less energy it consumes, at the cost of reduced speed.

Power models often break the power consumption of nodes into two separate parts: a static part representing the power consumption when the node is powered-on and idle; and a dynamic part that varies with the current utilization of CPUs [3]. The static part can represent a significant percentage of the maximum power consumption. For that reason, turning off servers during idle periods can save significant amounts of energy [4]. The relationship between the power consumption and load (utilization) of a CPU is linear for a given application at a given frequency, as explained in [1].

For HPC servers with few idle periods, DVFS constitutes a favorable alternative to switching off machines in order to save energy. DVFS adapts the processor frequency according to the application workload and, for instance, can decrease the frequency during communication phases [5].

Power consumption of interconnects can contribute up to 30% of the overall power consumption of the cluster but it is generally fixed and independent of their activity although some techniques for switching on and off links depending on traffic have been investigated [6]. The energy consumption of network cards (NICs) is often considered negligible for HPC servers, as it typically accounts for only 2% of the overall server's consumption [3], and it usually does not exhibit large variations related to traffic [1]. Accounting for a share of 20% to 30% of the power consumption of HPC nodes [3], memory (e.g., DRAM) plays also an important role.

Network cards and memory are typically accounted for in the static part of a server's power consumption [1]. This static part also includes the power consumption of the nodes' storage and other components.

B. Cloud and HPC Simulators

Energy optimization is a primary concern when operating a data center. Many simulators have been designed for a cloud context and include a power consumption model [7], [8]. For example, Guérout *et al.* [9] extended CloudSim [10] with

DVFS models to study cloud management strategies, while GreenCloud [11] is an extension of the NS2 simulator for energy-aware networking in cloud infrastructures. DCSim [8] is a simulation tool specifically designed to evaluate dynamic, virtualized resource management strategies, and it features power models that can be used to determine the energy used per host.

However, as explained by Velho *et al.* [12], several simulation toolkits have not been validated or are known to suffer from severe flaws in their communication models, rendering them ineffective in an HPC application-centric context. Although simulators that use packet-level and cycle-level models are arguably realistic (provided that they are correctly instantiated and used [13]), they suffer from severe scalability issues that make them unsuitable in our context.

Many simulators have been proposed for studying the performance of MPI applications on complex platforms, among others Dimemas [14], BigSim [15], LogGOPSim [16], SST [17], xSim [18] as well as more recent work such as CODES [19] and HAEC-SIM [20]. Most of these tools are designed to study or to extrapolate the performance of MPI applications at scale or when changing key network parameters (e.g., bandwidth, topology, noise). Surprisingly, few of them embed a sound model of multi-core architectures. A notable exception is Dimemas [14], which implements a network model that allows to clearly discriminate between communications within a node (going through shared memory) and communications that pass through the network. The PMAC framework [21] also uses a rather elaborate model of the cache hierarchy and can be combined with Dimemas to provide predictions of complex applications at scale. However, both tools solely rely on application traces, which can be limiting in terms of scalability and scope.

To the best of our knowledge, none of these tools except HAEC-SIM embeds a power model or allows researchers to study energy-related policies. HAEC-SIM allows to process OTF2 application traces and to apply simulation models (communication and power) that modify event properties. The simulation models are however quite specific to the envisioned HAEC use case and only cover a very small fraction of the MPI API. The validation is done at small scale (the NAS-LU benchmark with 32 processes), and although prediction trends seem very faithful and promising, it is common to have 20 to 30% of prediction errors in power estimation compared to reality.

III. EXPERIMENTAL SETUP AND METHODOLOGY

In this work, we rely on the Grid'5000 [22] infrastructure, in particular on the Taurus cluster¹, as each of its nodes is equipped with a hardware wattmeter. The measurements of these wattmeters are accessed through the Grid'5000 API, and power measurements are taken with a sampling rate of 1 Hz and an accuracy of 0.125 W.

¹Technical specification at <https://www.grid5000.fr/mediawiki/index.php/Lyon:Hardware#Taurus>.

The Taurus cluster is composed of 16 homogeneous nodes; each node consists of 2 Intel Xeon E5-2630 CPUs with 6 physical cores per CPU and 32 GiB of RAM. Each CPU has 3 cache levels of the following sizes: 32 KiB for L1, 256 KiB for L2 and 15 MiB for L3. These computing nodes are interconnected via 10 Gbit/sec Ethernet links to the same switch as two other smaller clusters and a service network. In order to rule out any performance issues caused by other users, in particular regarding network usage, we reserved the other smaller clusters during our experiments as well, although they are not part of this study. We deployed our own custom Debian GNU/Linux images before any experiment to ensure that we are in full control of the software stack used. We used Open MPI 1.6.5 for our experiments, but our approach is independent of the specific MPI version used. Finally, unless specified otherwise, CPU frequency was set to 2.3 GHz.

We use three MPI applications in our study. The first two originate from the MPI NAS Parallel Benchmark Suite (v3.3). The NAS-EP benchmark performs independent computations and calls three MPI_Allreduce operations at the end to check the correctness of the results. The NAS-LU benchmark performs a Lower-Upper decomposition using the Gauss-Seidel method and moderately relies on the MPI_Allreduce and MPI_Bcast operations. Most of its communication patterns are implemented through blocking and non-blocking point-to-point communications. Finally, we selected the HPL benchmark (v2.2), which is used to rank supercomputers in the TOP500 [23] and in the Green500 lists.

To allow researchers to inspect and easily build on our work, all the traces and the scripts used to generate the figures presented in the present document are available online² as well as an extended version detailing the importance of experimental control³. Likewise, all the developments we have done have been integrated to the trunk of the open-source SimGrid simulation toolkit⁴.

IV. PREDICTING THE PERFORMANCE OF MPI APPLICATIONS: THE SIMGRID APPROACH

Now, we present the main principles behind the simulation of MPI applications and explain more specifically how they are implemented in SimGrid, an open-source simulation toolkit initially designed for distributed systems simulation [24], which has been extended with the SMPI module to study the performance of MPI applications [25]. Most efforts of the SimGrid development team over the last years have been devoted to compare simulation predictions with real experiments as to validate the approach and to improve the quality of network and application models. The correctness of power consumption prediction is particularly conditioned by the faithfulness of runtime prediction, and so only recently, after the SMPI framework had been validated with many different use cases [25], has it become possible to invest in power models and an API to control them.

² <https://gitlab.inria.fr/fheinric/paper-simgrid-energy>

³ <https://hal.inria.fr/hal-01446134>

⁴ <http://simgrid.gforge.inria.fr/>

A. Modeling Computation Times

Two main approaches exist to capture and simulate the behavior of MPI applications: *offline* simulation and *online* simulation. In *offline* simulation, a trace of the application is first obtained at the level of MPI communication events and then replayed on top of the simulator. Such a trace comprises information about every MPI call (source, destination, payload, ...) and the (observed) duration of every computation between two MPI calls. Such a duration is simply injected in the simulator as a virtual delay. If the trace contains information on which code region this computation corresponds to, correction factors can be applied per code region. Such corrections are commonly used in Dimemas [14] to evaluate how much the improvement of a particular code region would influence the total duration of the application.

In the *online* simulation approach the actual application code is executed and part of the instruction stream is intercepted and passed to a simulator. Every MPI process of the application is mapped onto a lightweight simulation thread and every simulation thread is run in mutual exclusion from the others. Every time such a thread enters an MPI call, it yields to the simulation kernel and the time it spent computing (in isolation from every other thread) since the previous MPI call can thus be injected in the simulator as a virtual delay. This allows to dynamically capture the behavior of the application but needs to rely on the same precise simulation mechanisms used when replaying a trace. This form of emulation is technically much more challenging but is required when studying applications whose control flow depends on the platform characteristics, a property that is becoming more and more common. Note that this is actually the case for the HPL benchmark: It relies heavily on the MPI_Iprobe operation to poll for panel reception during its broadcast while overlapping the time for the transfer with useful computations. The main drawback of this approach is that it is usually quite expensive in terms of both simulation time and memory requirements since the whole parallel application is actually run on a single host machine. SMPI provides simple computation (sampling) and memory (folding) annotation mechanisms that make it possible to exploit the regularity of HPC applications and to drastically reduce both memory footprint and simulation duration [25]. The effectiveness of this technique will be illustrated in Section VI-B.

The online and the offline approach are implemented within SimGrid's SMPI layer. The SMPI runtime layer mimics the behavior of MPI in terms of semantic (synchronization, collective operations) and is used either for emulation (online simulation) or for trace replay (offline simulation). This organization allows users to benefit from the best of both worlds (e.g., using a lightweight replay mechanism combined with a dynamic load balancing [26] or easily implementing complex collective communication algorithms [25]). The price to pay compared to a simulator solely supporting offline simulation (e.g., LogGOPSim [16]) is that the SMPI replay mechanism systematically relies on simulation threads but careful opti-

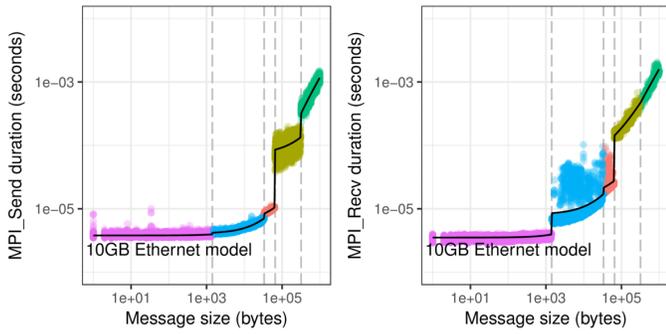


Figure 1. Communication time between two nodes of the Taurus cluster (Ethernet network). The duration of the communication with either MPI_Send or MPI_Recv are modeled as piece-wise linear functions of the message size.

mizations can drastically limit this overhead [27], [25].

A few other tools, e.g., SST [17] and xSim [18], support online simulation and mostly differ in technical implementation (emulation mechanism, communication models, etc.) and coverage of the MPI standard. SMPI implements the MPI-2 standard (and a subset of the MPI-3 standard but for MPI-IO) and allows users to execute unmodified MPI applications directly on top of SimGrid.

B. Modeling Communication Times

Several challenges arise when modeling communication of MPI applications. The first one is incurred by the complex network optimizations done in real MPI implementations. Different transmission protocols (short, eager, rendez-vous) may be used depending on the message size, which incurs different synchronization semantics even when using blocking Send and Receive (e.g., for short messages, MPI_Send generally returns before the message has actually been delivered to the receiver). Additionally, the low-delay high-latency network layer (IB, Omnipath, TCP/IP, ...) relies on different mechanisms, which leads to very different effective latency and bandwidth values depending on message size. To capture all such effects, SMPI relies on an a generalization of the LogGPS model [25] where several synchronization and performance modes can be specified (see Figure 1). The calibration procedure of such a model consists of sending a series of messages via MPI_Send and MPI_Recv, with carefully randomized sizes, between two nodes and to fit piece-wise linear models to the results with the R statistical language⁵. As illustrated in Figure 1, at least five modes can be distinguished depending on message size and correspond not only to different synchronization modes but also to different kinds of performances. Although the protocol switches from one mode to another could clearly be optimized, such kind of behavior is common and more than five modes are commonly found for TCP Ethernet networks.

The second key challenge is related to the modeling of network topology and contention. SMPI builds on the flow-level models of SimGrid and models communications, represented by *flows*, as single entities rather than as sets of individual packets. Assuming steady-state, the contention between active

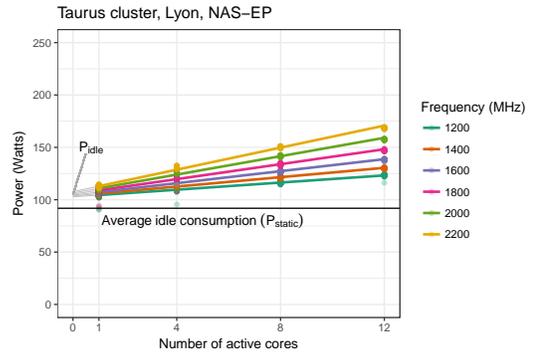


Figure 2. Power consumption on taurus-8 when running NAS-EP, class C, varying the frequency and the number of active cores.

communications is modeled as a bandwidth sharing problem that allows to account for non-trivial phenomena (e.g., RTT-unfairness of TCP, cross-traffic interference or simply network heterogeneity [12]). Every time a communication starts or ends, the bandwidth sharing has to be recomputed, which can be considered as too slow and complex to scale to large platforms. However, this approach not only leads to significant improvements in simulation accuracy over classical delay models but can also be efficiently implemented [28].

Finally, the third challenge is incurred by MPI collective operations which are generally of utmost importance to application performance. The optimization of the performance of MPI collective operations has received a lot of attention. MPI implementations thus have several alternatives for each collective operation and select one at runtime depending on message size and communicator geometry. For instance, in Open MPI, the MPI_Allreduce operation spans about 2300 lines of code. Ensuring that any simulated run of an application uses the same (or a similar) implementation as the real MPI implementation is thus key to simulation accuracy. The "SMPI runtime" layer SMPI implements all the specific collective communication algorithms from several real MPI implementations (Open MPI, MPICH, ...) and their selection logic. SMPI can hence account for performance variation based on the algorithm used for collective communications, allowing researchers to investigate a multitude of environments and configurations. Note that the applications we study in the following mostly rely on their own pipelined implementation collective operations.

C. Modeling the Energy Consumption of Compute Nodes

Power consumption of compute nodes is often modeled as the sum of two separate parts [1]: a static part that represents the consumption when the server is powered on but idle; and a dynamic part, which is linear in the server utilization and depends on the CPU frequency and the nature of the computational workload (e.g., computation vs. memory intensive, provided such characterization can be done). Therefore, we use the following equation to model the power consumption for a given machine i , a frequency f , a computational workload w (HPC application), and a given usage u (in percentage):

⁵See <https://gitlab.inria.fr/simgrid/platform-calibration> for more details.

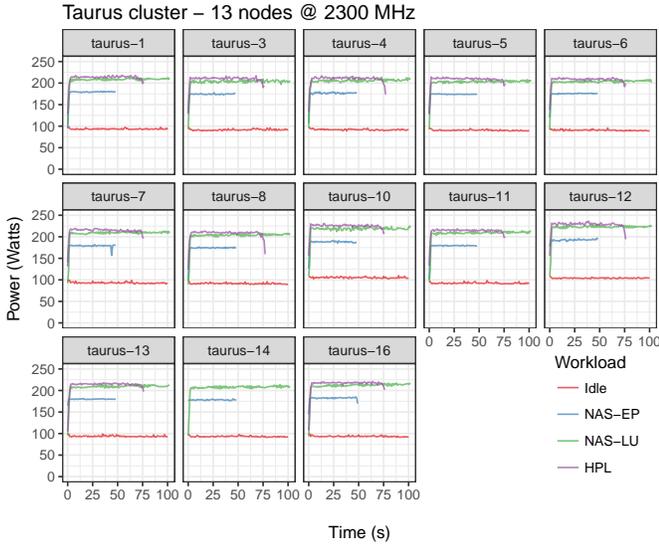


Figure 3. Power consumption over time when running NAS-EP, NAS-LU, HPL or idling (with 12 active cores and the frequency set to 2300 MHz).

$$P_{i,f,w}(u) = P_{i,f}^{\text{static}} + P_{i,f,w}^{\text{dynamic}} \times u \quad (1)$$

The linearity of our model is confirmed by measurements (see Figure 2). The parameters of the model in Equation (1) ($P_{i,f}^{\text{static}}$ and $P_{i,f,w}^{\text{dynamic}}$) can be inferred from running the target workload twice: Firstly using only one core and consequently all cores of the CPU and interpolating the values in between. Note that the measurements of Figure 2 show that it is generally safe to assume $P_{i,f}^{\text{static}}$ is independent on the frequency but that it should not be confused with the fully idle power consumption P^{idle} . This can be explained by the fact that when a CPU goes fully idle, it can enter a deeper sleep mode, which reduces its power consumption further.

When simulating an MPI application (either online or offline), it is easy to track whether a core is active or not, which allows the simulator to compute the instantaneous CPU usage (e.g., if 6 out of 12 cores of a given node are active, one would consider the load u to be 50%) and to integrate the resulting instantaneous power consumption to obtain the total energy consumed by the platform. Such a model implicitly assumes that all cores either run a similar workload w or are idling, which is generally true as HPC applications are regular. Figure 3 illustrates this regularity and how the workload (independent executions of the NAS-EP or of NAS-LU with all cores used of each node) influences power consumption at a macroscopic scale.

Subsequently, we therefore assume that this computational workload is constant throughout the execution of the application and is known at the beginning of the simulation. If the application consists of several phases of very different nature, they should be independently characterized. Note that such characterization can be quite difficult to make if switches from a regime to another occur quickly since making micro-

estimations of such operations requires extremely fine tracing and power measurement tools that are rarely available.

V. MODELING AND CALIBRATING PERFORMANCE AND ENERGY CONSUMPTION OF MULTI-CORE CLUSTERS

We now present how the SMPI framework had to be extended to provide faithful makespan and power consumption predictions and how important the calibration of the platform may be.

A. Computations: Unbiasing Emulation for Multi-core CPUs

1) *Problem:* All previously published work on the validation of SMPI focused on networking aspects and hence used solely one core of each node. In this section, we explain two flaws of the SMPI approach that were particularly problematic when handling multi-core architectures and which we had to overcome to obtain accurate predictions.

(a) In SimGrid, computing resources are modeled by a capacity (in FLOP/s) and are fairly shared between the processes at any point in time⁶. Hence, when p processes run on a CPU comprising n cores of capacity C , if $p \leq n$, each process progresses at rate C while if $p > n$, each process progresses at rate Cn/p . Although such a model is a reasonable approximation for identical CPU bound processes, it can be wildly inadequate for more complex processes. In particular, when several processes run on different cores of the same node, they often contend on the cache hierarchy or on the memory bus even without explicitly communicating. It is thus essential to account for the potential slowdown that the computations of the MPI ranks may inflict on each others.

(b) As we explained in Section IV-A, SMPI's emulation mechanism relies on a sequential discrete-event simulation kernel that controls when each process should be executed and ensures they all run in mutual exclusion between two MPI calls. When MPI applications are emulated with SMPI, each MPI rank is mapped onto a thread and folded within a single UNIX process, which raises semantic issues and requires to privatize global variables. This is done by making a copy of the data memory segment for each rank and by leveraging the virtual memory mechanism of the operating system to mmap this data segment every time we context-switch from one rank to another. Since ranks run in mutual exclusion, the time elapsed between two MPI calls can be measured and dynamically injected in the simulator. If the architecture on which the simulation is run is similar to the target architecture, we generally expect that such time is a good approximation of what would be obtained when running in a real environment.

Unfortunately, this combination of dynamic computation time measurement and of a simplistic computation model can lead to particularly inaccurate estimations. Let us consider on the one hand a target application consisting of many small computation blocks heavily exploiting the L1 cache and interspersed with frequent calls to MPI (for example to

⁶Note that the same property also holds for network links, which are fairly shared between flows.

```

28 ...
Region 43 if( iex .eq. 0 ) then
Region 43   if( north .ne. -1 ) then
30           call MPI_RECV( dum1(1,jst),
32             >           5*(jend-jst+1),
33             >           dp_type,
34             >           north,
35             >           from_n,
36             >           MPI_COMM_WORLD,
37             >           status,
38             >           IERROR )
Region 2   do j=jst,jend
Region 2     g(1,0,j,k) = dum1(1,j)
Region 2     g(2,0,j,k) = dum1(2,j)
Region 2     g(3,0,j,k) = dum1(3,j)
Region 2     g(4,0,j,k) = dum1(4,j)
Region 2     g(5,0,j,k) = dum1(5,j)
Region 2   enddo
Region 2   endif
Region 2   if( west .ne. -1 ) then
48           call MPI_RECV( dum1(1,ist),
50             >           5*(iend-ist+1),
51             >           dp_type,
52             >           west,
53             >           from_w,
54             >           MPI_COMM_WORLD,
55             >           status,
56             >           IERROR )
Region 3   do i=ist,iend
Region 3     g(1,i,0,k) = dum1(1,i)
Region 3     g(2,i,0,k) = dum1(2,i)
Region 3     g(3,i,0,k) = dum1(3,i)
Region 3     g(4,i,0,k) = dum1(4,i)
Region 3     g(5,i,0,k) = dum1(5,i)
Region 3   enddo
Region 3   endif
...

```

Figure 4. Excerpt of the NAS LU-PB (exchange_1.f) highlighting code regions between any two MPI calls.

ensure communication progress). Each MPI call would result in injecting the duration of the preceding computation in the simulator and immediately yielding to another rank. Despite all the care we took in implementing efficient and lightweight context switches, the content of the L1 cache will be cold for the new rank and its performance will therefore be much lower than the ones it would have had if it was running on its dedicated core (i.e., with dedicated L1 cache). Our emulation may therefore be biased, resulting in a significant apparent slowdown for such applications.

On the other hand, let us consider a target application consisting of relatively coarse-grained computation blocks which shall be considered to be memory-bound, i.e., that contend on L3 or on the memory bus when using all the cores of the machine. Since we measure each computation in mutual exclusion, during the simulation each rank benefits from an exclusive access to the L3 cache and the computation times injected in the simulation will thus be very optimistic compared to what they would have been in a normal execution.

Obviously, real HPC codes comprise both kinds of situations and knowing beforehand whether a given code region will be sped up or slowed down during the emulation compared to the real execution is very difficult as it is dependent on both the memory access pattern and the memory hierarchy.

Calibration ^{RL} trace (MPI)					Calibration ^{SG} trace (uncorrected SMPI)				
rank	start (s)	duration (mus)	state		start (s)	duration (mus)	state	Filename	Line
...
1	1.643388	1293	mpi_allreduce	0.550426	1130	mpi_allreduce	l2norm.f	57	
1	1.644681	62	Computing	0.551556	18	Computing			
1	1.644743	82	mpi_barrier	0.551574	47	mpi_barrier	ssor.f	74	
1	1.644825	6454	Computing	0.551621	5303	Computing			
1	1.651279	549	mpi_recv	0.556924	617	mpi_recv	exchange_1.f	30	
1	1.651828	474	Computing	0.557541	608	Computing	Region 3		
1	1.652302	53	mpi_send	0.558149	4	mpi_send	exchange_1.f	113	
1	1.652355	2	Computing	0.558153	12	Computing	Region 17		
1	1.652357	15	mpi_send	0.558165	4	mpi_send	exchange_1.f	130	
1	1.652372	359	Computing	0.558169	652	Computing	Region 18		
1	1.652731	11	mpi_recv	0.558821	8	mpi_recv	exchange_1.f	30	
1	1.652742	462	Computing	0.558829	587	Computing	Region 3		
1	1.653204	15	mpi_send	0.559416	5	mpi_send	exchange_1.f	113	
1	1.653219	1	Computing	0.559421	12	Computing	Region 17		
1	1.653220	9	mpi_send	0.559433	5	mpi_send	exchange_1.f	130	
1	1.653229	376	Computing	0.559438	699	Computing	Region 18		
1	1.653605	22	mpi_recv	0.560137	9	mpi_recv	exchange_1.f	30	
1	1.653627	465	Computing	0.560146	597	Computing	Region 3		
1	1.654092	16	mpi_send	0.560743	4	mpi_send	exchange_1.f	113	
1	1.654108	1	Computing	0.560747	14	Computing	Region 18		
...



Region-based speedup/slowdown factors

"bcast_inputs.f:37:exchange_3.f:42",0.1655	Region 1
"exchange_1.f:30:exchange_1.f:48",14.6704	Region 2
"exchange_1.f:30:exchange_1.f:113",1.2967	Region 3
"exchange_1.f:30:exchange_1.f:130",1.2994	Region 4
...	...
"exchange_1.f:113:exchange_1.f:130",11.7101	Region 17
"exchange_1.f:130:exchange_1.f:30",1.9696	Region 18
...	...
"exchange_3.f:288:exchange_1.f:30",0.8933	Region 43
...	...

Figure 5. Trace merging process used for the NAS-LU benchmark to compute region-based speedup/slowdown factors and correct the simulation.

2) *Solution*: To unbiased our emulation and characterize the true performance of the application, we first run the target application with a small workload **using all the cores of a single node**. This execution is traced as lightly as possible at the MPI level and the duration of every computation is recorded (Calibration^{RL} in Figure 5). We then re-execute the application with the exact same workload but on top of the simulator (hence **using a single core**, possibly on another machine) and trace accordingly the duration of every computation as well as the portion of code it corresponds to (Calibration^{SG} in Figure 5). We propose to identify the origin of the code by the filename and the line numbers of the surrounding two MPI calls as it can be obtained during compilation and therefore incurs a minimal overhead during the simulation (see Figure 4). Such identification of code regions may be erroneous, for example when MPI calls are wrapped in the application through some portability layer (in fact, this is the case of HPL). In this case, it might be required to identify code regions by the whole call-stack, as done for instance by SST/DUMPI [17]. Yet, as we will see, such level of complexity was not needed in our cases.

Since the application code is emulated by SimGrid, the duration of computations in Calibration^{RL} may be quite different from the ones in Calibration^{SG}. We automatically align the Calibration^{RL} and Calibration^{SG} traces (see Figure 5)

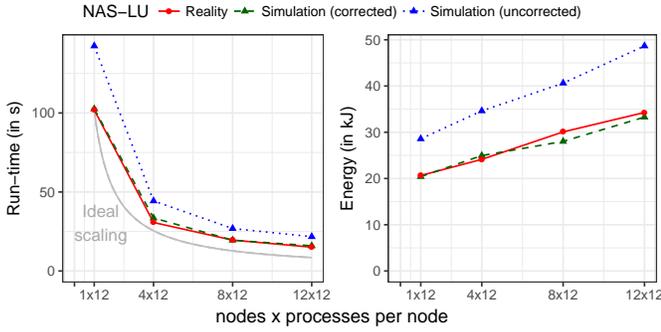


Figure 6. Illustrating the importance of unbiasing the emulation when simulating multi-core CPUs, NAS-LU, class C.

with an R script to identify for each code region a speed-up or slow-down factor that should be applied when emulating the target application. For a given code region c , this factor is defined as the ratio of the total time over all ranks spent in c in Calibration^{SG} to the total time over all ranks spent in c in Calibration^{RL}, which enables SimGrid to scale dynamically measured elapsed times accordingly.

Figure 5 depicts an excerpt of a file resulting from the calibration of computations. This file serves as input to SMPI and is used to correctly account for the duration of the computations on the target architecture. Some code regions have a speedup factor of around 1.29, which means that the duration of the corresponding code is actually faster when emulating than when running in a normal environment, while some other code regions have a speedup around 0.9, which means they are slower when emulating.

3) *Effectiveness of the Solution:* For some applications, like NAS-EP or for HPL, most factors are very close to 1 and such correction has therefore almost no impact on the overall makespan prediction. However, for a code like NAS-LU, not accounting for such slowdowns and speed ups leads to an overall runtime estimation error of the magnitude of 20 to 30% (see Figure 6) and hence to a major energy-to-solution estimation error.

It is interesting to note that some code regions (e.g., the first one in Figure 5) can have very low speedup factors while others (e.g., the second one) can have large and hence important speedup factors. In our experience, the ones with low speedup factors are seldom called (e.g., only once per rank) while the ones with large speedup factors have very frequent calls (possibly hundreds of thousands) but a very short duration. In both cases, their impact on the overall simulated time is negligible.

4) *Limitation:* Aside from the region identification that could be implemented in a more robust way, this method implicitly assumes that the correction factors determined for a single node still hold when the application spans several nodes. Intuitively, these correction factors are governed by cache locality and reuse and may thus be quite sensitive to problem size. The approach should therefore naturally work when conducting weak scaling studies but could break when conducting strong scaling studies. Yet, as can be seen for the

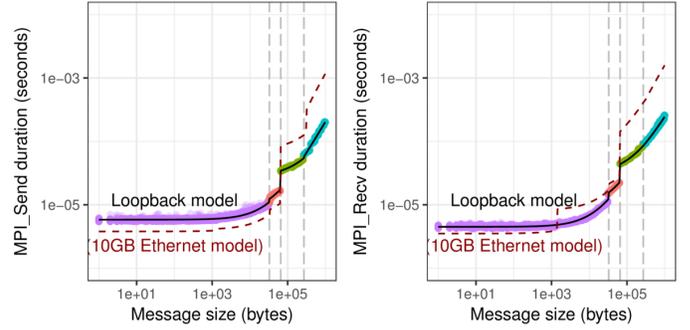


Figure 7. Communication time between two CPUs of the same node of Taurus (i.e., over shared memory). Compared to Figure 1, communications are not only less noisy but can also be almost one order of magnitude faster for large messages. Small messages appear faster over network links than over shared memory because they are sent asynchronously (the duration of MPI_Send and MPI_Recv does not account for transmission delay).

previous example (Figure 6) where the class of the problem is fixed, this did not happen in our experiments so far. This may be explained by the fact that the code is relatively well optimized and that there is thus no significant difference between the correction factors obtained when using a class C or a when using a smaller class workload.

B. Communications: Local Communications

1) *Problem:* As explained in Section IV-B, the communication model implemented in SMPI is a hybrid model between the LogP family and a fluid model that takes into account whether messages are sent fully asynchronously, in eager mode or in a synchronized way. Switches from one mode to another depend on message size and the resulting performance can be modeled through a piece-wise linear model with as many pieces as needed (5 modes in Figure 1). Unfortunately, the model presented in Section IV-B only makes sense for (remote) communications between distinct nodes. Communications that remain internal to a node use shared memory rather than the network card. Since such communications use shared memory, it is common to observe not only very different performances, but also slightly different behaviors (protocol changes are not done for the same messages and the regressions are expected to be different).

2) *Solution:* A similar series of measurements was run between two cores of the same node to calibrate accordingly the model for local communications (see Figure 7). Although they are much more stable, simpler and more efficient than remote communications, using a completely different model to distinguish between local and remote communications turned out to be of little importance because the applications we considered do not exploit locality and communication is dominated by remote communications. Communications over memory were therefore simply modeled by a 40 Gbit/sec shared link, which allows to account for both contention and heterogeneity.

3) *Effectiveness of the solution:* We illustrate the consequences of distinguishing between local and remote communications with the HPL benchmark. As can be seen in Fig-

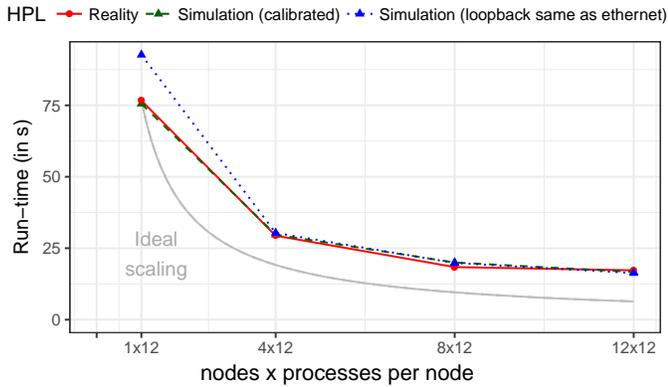


Figure 8. Comparison of simulation results for HPL between a correctly calibrated simulation and simulation that would not account for specific shared memory communication characteristics.

ure 8, ignoring heterogeneity (blue dotted line) is particularly misleading at small scale since it incurs an overall runtime estimation error of the magnitude of 25 % whereas accounting for fast local links (green dashed line) provides a perfect prediction at any scale. Since this modeling error solely incurs additional communication and idle times, the additional power consumption remains relatively small compared to the full load consumption of pure computations. The prediction error is thus around a few percents (even when there is a 25 % error in runtime) and is within the variability of real experiments. The version of HPL we used does not specifically exploit locality, and hence, as soon as more than one node is used, the whole application gets slowed down by the slower Ethernet links and the runtime and power estimations become equivalent to the ones obtained when correctly modeling network heterogeneity.

4) *Limitation:* When comparing Figures 1 and 7, it appears that, although the common regimes can be found, the regressions are very different. Ideally, to faithfully predict the behavior of applications that are highly sensitive to communications and potentially use the whole spectrum of message sizes, we should allow SimGrid users to model completely different latency/bandwidth correction factors that could then be used depending on which group of nodes is communicating. Such modification is underway and will leverage the hierarchical platform representation of SimGrid [27]. But again, in all the experiments we conducted so far, correctly evaluating the effective latency and bandwidth of shared memory communications was all that was needed to obtain faithful predictions.

It should be noted that if the network topology is known or expected to be decisive (as it was the case in [25], where a much more contended network topology was considered), then some saturation experiments should be done to properly evaluate where bottlenecks may occur. We ran such experiments for consistency but as our cluster is of limited size with a well provisioned router, a flat topology was sufficient.

Finally, one should make sure that the same collective communication selector is used for both real life experiments and the simulation. Yet, the applications we used to evaluate our new models barely rely on collective communications, so

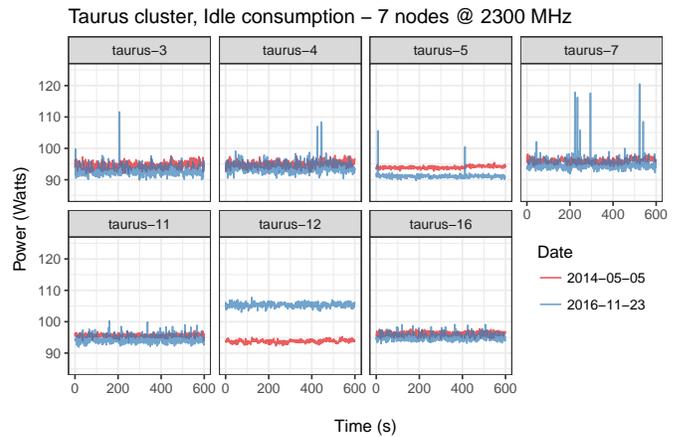


Figure 9. Idle power consumption along time when the frequency is set to 2300 MHz for several nodes of the Taurus cluster in 2014 and in 2016. The Y-axis does not start at 0 to provide a better appreciation of the variations.

the impact of this particular configuration is limited as well.

C. Energy: Heterogeneity and Communication Polling

1) *Problem:* Although it is typically assumed that a cluster is homogeneous, a more systematic calibration often demonstrates this to be false. For illustration, Figure 9 depicts the power consumption along time at two different dates (May 2014 and October 2016) for various nodes. Not only can significant differences be observed between nodes, but the power consumption of taurus-12 has for example increased by 11 W while the one of taurus-5 has decreased by 3 W. In 2014, the cluster could be considered as homogeneous but in 2016, this is evidently not the case anymore. These measurements are however quite stable. On a two hours time scale, a few outliers (around 0 W or 50 W) per node can be easily detected and removed as they can be attributed to powermeter glitches. The sample mean is thus a very good approximation of the distribution and we calibrated our models accordingly. Although not everyone may want to conduct a large scale calibration of its platform, monitoring infrastructures are generally deployed on large platforms and can be used to detect nodes that behave differently and require individual calibration. This kind of heterogeneity remains limited (within a few percents of the overall capacity since P_{static} is typically around 92 W) and can easily be provided to SimGrid if needed. Yet, in our experiments, accounting for the heterogeneity of the platform only incurred $\approx 1\%$ of difference, which makes it indistinguishable from the noise of real experiments.

More importantly, as noted in Section IV-C, although $P_{i,f}^{static}$ does not appear to depend on the frequency, it should neither be confused with the fully idle power consumption P_{idle} nor with the "turned-off" power consumption or with the power consumption during the boot procedure. These different states lead to very different behaviors and should all be characterized if a power estimation of the whole cluster under a mixed workload is expected. Every such state and every new application actually calls for a specific series of potentially

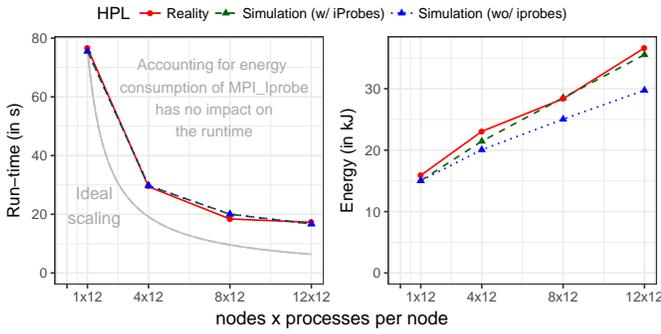


Figure 10. Comparison of predicted energy usage of HPL with and without accounting for the additional energy consumption of MPI_Iprobe calls.

tedious measurements. However, in our opinion, they can hardly be avoided. Alas, some of these "states" can at times be rather difficult to anticipate. For example, the MPI_Iprobe operation is actually not used by the NAS benchmarks but heavily used by HPL in its custom re-implementation of broadcast operations that support an efficient overlapping with computations. In our earlier versions of SMPI we had already taken care of measuring the time it takes to execute a call to MPI_Iprobe. However, the resulting call was simply modeled as a pure delay, hence leaving the simulated core fully idle for a small period of time. However, when HPL enters a particular region with intense communication polling, constantly looping over MPI_Iprobe actually incurs some non-negligible CPU load that can lead to significant power estimation inaccuracies if not modeled correctly.

2) *Solution*: We have extended our benchmark of MPI_Iprobe and it now detects what energy consumption is incurred by repeated polling. For example, when all the cores of a node are polling communications, the power consumption was measured to be around 188 W, which is lower than the power consumption incurred by running for example HPL (≈ 214 W at maximal frequency) on the whole node but much higher than the idle power consumption (≈ 110 W). We have therefore extended SMPI so that such power consumption can be specified and accounted for.

3) *Effectiveness of the solution*: Figure 10 depicts how the time-to-solution and energy-to-solution of HPL evolve when adding more resources. Since the network performance and the average duration of the MPI_Iprobe have been correctly instantiated, the run-time prediction matches perfectly the ones of real executions. When modeling the MPI_Iprobe as a pure delay, the resulting core idleness leads to a gross underestimation of energy consumption (blue dotted line). Fortunately, correctly accounting for the power consumption of the MPI_Iprobe operation ensures that perfect predictions (green dashed line) of the total energy consumption are yielded.

VI. EVALUATION

A. Validation Study

In the previous section, we explained how important it can be to correctly account for various effects and to correctly

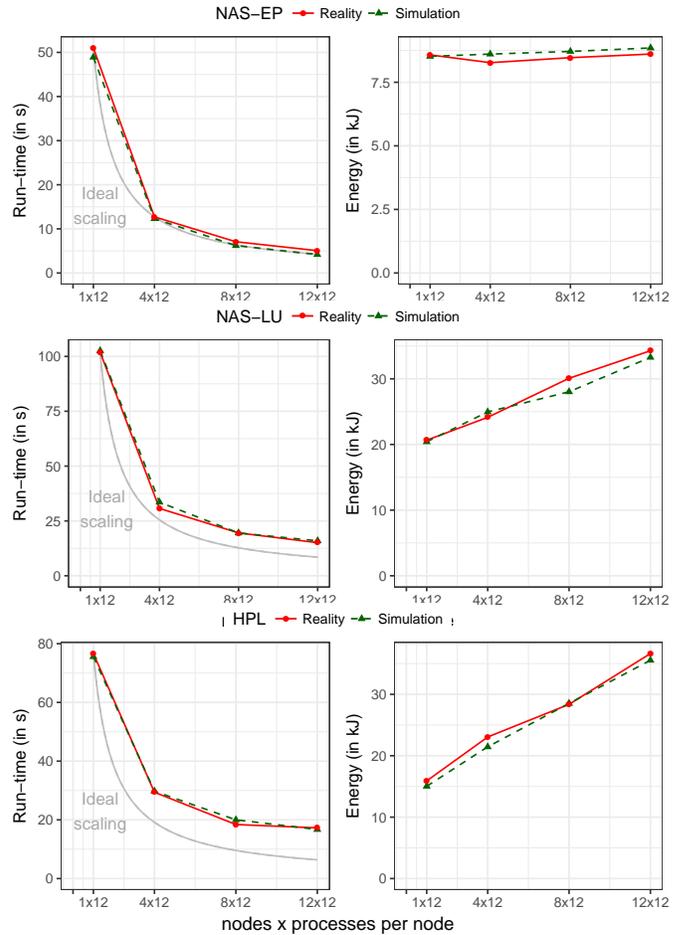


Figure 11. Validating simulation results for NAS-EP, NAS-LU, and HPL, on up to 12 nodes with 12 processes per node.

instantiate the different models. We recap in Figure 11 the comparison of careful simulations with real executions for the three applications presented earlier: NAS-EP, NAS-LU and HPL. In all cases, the performance prediction is almost indistinguishable from the outcome of the real experiments.

Although the previous general behavior is somehow expected (perfect speed up for NAS-EP but sub-linear for NAS-LU and HPL, causing an increasing energy consumption), we manage to systematically predict both performance and power consumption within a few percents.

B. Scalability and Extrapolation

To illustrate the benefits of such a simulation framework, we performed a strong scaling of HPL on a hypothetical platform made of 256 12-core CPUs similar to the ones of the Taurus platform but interconnected with a two level fat-tree made of 16-port switches and where the top (resp. bottom) layer comprises 2 (resp. 16) switches and 10 Gbit/sec Ethernet links.

The previous validation experiments were done leveraging solely the default emulation mechanism which allows users to evaluate unmodified MPI applications. In this mode, every computation of each application is performed. At scale, this quickly becomes prohibitive and generally requires much more

VII. CONCLUSIONS

Predicting the energy usage of MPI applications through simulation is a complex problem. In the present article, we have taken first steps towards solving the problem. We have described the models that can be used to predict the computation and communication time of MPI applications, which form the basis for our simulator to predict their energy consumption. Despite the simplicity of these models, obtaining accurate predictions is not a straight-forward task. Instead, each model needs to be carefully instantiated and calibrated. To that end, we have identified several key elements that need to be accounted for in this calibration process. The advantage of our simulation process is that we can obtain accurate predictions by using only one node of a compute cluster, assuming that we have a homogeneous cluster system. Another key feature of our framework is that it allows to study unmodified MPI applications, chiefly those that are adaptive to network performance (e.g., by overlapping communications with computations or by asynchronously pipelining transfers).

In sum, we have devised and implemented a first model to obtain energy predictions of complex MPI applications through simulation. We have shown that the energy predictions obtained from simulation match experimental measurements of the energy usage of MPI applications. Thus, we have demonstrated that simulation can be a useful method to obtain faithful insights into the problem of energy-efficient computing without expensive experimentation.

As future work, we are considering adding energy models for the network devices. Network architecture can indeed greatly impact the performance of applications [29] and through smart energy-efficient techniques – like IEEE 802.3az [30] that is putting network ports into low power idle modes when unused – consequent energy savings can be made in HPC infrastructures [6]. This network dimension would increase the potential of SimGrid to be used as a capacity planner for supercomputer manufacturers and HPC application users.

Another envisioned extension targets the modeling of the energy consumption of hybrid architectures (multi-core, multi-GPUs, big.LITTLE processors, etc.). Such heterogeneous architectures are probably the best way to answer energy constraints but their control-space grows rapidly. SimGrid has successfully been used to predict the performance of adaptive task-based runtimes [31] and could guide the development and the evaluation of energy-aware scheduling heuristics.

ACKNOWLEDGMENTS

The authors would like to thank the SimGrid team members and collaborators who contributed to SMPI. This work is partially supported by the Hac Specis Inria Project Lab, the ANR SONGS (11-ANR-INFR-13), and the European Mont-Blanc (EC grant 288777) projects. Experiments were carried out on the Grid’5000 experimental testbed, supported by a scientific interest group hosted by Inria and including CNRS, RENATER, and other Universities and organizations (see <https://www.grid5000.fr>).

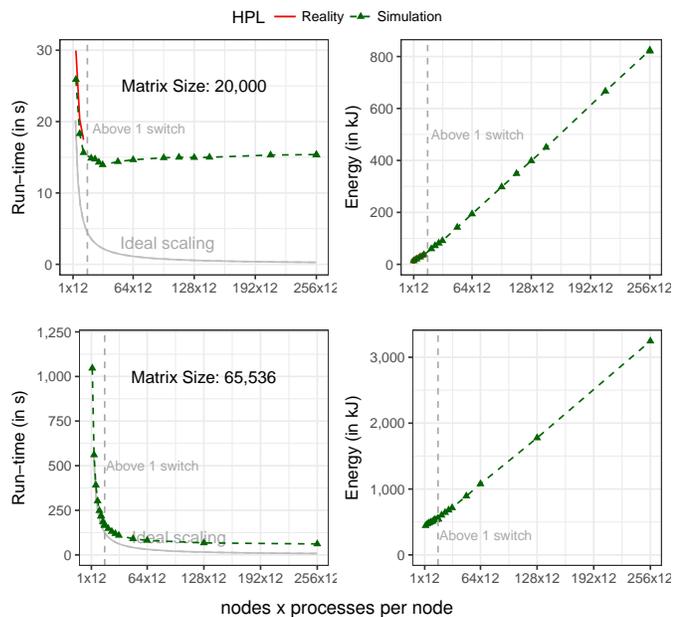


Figure 12. Extrapolating time- and energy-to solution on a fat-tree topology with up to $256 \times 12 = 3,072$ MPI processes.

time than a real life execution since all MPI processes are then folded on a single machine. As an illustration, running HPL for real on 144 cores with a $20,000 \times 20,000$ matrix (i.e., with a memory consumption of 3.2 GB in total) requires less than 20 seconds whereas a full emulation requires almost two hours. However, as explained in Section IV-A, since HPC applications are very regular, it is possible to drastically reduce this cost by modeling the duration of computation kernels (hence skipping their execution during the emulation) and folding memory allocations (hence reducing memory footprint). With such mechanisms, it is possible to simulate the same scenario (a $20,000 \times 20,000$ matrix with 144 processes) *on a single core of a commodity laptop* in less than two minutes using 43 MB of memory. Simulating an execution with $256 \times 12 = 3,072$ MPI processes requires about one hour and a half and less than 1.5 GB of memory.

Figure 12 depicts a typical scalability evaluation when the matrix size is fixed to either 20,000 (3.2 GB in total) or 65,536 (34.3 GB). With the smaller matrix, this quickly leads to a fully network bound scenario where slow-down is expected. The values obtained with up to 12 nodes (144 processes) are perfectly coherent with real life experiments since the application remains located within a switch. When spreading over more than one switch (i.e., above 196 processes) however, the additional latency becomes a hindrance, which leads to both a slowdown and an even faster increase of power consumption. For the larger matrix, we observe as expected a better scaling. Energy consumption is larger not only because the whole duration is larger but also because the ratio of communication to computations is very different.

REFERENCES

- [1] A.-C. Orgerie, M. Dias de Assunção, and L. Lefèvre, "A Survey on Techniques for Improving the Energy Efficiency of Large-Scale Distributed Systems," *ACM Computing Surveys (CSUR)*, vol. 46, no. 4, 2014.
- [2] M. Etinski, J. Corbalan, J. Labarta *et al.*, "Understanding the future of energy-performance trade-off via DVFS in HPC environments," *Journal of Parallel and Distributed Computing (JPDC)*, vol. 72, no. 4, Apr. 2012.
- [3] M. Dayarathna, Y. Wen, and R. Fan, "Data Center Energy Consumption Modeling: A Survey," *IEEE Communications Surveys Tutorials*, vol. 18, no. 1, 2016.
- [4] M. Lin, A. Wierman, L. L. H. Andrew *et al.*, "Dynamic Right-sizing for Power-proportional Data Centers," *IEEE/ACM Transactions on Networking (TON)*, vol. 21, no. 5, Oct. 2013.
- [5] E. Le Sueur and G. Heiser, "Dynamic voltage and frequency scaling: the laws of diminishing returns," in *USENIX International conference on Power aware computing and systems (HotPower)*, 2010.
- [6] K. P. Saravanan, P. M. Carpenter, and A. Ramirez, "Power/performance evaluation of energy efficient ethernet (eee) for high performance computing," in *2013 IEEE International Symposium on Performance Analysis of Systems and Software (ISPASS)*, April 2013, pp. 205–214.
- [7] S. Ostermann, R. Prodan, and T. Fahringer, "Dynamic Cloud Provisioning for Scientific Grid Workflows," in *Proc. of the 11th ACM/IEEE Intl. Conf. on Grid Computing (Grid)*, Oct. 2010.
- [8] M. Tighe, G. Keller, M. Bauer *et al.*, "DCSim: a data centre simulation tool for evaluating dynamic virtualized resource management," in *Int. Conf. on Network and Service Management*, 2012.
- [9] T. Guérout, T. Monteil, G. D. Costa *et al.*, "Energy-aware simulation with DVFS," *Simulation Modelling Practice and Theory*, vol. 39, dec 2013.
- [10] R. N. Calheiros, R. Ranjan, A. Beloglazov *et al.*, "CloudSim: A Toolkit for Modeling and Simulation of Cloud Computing Environments and Evaluation of Resource Provisioning Algorithms," *Software: Practice and Experience*, vol. 41, no. 1, Jan. 2011.
- [11] D. Kliazovich, P. Bouvry, and S. U. Khan, "A packet-level simulator of energy-aware cloud computing data centers," *Journal of Supercomputing*, vol. 62, no. 3, 2012.
- [12] P. Velho, L. M. Schnorr, H. Casanova *et al.*, "On the validity of flow-level tcp network models for grid and cloud simulations," *ACM Trans. Model. Comput. Simul.*, vol. 23, no. 4, Dec. 2013.
- [13] T. Nowatzki, J. Menon, C. H. Ho *et al.*, "Architectural simulators considered harmful," *IEEE Micro*, vol. 35, no. 6, Nov 2015.
- [14] R. M. Badia, J. Labarta, J. Giménez *et al.*, "Dimemas: Predicting MPI Applications Behaviour in Grid Environments," in *Proc. of the Workshop on Grid Applications and Programming Tools*, Jun. 2003.
- [15] G. Zheng, G. Kakulapati, and L. Kale, "BigSim: A Parallel Simulator for Performance Prediction of Extremely Large Parallel Machines," in *Proc. of the 18th IPDPS*, 2004.
- [16] T. Hoefler, T. Schneider, and A. Lumsdaine, "LogGOPSim - Simulating Large-Scale Applications in the LogGOPS Model," in *Proc. of the LSAP Workshop*. New York, NY, USA: ACM, 2010, pp. 597–604. [Online]. Available: <http://doi.acm.org/10.1145/1851476.1851564>
- [17] C. L. Janssen, H. Adalsteinsson, S. Cranford *et al.*, "A simulator for large-scale parallel architectures," *International Journal of Parallel and Distributed Systems*, vol. 1, no. 2, 2010.
- [18] C. Engelmann, "Scaling To A Million Cores And Beyond: Using Light-Weight Simulation to Understand The Challenges Ahead On The Road To Exascale," *Future Generation Computer Systems*, vol. 30, Jan. 2014.
- [19] M. Mubarak, C. D. Carothers, R. B. Ross *et al.*, "Enabling Parallel Simulation of Large-Scale HPC Network Systems," *IEEE Transactions on Parallel and Distributed Systems*, vol. 28, no. 1, pp. 87–100, Jan. 2017. [Online]. Available: <https://doi.org/10.1109/TPDS.2016.2543725>
- [20] M. Bielert, F. M. Ciorba, K. Feldhoff *et al.*, "HAEC-SIM: A simulation framework for highly adaptive energy-efficient computing platforms," in *Proceedings of the 8th International Conference on Simulation Tools and Techniques (SIMUTools)*. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2015, pp. 129–138. [Online]. Available: <https://doi.org/10.4108/eai.24-8-2015.2261105>
- [21] A. Snavelly, L. Carrington, N. Wolter *et al.*, "A Framework for Performance Modeling and Prediction," in *Proc. of the ACM/IEEE Conference on Supercomputing*, Baltimore, MA, Nov. 2002.
- [22] D. Balouek, A. Carpen-Amarie, G. Charrier *et al.*, "Adding virtualization capabilities to the Grid'5000 testbed," in *Cloud Computing and Services Science*, ser. Communications in Computer and Information Science, I. Ivanov, M. Sinderen, F. Leymann *et al.*, Eds. Springer International Publishing, 2013, vol. 367.
- [23] "TOP500," <https://www.top500.org>, 2016.
- [24] H. Casanova, A. Giersch, A. Legrand *et al.*, "Versatile, Scalable, and Accurate Simulation of Distributed Applications and Platforms," *Journal of Parallel and Distributed Computing*, vol. 74, no. 10, 2014.
- [25] A. Degomme, A. Legrand, G. Markomanolis *et al.*, "Simulating MPI applications: the SMPI approach," *IEEE Transactions on Parallel and Distributed Systems*, p. 14, Feb. 2017. [Online]. Available: <https://hal.inria.fr/hal-01415484>
- [26] R. Keller Tesser, L. Mello Schnorr, A. Legrand *et al.*, "Using Simulation to Evaluate and Tune the Performance of Dynamic Load Balancing of an Over-decomposed Geophysics Application," in *Euro-par - 23rd International Conference on Parallel Processing*. Springer International Publishing Switzerland, Aug. 2017.
- [27] L. Bobelin, A. Legrand, D. A. G. Márquez *et al.*, "Scalable Multi-Purpose Network Representation for Large Scale Distributed System Simulation," in *Proc. of the 12th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing*, Ottawa, Canada, 2012.
- [28] B. Donassolo, H. Casanova, A. Legrand *et al.*, "Fast and Scalable Simulation of Volunteer Computing Systems Using SimGrid," in *Proc. of the Workshop on Large-Scale System and Application Performance*, Chicago, IL, Jun. 2010.
- [29] M. Chowdhury, M. Zaharia, J. Ma *et al.*, "Managing data transfers in computer clusters with orchestra," in *SIGCOMM*, 2011, pp. 98–109.
- [30] K. Christensen, P. Reviriego, B. Nordman *et al.*, "IEEE 802.3az: the road to energy efficient ethernet," *IEEE Communications Magazine*, vol. 48, no. 11, pp. 50–56, 2010.
- [31] L. Stanisc, S. Thibault, A. Legrand *et al.*, "Faithful Performance Prediction of a Dynamic Task-Based Runtime System for Heterogeneous Multi-Core Architectures," *Concurrency and Computation: Practice and Experience*, May 2015. [Online]. Available: <https://hal.inria.fr/hal-01147997>