

Shadow Computing

An Energy-Aware Resiliency Scheme for High Performance Computing

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ABSTRACT

Current fault-tolerance frameworks are designed to deal with both physical and logical fail stop errors and typically rely on the classic checkpoint-restart approach for recovery. The proposed solutions differ in their design, the type of faults they manage and the fault tolerance protocol they use. The major shortcoming of checkpoint-restart stems from the potentially prohibitive costs, in terms of execution time and energy consumption. Since faults are both voluminous and diverse, the inherent instability of future large-scale high performance computing infrastructure calls for a wholesale reconsideration of the fault tolerance problem and the exploration of radically different approaches that go beyond adapting or optimizing existing checkpointing and rollback techniques. To this end, we propose Shadow Computing, a novel energy-aware computational model to support scalable fault-tolerance in future large-scale high-performance computing infrastructure. We present three techniques for applying shadow computing to high performance computing: energy optimal replication, stretched replication, and minimum work replication. All of the proposed schemes provide the same fault-tolerance as pure replication while providing significant energy savings.

1. INTRODUCTION

To enable future scientific breakthroughs and discoveries, the next-generation of scientific applications will require exascale computing performance to support the execution of predictive models and the analysis of massive quantities of data, with orders of magnitude higher resolution and fidelity than what is possible in existing computing infrastructure [25, 18]. In order to deliver exascale computing and effectively harness its capabilities, several daunting scalability challenges must be addressed. In the late 90's, terascale performance was achieved with fewer than 10,000 single-core processors. A decade later, petascale performance required about 10 times as many processors as terascale performance.

If such trends continue, delivering exascale computing will require a million processors, each supporting 1000 cores, resulting in a billion-core computing infrastructure with a massive increase in the number of memory modules, communications devices and storage components. Beyond raw computing, communications and storage requirements, future exascale computing systems are faced with unprecedented energy and resiliency challenges.

Power consumption is widely recognized as one of the most significant challenges facing exascale computing [18, 25]. The expected energy consumption increase in exascale computing is staggering. If current trends hold true, an exascale computing system is expected to consume over a gigawatt of power. This represents a 10 fold increase in the energy consumption of today's largest data centers, which typically ranges between 100 and 200 Megawatts. Reducing the power consumption of an exascale computing system to the DoE's target of 20 Megawatts is undoubtedly a formidable challenge, with a pervasive effect on next generation scientific applications. Addressing such a challenge requires building power and energy awareness into the foundations of future exascale computing infrastructure, with "performance per watt" as the metric of merit to measure efficiency. Radical approaches must be developed to achieve efficient energy management across all hardware and software components of the system.

In addition to its impact on energy consumption, the upward trend in the number of computing nodes also has a direct negative effect on the overall system reliability. Even if the individual node failure rate is low, the overall system failure rate quickly becomes unacceptable as the number of components increases. For example, a computing system with 200,000 nodes will experience a mean time between failure (MTBF) of less than one hour, even when the MTBF of an individual node is as large as 5 years [24]. The dramatic decrease in system reliability as the number of computing nodes increases is depicted in Figure 1 [24]. Other factors are also expected to increase failure rates in exascale computing, including the expected high fault rates of advanced-technology computing components operating at lower voltage levels and the impact of undesirable aging effects as they become significant [26]. Addressing these concerns brings about unprecedented resiliency challenges, which puts in question the ability of next generation high performance computing to continue operation in the presence of faults

without compromising the requirements of the supported applications.

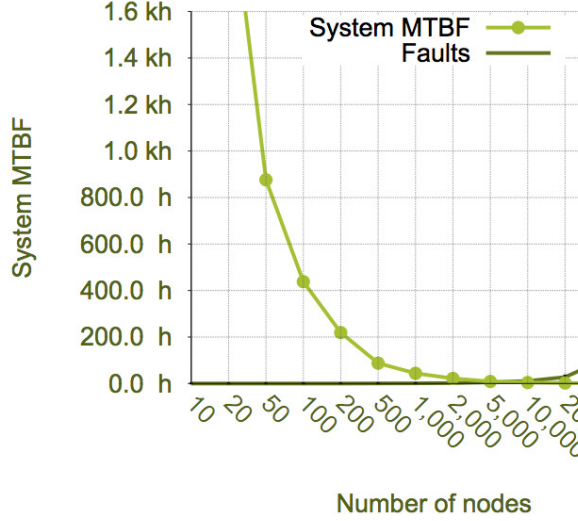


Figure 1: Effect on system MTBF as number of nodes increase.

The current response to faults consists of restarting the execution of the application, including those components of its software environment that have been affected by the occurring fault. To avoid the full re-execution of the failing application, fault-tolerant techniques typically checkpoint the execution periodically; upon the occurrence of a hardware or software failure, recovery is achieved by restarting the computation from a safe checkpoint. In some situations, however, several components of the software environment associated with the failed application may have to be restarted.

Given the anticipated increase in failure rate and the time required to checkpoint large-scale compute- and data-intensive applications, it is very likely that the time required to periodically checkpoint an application and restart it upon failure may exceed the mean time between failures. Consequently, applications may achieve very little computing progress, thereby reducing considerably the overall performance of the system. For example, a study carried out at Sandia National Laboratories focused on evaluating the overhead incurred by checkpointing in exascale computing environments. The results of the study, depicted in Figure 2, clearly show that beyond 50,000 nodes the application spends only a fraction of the elapsed time performing useful computation.

The main objective of this paper is to explore radically different paradigms to enable scalable resiliency with minimum energy consumption in the future exascale computing infrastructure. To this end, we propose a new energy-aware “shadow computing” model, as the basis for an efficient and

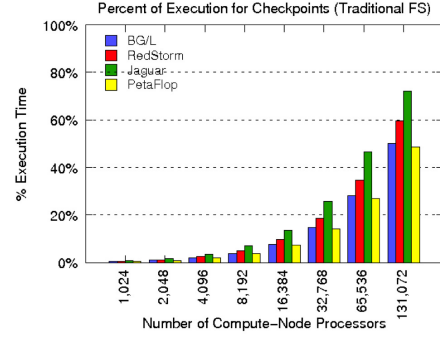


Figure 2: Percent of time to perform checkpoints.

scalable computational framework to achieve desired levels of fault tolerance, while minimizing energy consumption. The proposed model goes beyond traditional check-pointing and roll-back recovery techniques, and uses a multi-level, energy-aware replication approach to achieve scalable fault tolerance in exascale computing.

The basic idea of the shadow computing model is to associate with each process a suite of “shadow processes”, whose size depends on the “criticality” and performance requirements of the underlying application. A shadow is an exact replica of the main process. In order to overcome failure, the shadow is scheduled to execute concurrently with the main process, but at a different computing node. Furthermore, in order to minimize energy, shadow processes initially execute at decreasingly lower processor speeds. The successful completion of the main process results in the immediate termination of all shadow processes. If the main process fails, however, the primary shadow process immediately takes over the role of the main process and resumes computation, possibly at an increased speed, in order to complete the task. Moreover, one among the remaining shadow processes becomes the primary shadow process.

It is worth noting that, since the failure of an individual component is much lower than the aggregate system failure, it is very likely that most of the time the main processes complete their execution successfully. Successful completion of a main process automatically results in the immediate halting of its associated shadow processes, with a significant saving in energy consumption. Furthermore, the number of shadow processes to be instantiated in order to achieve the

desired level of fault-tolerance must be determined based on the likelihood that more one process failure within the execution time interval of the main task.

The main challenge in realizing the potential of the shadow computing model stems from the need to compute the speed of execution of the main process and the speed of execution of its associated shadows, both before and after a failure occurs, so that the target response time is met, while minimizing energy consumption. Given the nature of failure in exascale computing, it is unlikely that both the main and its primary shadow fail simultaneously. Therefore, only a dual level of redundancy, whereby only one shadow process is executed concurrently with the main process, is needed in most cases to achieve the desired level of fault-tolerance. The completion of a main or its shadow results in the successful execution of the underlying task.

The main contributions of this paper are threefold. First, we present an optimization framework to explore the applicability of the shadow computing model to support fault-tolerance in a high-performance computing environment, where the main computation is expected to execute at maximum speed in order to harness the full potential of the computing infrastructure. The model assumes that the desired level of fault tolerance can be achieved with the instantiation of a single shadow process, although the model can be extended to support multiple shadow processes.

Second, using the optimization framework, we propose and study three implementation methods of the shadow computing model. The first method, referred to as “stretched” replication, takes a straight-forward approach to minimizing energy by computing a uniform speed of execution across the execution interval. Although simple to implement, stretched replication is oblivious to the dynamics of the failure, resulting in sub-optimal energy performance. The second method, referred to as minimum-work replication, takes into consideration the minimum time between failures for a single node is likely to exceed the execution time of the task. Based on this observation, the method computes a near-optimal execution speed of the shadow. The third method, referred to as optimal energy replication, addresses shortcomings in these two models and uses an optimal energy-consumption approach to derive the shadow’s minimum-energy speed, both before and after failure, in order to meet the expected response time of the underlying application regardless of failure rates. It is worth noting that the implementation complexity of the optimal approach does not increase significantly in comparison with the stretched and minimum-work replication schemes.

Third, we propose a performance evaluation framework to assess the performance of the proposed methods for different workload characteristics and performance requirements of the main task. Throughout the study, the performance of the proposed shadow computing implementation methods are compared to that of the “pure” replication scheme described in [10]. The major difference between the methods proposed in this paper and current replication schemes is that shadow computing does not force the process replica to execute at the same speed as the main process. As the results of the performance study show, relaxing this restriction

allows shadow computing to save up to 50% of the expected energy consumed by pure replication.

The remainder of the paper is organized as follows: Section 2 reviews work related to fault-tolerance in large-scale high-performance computing systems. Section ?? presents the shadow computing model and discusses the building components of its execution model. Section 3 the shadow computing model is cast as an energy optimization problem to achieve fault-tolerance, while minimizing energy consumption without violating the expected performance requirements of the supported application. In Section 5 three different approaches to solving the energy optimization problem and their potential implementation are explored. The methods differ in their approach to energy minimization and their reaction to failures. In Section 5, we develop a performance evaluation framework to analyze and assess the performance of the three shadow computing methods, including their sensitivity to critical workload and performance parameters. Throughout the study, the performance of the three methods is compared to pure replication, a recently proposed alternative to check-pointing in exascale computing. Section 6 presents the conclusion of this work and discusses future work.

2. RELATED WORK

Checkpointing and rollback recovery are frequently used to deal with failures in computing systems. The process involves periodically saving the current state of the computation in a stable storage, with the anticipation that in case of a system failure computation can be rolled back to the most recent safely saved state before failure occurred [1, 5, 6, 9, 8, 13, 16, 17, 19, 20].

Approaches to distributed checkpointing differ in the level of process coordination required to construct a consistent global state, the size of the state, and the frequency at which checkpointing occurs [23, 27]. Based on independent checkpointing, processes coordination among processes is not required, thereby considerably reducing checkpointing overhead. At the occurrence of a failure, all processes resume computation from the most recent consistent global state [3, 5, 15, 21].

The major drawback of this approach stems from the potentially high computational cost incurred to roll-back to a consistent global state, assuming that such a state exists. This process typically requires deep analysis of the dependencies among the distributed computations to determine the existence of a roll-back state or the need to resume computations from their initial states.

Coordinated checkpointing, a widely used technique to deal with failures in distributed systems, requires coordination among processes to establish a state-wide consistent state [5]. The major benefit of this approach stems from its simplicity and ease of implementation, which lead to its wide adoption in high-performance computing environments. However, its major drawback is lack of scalability, since it requires concurrent checkpointing. Approaches have been proposed to reduce the level of coordination depending on the nature of the applications and the patterns of communications among processes [15].

In communication-induced checkpointing schemes, processes perform independent checkpoints to provide the basis for a system-wide consistent state [2, 4]. Although it reduces the coordination overhead, the approach may lead processes to store useless states that are never used in future rollbacks. To address this shortcoming, “forced checkpoints” have been proposed [14]. The approach, in most cases, reduces the number of useless checkpoints; it may, however, lead to unpredictable checkpointing rates.

Despite numerous improvements of the basic checkpointing scheme, recent studies show that high failure rates in high-performance computing systems, coupled with high checkpointing and restart overhead, considerably reduces the practical feasibility of existing centralized, hard disk drive centric checkpointing and rollback recovery schemes. Additionally, checkpointing techniques produce a significant amount of energy overhead [7] and therefore exascale computing requires new approaches.

Recently, redundant computing has been proposed as a viable alternative to checkpointing to handle fault-tolerance requirements of high-performance applications [10, 24]. Process replication, however, can be prohibitively costly in terms of computing resources and energy consumption. To the best of our knowledge, this is the first attempt to explore a state-machine-replication based framework to reduce energy while meeting the computational requirements of the underlying application.

In addition to its significant energy saving, shadow computing has potential to significantly increase an application’s mean time to interrupt (MTTI). This model can be further enhanced to allow for diversity through the execution of multiple shadow processes in different geographical environments, using different implementations of the underlying computation to potentially detect or correct faults that do not necessarily lead to abnormal termination of the process, but instead cause it to produce incorrect results.

3. ENERGY OPTIMIZATION MODEL

As stated previously, the basic idea of shadow computing is to associate a number of “shadow processes” with each main process. The main responsibility of a shadow process is to take over the responsibility of a failed main process and bring the computation to a successful completion. In this section, we define a framework for evaluating shadow computing and then use this to derive a model for representing the expected energy consumed by the system.

3.1 Shadow Computing Framework

The focus of this paper is on non-interactive batch jobs, such as scientific applications, financial analytics and image processing running on a cloud computing infrastructure. This class of applications is typically defined in terms of their workload, maximum resource consumption, and completion time, which varies from several hours to several days. They are usually delay tolerant and can be run anytime, as long as the target deadline is met. Each application is composed of a large number of collaborative tasks. The successful execution of the application depends on the successful completion of all of these tasks. Therefore, the failure of a single process delays the entire application, increasing the need for fault

tolerance. Each task must complete a specified amount of work, W , by a targeted response time, R . The amount of work is expressed in terms of the number of cycles required to complete the task. Each computing node has a variable speed, σ , given in cycles per second and bounded such that $0 \leq \sigma \leq \sigma_{max}$. Therefore the minimum response time for a given task is $R_{min} = W/\sigma_{max}$.

In order to achieve our desired fault tolerance a shadow process executes in parallel with the main process on a different computing node. The main process executes at a single execution speed denoted as σ_m . In contrast the shadow process executes at two different speeds, a speed before failure detection, σ_b , and a speed after failure detection, σ_a . This is depicted in Figure 3.

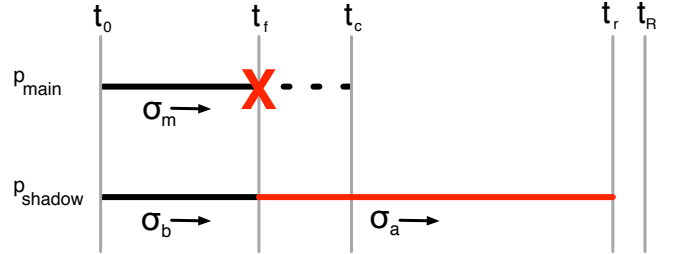


Figure 3: Overview of Shadow Computing

3.2 Power Model

Dynamic voltage and frequency scaling (DVFS) has been widely exploited as a technique to reduce CPU dynamic power [12, 22]. It is well known that by varying the execution speed of the computing nodes one can reduce their dynamic power consumption at least quadratically by reducing their execution speed linearly. The power consumption of a computing node executing at speed σ is given by the function $p_d(\sigma)$, represented by a polynomial of at least second degree, $p_d(\sigma) = \sigma^n$ where $n \geq 2$. In addition to the dynamic power, CPU leakage and other components (memory, disk, network etc.) all contribute to static power consumption, which is constant as long as the system is on. In this paper we use ρ to represent the weight of static power and $1 - \rho$ the weight of dynamic power, when the node is running at the maximum speed. Therefore, the power consumption is expressed as $p(\sigma) = \rho \times \sigma_{max}^n + (1 - \rho) \times \sigma^n$. The energy consumed by a computing node executing at speed σ during an interval of length T is given by $E(\sigma, T) = \int_{t=0}^T p(\sigma) dt$. For an interval during which the speed is constant, the energy consumption can be calculated as $p(\sigma)t$. Throughout this paper we assume that dynamic power is cubic in relation to speed, i.e., $p(\sigma) = \rho \times \sigma_{max}^3 + (1 - \rho) \times \sigma^3$. We further assume that the computing node speed is bounded by the following equation $0 \leq \sigma \leq \sigma_{max}$.

3.3 Failure Model

The failure can occur at any point during the execution of the main task and the completed work is unrecoverable. Because the processes are executing on different computing nodes we assume failures are independent events. We also assume that only a single failure can occur during the

execution of a task. If the main task fails it is therefore implied that the shadow will complete without failure. We can make this assumption because we know the failure of any one node is a rare event thus the failure of any two specific nodes is very unlikely. In order to achieve higher resiliency one would make use of multiple shadow processes and this failure model will still be valid.

We assume that a probability density function, $f(t)$ ($\int_0^\infty f(t)dt = 1$), exists which expresses the probability of the main task failing at time t . It is worth noting, that the lazy shadowing computation model does not depend on any specific distribution. However, in the remainder of this paper we use an exponential probability density function, $f(t) = \lambda e^{-\lambda t}$. Numerous works have studied the impact of DVFS on the failure rate or soft error rate [11, 28]. To take this effect into consideration, we adopt the most widely used model from [28] and expressed it within our framework as $\lambda(\sigma) = \lambda_0 10^{1-\sigma/\sigma_{max}}$.

3.4 Energy Model

Given the power model and the failure distribution, the expected energy consumed by a shadow computing task can be derived as the weighted average considering all possible cases. First consider the case where no failure occurs and the main process successfully completes the task at time t_c^m .

$$E_1 = (1 - \int_0^{t_c^m} f_m(t)dt) \times (1 - \int_0^{t_c^m} f_s(t)dt) \times (E(\sigma_m, t_c^m) + E(\sigma_b, t_c^m)) \quad (1)$$

The first line is the probability of fault-free execution of the main process and shadow process. Then we multiple this probability by the energy consumed by the main and the shadow process during this fault free execution, ending at t_c^m .

Next, consider the case where the shadow process fails at some point before the main process successfully completes the task.

$$E_2 = (1 - \int_0^{t_c^m} f_m(t)dt) \times \int_0^{t_c^m} (E(\sigma_m, t_c^m) + E(\sigma_b, t)) \times f_s(t)dt \quad (2)$$

The first factor is the probability that the main process does not fail, and the probability of shadow fails is included in the second factor which also contains the energy consumption since it depends on the shadow failure time. Energy consumption comes from the main process until the completion of the task, and the shadow process before its failure.

The one remaining case to consider is when the main process fails and the shadow process must continue to process until the task completes.

$$E_3 = (1 - \int_0^{t_c^m} f_s(t)dt) \times \int_0^{t_c^m} (E(\sigma_m, t) + E(\sigma_b, t) + E(\sigma_a, t_c^s - t)) f_m(t)dt \quad (3)$$

Similarly, the first factor expresses the probability that the shadow process does not fail. In this case, the shadow process executes from the beginning to t_c^s when it completes

the task. However, under our “at most one failure” assumption, the period during which shadow process may fail ends at t_c^m , since the only reason why shadow process is still in execution after t_c^m is that main process has already failed. There are three parts of energy consumption, including that of main process before main’s failure, that of shadow process before main’s failure, and that of shadow process after main’s failure, all of which depend on the failure occurrence time.

By summing these three parts we will have the expected energy consumed by shadow computing for completing a task.

$$E[\text{energy}] = (E_1 + E_2 + E_3) \quad (4)$$

3.5 Optimization problem formulation

Using the models above we formulate our objective as the following optimization problem.

$$\begin{aligned} \min_{\sigma_m, \sigma_b, \sigma_a} \quad & E[\text{energy}] \\ \text{s.t.} \quad & 0 \leq \sigma_m \leq \sigma_{max} \\ & 0 \leq \sigma_b \leq \sigma_m \\ & 0 \leq \sigma_a \leq \sigma_{max} \\ & t_m \leq t_R \\ & t_s \leq t_R \end{aligned} \quad (5)$$

The first three constraints represent the physical limit on the execution speeds. The last two constraints guarantee that the task can be completed by the target response time both with and without failure.

It should be noted that it is assumed that node failures are unchangeable system properties and task properties are given, therefore the system parameters we can change are the execution speeds of the processes. Thus, the output of this optimization problem is the execution speeds, σ_m , σ_b and σ_a .

4. APPLICATION TO HPC

One of the primary goals of high performance computing is to achieve the maximum possible throughput of the system. Thus when we apply shadow computing to this environment we assume that the execution speed of the main process should be the maximum possible execution speed, $\sigma_m = \sigma_{max}$. If no failure occurs then the task will be completed as soon as possible, known as the minimum response time. If the main process fails it is assumed that the task has some laxity as to when it will complete. The amount of laxity is bounded by the task’s targeted response time, which is the time at which the task must be completed regardless of failure. The targeted response time is typically represented as a laxity factor, α , of the minimum response time. For example if the minimum response time is 100 seconds and the targeted response time is 125 seconds, the laxity factor is 1.25.

We propose two different schemes for applying shadow computing to high performance computing.

- Energy Optimal Replication - Shadow execution speeds are those that minimize the consumed energy and guarantee completion by the targeted response time. This requires us to find σ_b and σ_a that solve Equation 5.
- Stretched Replication - Shadow execution is set to a single speed that guarantees completion by the targeted response time, $\sigma_b = \sigma_a = W/R$.

The remainder of this section discusses the solution to finding σ_b and σ_a for energy optimal replication.

The last constraint in Equation 5 requires that if the main process fails the shadow process must be able to complete the given work, W , by the targeted response time, R . The effect of this constraint on the execution speeds depends on the failure detection time t_f . Since σ_b would be set to slower to save energy, the larger t_f is, the less time is left for the shadow to catch up, and thus σ_a needs to be larger. To enforce this constraint for all possible values of t_f , we transform it to the following inequality:

$$t_c * \sigma_b + (R - t_c) * \sigma_{max} \geq W \quad (6)$$

The intuition for this constraint is that in the worst case the shadow will have to execute at the maximum possible speed after failure to achieve the targeted response time. This enforces the constraint such that if the main process fails at the very last time point, t_c , then the shadow process will still be able to complete the work by the targeted response time. This places a lower bound on the value for σ_b . With this modification, we can use the MATLAB Optimization Toolbox to solve Equation 5 and derive the optimal σ_m , σ_b , and σ_a .

5. ANALYSIS

With the analytical models developed in the previous sections, now we compare the energy savings among different fault tolerance approaches, i.e., lazy shadowing, stretched replication, and state machine replication. Without loss of generality, we assume the maximal execution rate is normalized such that $\sigma_{max} = 1$. The derived optimal execution rates are presented as fractions of the maximal execution rate.

During the experiments, we identified several critical parameters in the analytical models, which represents the characteristics of the task, and the underlying system. These parameters include:

- ρ – static power ratio, which determines how much power consumption is independent of the execution rate.
- W – workload of the task.
- MTBF – the reliability of the system that runs the task.
- α – the laxity in the response time that can be tolerated.

In the following, we will present our sensitivity study results with respect to the above parameters. In each of the sensitivity study, we normalize the energy consumption of lazy

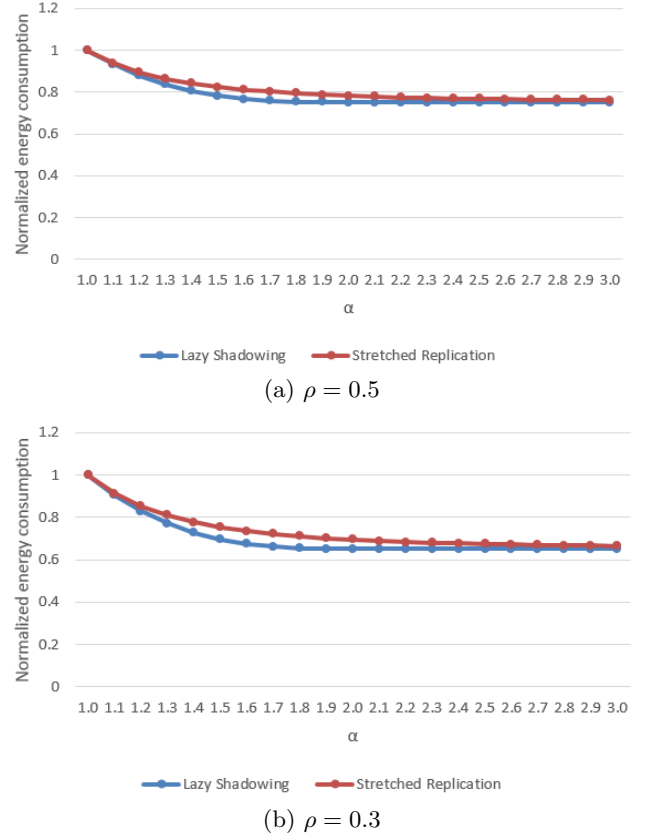


Figure 4: Energy consumption comparison for various response time laxity. $W=240$ hours, MTBF=5 years.

shadowing and stretched replication to that of state machine replication.

5.1 Response time laxity

Response time is always an important factor to consider in HPC as system efficiency is critical and high throughput is desirable. In the experiments we find that the energy savings of lazy shadowing and stretched replication versus traditional replication are largely impacted by the laxity in response time. This is mainly due to the fact that both of the proposed approaches rely on reducing the execution rates to save energy, while the laxity in response time determines how much the execution rate can be reduced. The results for $W = 240$ hours and MTBF=5 years are shown in Figure 4. Two values for ρ are used.

Figure 4 shows that both lazy shadowing and stretched replication can achieve over 20% of energy savings compared to state machine replication, when there is enough laxity in the response time. When there is no laxity in the response time ($\alpha = 1$), lazy shadowing and stretched replication don't have any freedom to reduce the execution rate of the shadow process, thus will execute both the main and shadow processes at the maximal execution rate, which essentially converges to state machine replication. In this case, it is straightforward that all three approaches have the same energy con-

sumption. However, as laxity in response time increases, lazy shadowing and stretched replication immediately gain the ability to slow down the shadow process and thus save energy. It is also clear that lazy shadowing has more potential than stretched replication in energy saving. It can take better advantage of the laxity in response time as it is more flexible in controlling the execution rate than stretched replication. The highest difference is 4.5% when α is around 1.5. As the laxity keeps increasing, the energy savings by lazy shadowing and stretched replication flatten out, as a result of the static power consumption. Since the static power consumption is independent of the execution rate, reducing the execution rate would extend the execution time, resulting in an increase in the energy consumption corresponding to the static power. Therefore, the minimal energy consumption would be achieved when there is a balance between energy from dynamic power and energy from static power, which may not be necessarily equivalent to using all the laxity in response time. It can be projected that if the static power ratio is lower, lazy shadowing and stretched replication can take advantage of more laxity and achieve more energy saving compared to state machine replication. This will be discussed further in later section. At the right side of Figure 4(a) and Figure 4(b), lazy shadowing and stretched replication converge when there is enough laxity for both of them.

5.2 Task vulnerability

The objective of lazy shadowing is to minimize the expected energy consumption, considering the characteristics of both the task to execute and the underlying system. The probability of failure during the execution of the task is an important factor that will impact how the proposed fault tolerance approaches execute the task. Specifically, they will choose different process execution rates according to the likelihood of failures. The ratio between the task workload and the MTBF is an approximation of the likelihood of failure, assuming task workload is far less than the MTBF. In our experiments, we find that there is a linear relationship between task workload and MTBF in determining the optimal execution rates. Specifically, increasing the task workload has the same effect as decreasing the MTBF in our analytical models. Therefore, we combine them as a single parameter and refer to it as task vulnerability.

The results of the sensitivity study to task vulnerability, when $W = 240$ hours and $\rho = 0.5$, are shown in Figure 5. From left to right, the task vulnerability decreases, meaning that the likelihood of failure decreases. We can see that for all task vulnerabilities considered, both lazy shadowing and stretched replication can achieve significant energy savings over state machine replication. This indicates that the proposed approaches are scalable to future large-scale and failure-prone HPC environments. As task vulnerability decreases, lazy shadowing and stretched replication gains more energy savings. This is because the probability that the main process can complete the task without failure increases when task vulnerability decreases, increasing the probability that the shadow process can be terminated early to save energy. Again, lazy shadowing outperforms stretched replication because of its more flexibility in controlling the execution rate of its shadow process.

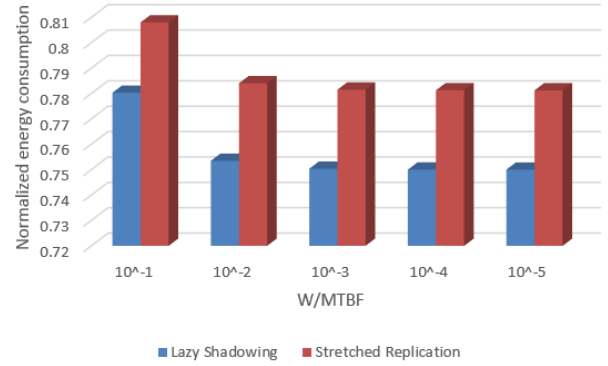


Figure 5: Energy consumption consumption for various task vulnerabilities. $W=240$ hours, $\rho=0.5$.

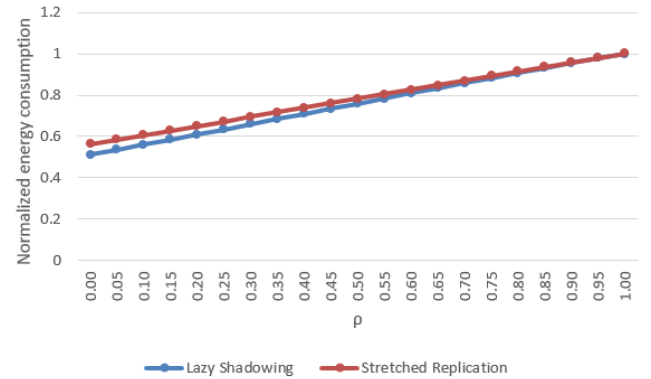


Figure 6: Energy consumption consumption for various static power ratios. $W=240$ hours, $\alpha=2$, MTBF=5 years.

5.3 Static power ratio

The computing nodes of each supercomputers have different power consumption characteristics, depending on the various computer organization and architecture technologies. Since our approaches are based on DVFS to control the process execution rates, the power consumption is partitioned into dynamic power, which has a superlinear relationship with the execution rate, and static power, which is unaffected by the execution rate. Static power ratio is an effective way to abstract the power saving ability of the proposed approaches on different machines.

DVFS saves dynamic power while not changing static power. These two aspects have conflicting effects on the total energy consumption. By reducing the execution rate, the execution time increases proportionally. This also increases the energy consumption from static power proportionally as the static power is constant. However, since the dynamic power can be reduced superlinearly, the energy consumption corresponding to dynamic power is reduced, even though the execution is extended. The above analysis can be illustrated with Figure 6. In addition, Figure 6 reveals that lazy shadowing can save up to 49% of energy over state machine replication when consider dynamic power only. On the other hand, lazy shadowing

owing and stretched replication are forced to execute both the main and shadow processes at the maximal rate when dynamic power is negligible, converging to the behavior of state machine replication. Current supercomputers have a static power ratio between 40%-70%, and it is reasonable to suspect that this will continue to be the case. Within this range, the energy saving is 14%-29% for lazy shadowing, and 13%-26% for stretched replication.

6. CONCLUSION

The major contribution of this paper is a new technique, called “shadow computing” that provides energy-aware fault tolerance in large-scale distributed computing environments. We also presented details on the shadow computing execution model and showed the feasibility of implementing such a system in distributed computing environment. We then explored different methods for applying this model to a high performance computing environment. Through this exploration we develop a general framework for evaluating the energy consumption of process replication schemes. Using this energy model we then analyzed our proposed solutions.

We proposed three different schemes for applying “shadow computing” to the high performance computing environment. Through evaluating the expected energy consumption of those schemes we showed that “shadow computing” has the ability to save significant energy. The energy savings is highly dependent upon the laxity available in the event of failure, represented as α in our analysis. We then showed that other factors such as component MTBF and task size have a minimum impact on the energy consumption. Furthermore, we demonstrated that simple, low-cost schemes such as stretched and minimum work replication can achieve near optimal behavior.

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