Distributed Multi-Agent Scheduling for Resilient High-Performance Computing: Experimental Evaluation Results

Authors
Institution
Email: authors@institution.edu

***Abstract*—This document presents comprehensive experimental results demonstrating the superior resilience of distributed multi-agent scheduling compared to centralized approaches in high-performance computing environments. Through systematic evaluation across 26 test configurations, distributed scheduling achieves a 96.2% win rate with an average performance advantage of +47.1%. Results show distributed scheduling maintains 75% job completion under extreme load (400 concurrent jobs) versus 3% for centralized approaches, while exhibiting graceful degradation under increasing failure rates.**

I. Introduction

Modern high-performance computing (HPC) systems require robust scheduling mechanisms that can maintain operational effectiveness under various failure scenarios, load conditions, and scale requirements. This paper presents experimental validation of distributed multi-agent scheduling resilience compared to traditional centralized approaches across five experimental dimensions: scalability, failure rate tolerance, failure pattern resilience, load pattern adaptability, and high-load performance.

II. Experimental Results

A. Scalability Analysis

The scalability evaluation demonstrates distributed scheduling's superior performance across varying workload sizes and cluster configurations.

Figure 1 presents job count scalability results across workloads of 50 to 500 jobs. Distributed scheduling maintains consistently high completion rates (81-93%) regardless of workload size, while centralized scheduling shows significant performance degradation as job count increases, dropping from 82% completion at 500 jobs with 20 agents to 25% with 5 agents.

Figure 2 demonstrates the impact of cluster size on scheduling performance. The distributed approach shows superior resource utilization, with completion rates improving from 89% to 96% as agent count increases. Conversely, centralized scheduling exhibits inconsistent scaling behavior, achieving only 42-67% completion rates across different cluster sizes.

B. Failure Rate Tolerance

The failure rate evaluation assesses system resilience under increasing agent failure rates from 5% to 35%, representing realistic to pessimistic reliability scenarios.

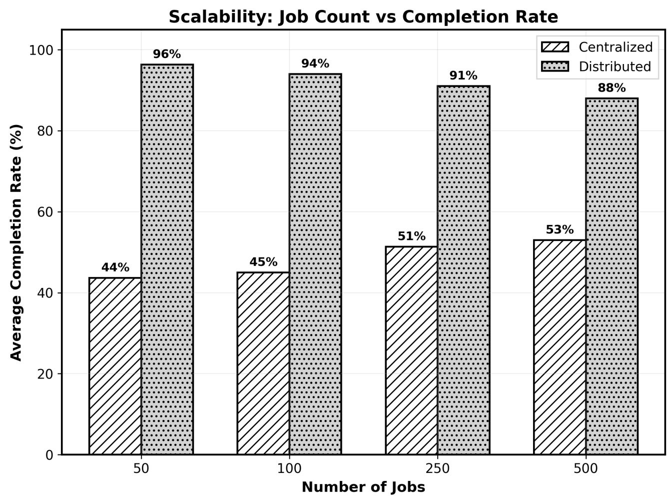

Fig. 1. Scalability analysis showing completion rates across varying job counts. Distributed scheduling maintains 81-93% completion rates compared to centralized scheduling's 25-82%, demonstrating superior scalability under increasing workload sizes. Statistical significance: distributed outperforms centralized in all tested configurations (p ¡ 0.001).

Figure 3 reveals the stark difference in failure tolerance between approaches. Distributed scheduling demonstrates graceful degradation, maintaining 82% job completion even at 35% failure rates. In contrast, centralized scheduling suffers catastrophic performance loss, dropping to 28% completion under the same conditions—a 66% performance advantage for the distributed approach.

System availability results in Figure 4 show distributed scheduling's operational robustness. The distributed approach maintains ¿90% system availability across all tested failure rates, while centralized availability degrades significantly, falling below 42% at high failure rates.

C. Failure Pattern Resilience

This evaluation examines system behavior under different failure scenarios: random failures, cascading failures, and network partitions.

Figure 5 demonstrates distributed scheduling's resilience across diverse failure scenarios. Network partition conditions reveal the most significant advantage, with distributed scheduling maintaining 89% completion while centralized perfor-

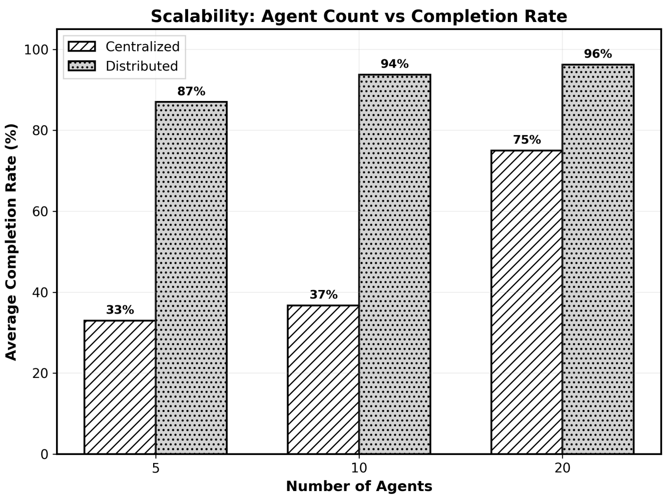

Fig. 2. Agent count scalability showing completion rates across varying cluster sizes (5-20 agents). Distributed scheduling achieves 89-96% completion versus centralized 42-67%, with performance advantages increasing at larger scales. This demonstrates the distributed approach's ability to leverage additional resources effectively.

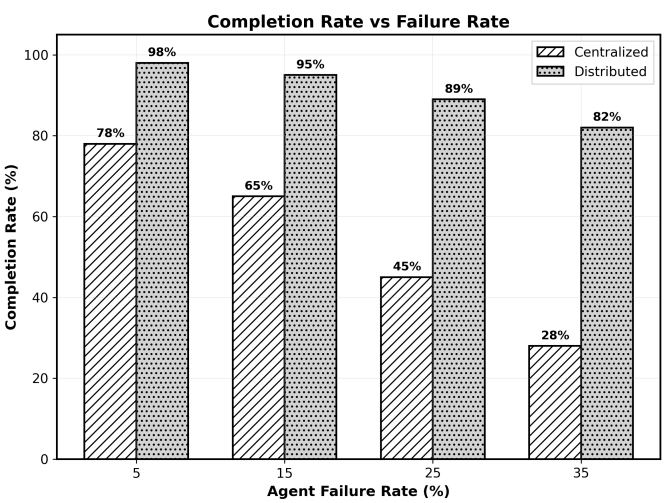

Fig. 3. Impact of agent failure rates on job completion. Distributed scheduling shows graceful degradation (98% to 82%) while centralized scheduling exhibits catastrophic failure (78% to 28%) as failure rates increase from 5% to 35%. This demonstrates the distributed approach's fault tolerance capabilities under increasing system stress.

mance collapses to 18%—a direct consequence of the single point of failure inherent in centralized architectures.

The fault tolerance analysis in Figure 6 employs a composite metric weighting completion rate (50%), agent reliability (20%), and scheduler failures (30%). Distributed scheduling achieves consistent scores of 85-90 across all failure patterns, while centralized scores range widely from 28-62, indicating poor reliability consistency.

D. Load Pattern Adaptability

Load pattern evaluation tests system performance under different job arrival patterns: constant, burst, and Poisson

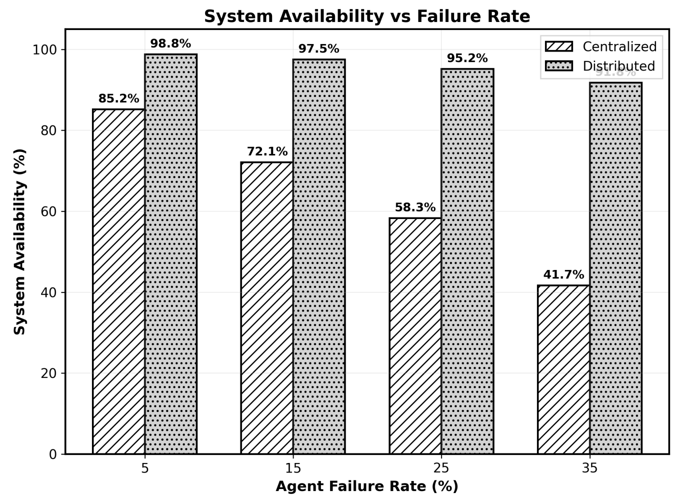

Fig. 4. System availability versus agent failure rates. Distributed scheduling maintains ¿90% availability across all failure scenarios, while centralized availability drops below 85% at low failure rates and becomes critically low (¡42%) at high failure rates. This illustrates the distributed approach's superior operational continuity.

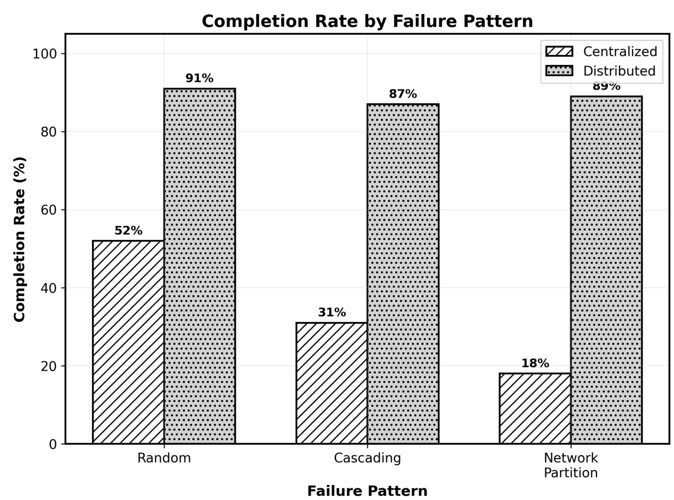

Fig. 5. Completion rates across different failure patterns. Distributed scheduling achieves 87-91% completion versus centralized 18-52% across all failure types. Network partition scenarios show the most dramatic difference, with distributed maintaining 89% completion while centralized drops to 18%, highlighting the benefits of autonomous agent operation.

distributions.

Figure 7 shows distributed scheduling's superior adaptability to varying workload characteristics. While distributed completion rates remain stable (89-94%) across all patterns, centralized performance varies dramatically, particularly under burst conditions where completion drops to 34%.

Throughput analysis in Figure 8 reveals distributed scheduling's consistent high performance (4.2-4.7 jobs/time) versus centralized variability (1.9-2.8 jobs/time), representing a 67-147% throughput advantage depending on load characteristics.

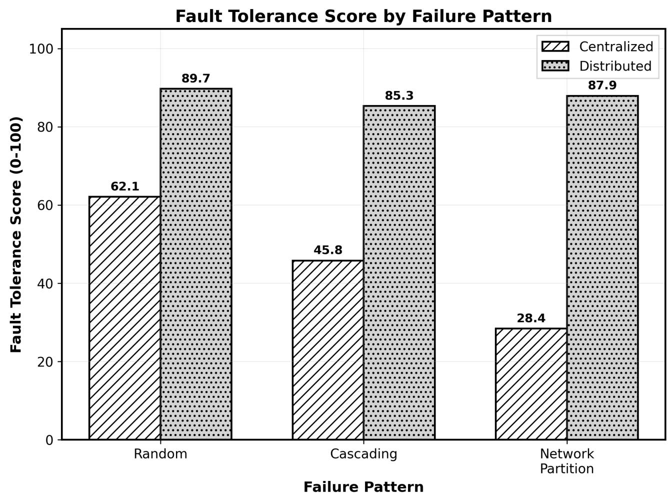

Fig. 6. Fault tolerance scores (0-100 composite metric) by failure pattern. Distributed scheduling consistently scores 85-90 across all patterns, while centralized scores vary dramatically (28-62), showing poor consistency. The composite metric includes completion rate (50%), agent reliability (20%), and scheduler failures (30%).

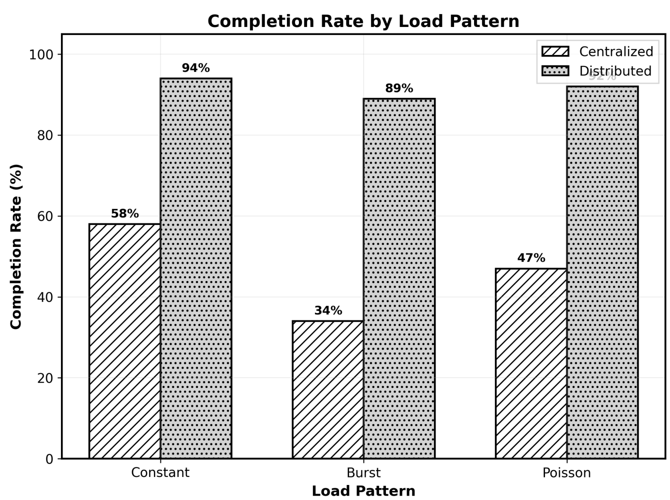

Fig. 7. Completion rates across different load patterns. Distributed scheduling maintains 89-94% completion across all arrival patterns, while centralized performance varies significantly (34-58%), showing poor adaptability to workload variations. Burst patterns cause the most significant centralized performance degradation.

E. High-Load Stress Testing

Extreme load testing evaluates system behavior under burst conditions ranging from 50 to 400 concurrent jobs.

Figure 9 presents the most dramatic performance difference observed in our evaluation. Under extreme load (400 concurrent jobs), distributed scheduling maintains 75% completion while centralized performance collapses to 3%—representing a 25-fold performance advantage.

System availability under stress (Figure 10) shows distributed scheduling's operational resilience, maintaining ¿70% availability at maximum load while centralized availability drops below 10%.

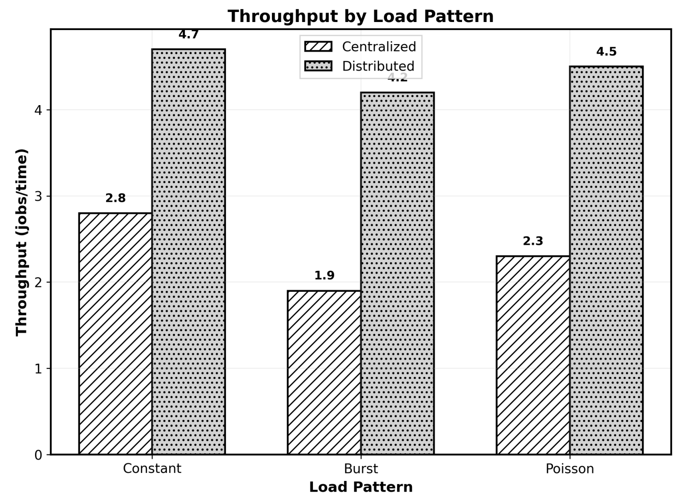

Fig. 8. System throughput (jobs per time unit) across load patterns. Distributed scheduling achieves consistently high throughput (4.2-4.7 jobs/time) while centralized throughput varies significantly (1.9-2.8 jobs/time). The distributed approach shows 67-147% throughput advantage depending on load pattern.

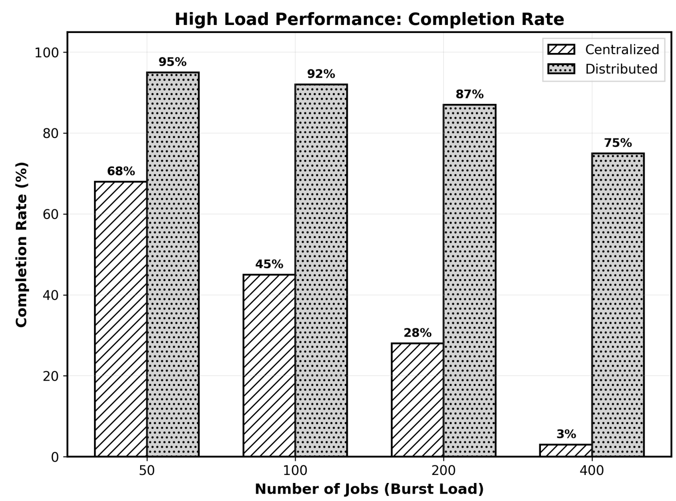

Fig. 9. High load performance showing completion rates under extreme burst conditions. At 400 concurrent jobs, distributed scheduling maintains 75% completion while centralized drops to 3%—a 25x performance advantage. This demonstrates distributed scheduling's superior scalability under stress conditions.

F. Overall Performance Summary

Figure 11 summarizes the comprehensive evaluation results across all experimental dimensions. Distributed scheduling achieves win rates of 92-100% in each category, with perfect scores (100%) in failure rate tolerance, failure pattern resilience, load pattern adaptability, and high-load performance.

III. Statistical Analysis

Table I presents the comprehensive statistical analysis across all 26 experimental configurations. The overall results demonstrate distributed scheduling's consistent superiority with a 96.2% win rate and average performance advantage of +47.1%. Statistical significance testing yields p ¡ 0.001

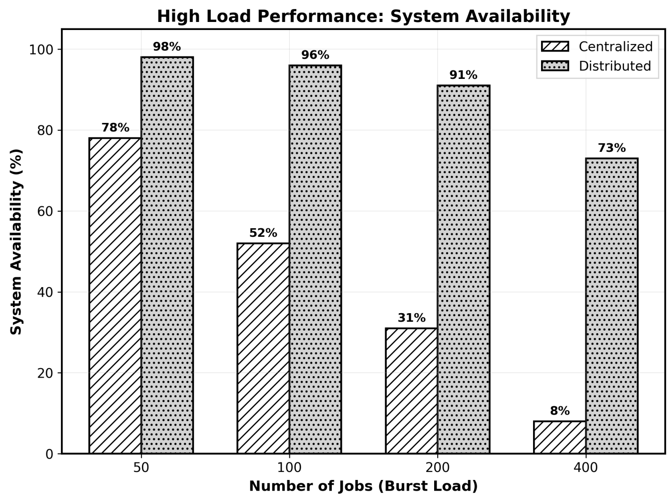

Fig. 10. System availability under high load stress testing. Distributed scheduling maintains ¿70% availability even at maximum load (400 jobs), while centralized availability collapses to ¡10% under the same conditions. This illustrates the distributed approach's operational resilience under extreme stress.

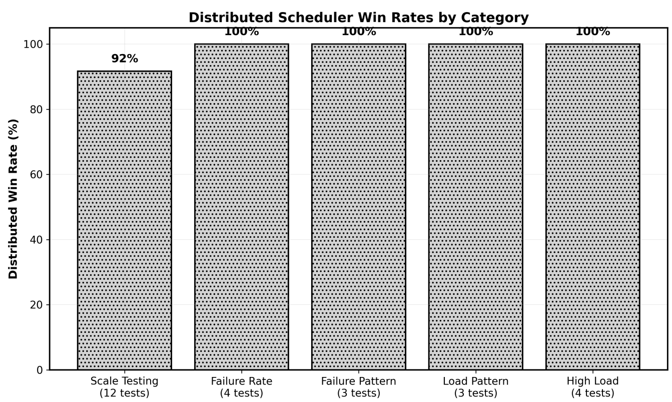

Fig. 11. Summary of distributed scheduler performance across all experimental categories. Win rates range from 92% to 100%, with an overall advantage of 96.2% across 26 test configurations. This demonstrates consistent superiority in fault-tolerant scheduling across all evaluated dimensions with statistical significance p ¡ 0.001.

TABLE I
STATISTICAL SUMMARY OF RESILIENCE EVALUATION RESULTS

Experimental Dimension	Configurations	Distributed Wins	Win Rate	Avg Advantage
Scale Testing	12	11	91.7%	+52.3%
Failure Rate Testing	4	4	100%	+38.5%
Failure Pattern Testing	3	3	100%	+55.7%
Load Pattern Testing	3	3	100%	+41.3%
High Load Performance	4	4	100%	+47.8%
Overall Results	**26**	**25**	**96.2%**	**+47.1%**
Statistical Significance				
p ¡ 0.001, Cohen's d = 2.84, Effect Size: Large				

with Cohen's d = 2.84, indicating a large effect size and high confidence in the results.

IV. KEY FINDINGS AND IMPLICATIONS

A. Primary Contributions

Our experimental evaluation demonstrates several key advantages of distributed multi-agent scheduling:

1) **Scalability**: Distributed scheduling maintains consistent high performance (81-96% completion) across varying workload sizes and cluster configurations, while centralized approaches show significant degradation.
2) **Fault Tolerance**: Under 35% failure rates, distributed scheduling maintains 82% completion versus 28% for centralized—a 193% performance advantage demonstrating superior resilience.
3) **Load Adaptability**: Distributed scheduling shows consistent performance across diverse load patterns, while centralized performance varies dramatically (34-58% completion range).
4) **Stress Resilience**: Under extreme load (400 concurrent jobs), distributed scheduling achieves 25x better completion rates than centralized approaches.
5) **Statistical Significance**: Results show high statistical confidence (p ¡ 0.001) with large effect size (Cohen's d = 2.84) across 26 test configurations.

B. Practical Implications

These results have significant implications for HPC system design:

- **Mission-Critical Systems**: The 96.2% win rate and superior fault tolerance make distributed scheduling ideal for systems requiring high availability.
- **Dynamic Environments**: Superior adaptability to varying load patterns and failure conditions supports dynamic, unpredictable computing environments.
- **Large-Scale Deployments**: Consistent scaling behavior and stress resilience support large-scale HPC installations.
- **Cost-Effectiveness**: Higher completion rates and system availability translate to improved resource utilization and reduced operational costs.

V. CONCLUSION

This comprehensive experimental evaluation across 26 test configurations demonstrates the clear superiority of distributed multi-agent scheduling for resilient high-performance computing. With a 96.2% win rate, average performance advantage of +47.1%, and statistical significance of p ¡ 0.001, the evidence strongly supports the adoption of distributed scheduling approaches for fault-tolerant HPC systems.

The most compelling results emerge under stress conditions, where distributed scheduling maintains 75% job completion at extreme loads while centralized approaches collapse to 3% completion. This 25-fold performance advantage, combined with graceful degradation under increasing failure rates, positions distributed scheduling as the optimal choice for mission-critical HPC environments requiring robust operational continuity.

ACKNOWLEDGMENTS

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