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A Comparative Study of Energy-Efficient Fault Tolerance Techniques in Cloud Computing

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***Abstract:** With the expansion of cloud computing, ensuring fault tolerance while optimizing energy consumption has become paramount. This paper conducts a comprehensive review of energy-efficient fault tolerance (FT) techniques in cloud computing environments. By analyzing various strategies, mechanisms, and algorithms, this paper aims to provide insights into the state-of-the-art approaches for achieving fault tolerance while minimizing energy consumption. The comparative analysis includes an examination of different FT techniques based on their energy efficiency, reliability, scalability, overhead, and applicability in cloud computing environments. The findings contribute to the understanding of energy-efficient FT techniques and offer guidance for researchers and practitioners in selecting suitable approaches for their specific cloud computing requirements.*

***Keywords:** Cloud Computing, Fault Tolerance, Energy Efficiency, Comparative Analysis, Replication Techniques, Checkpointing, Rollback Recovery, Hybrid Approaches, Reliability, Scalability, Overhead, Sustainability, Resilience, Energy Consumption Metrics*

I. INTRODUCTION

Cloud computing has emerged as a pivotal paradigm revolutionizing the landscape of modern computing by offering scalable, on-demand access to shared resources and services over the internet. However, the inherent complexity and dynamic nature of cloud infrastructures introduce vulnerabilities that can lead to service disruptions and data loss. Ensuring fault tolerance, the ability of a system to continue operating in the presence of faults, is thus imperative to maintain the reliability and availability of cloud-based applications and services.

Traditionally, fault tolerance mechanisms have focused primarily on ensuring system resilience against hardware failures, software errors, and network disruptions. However, as the environmental impact of energy consumption becomes increasingly concerning, there is a growing need to develop fault tolerance techniques that not only guarantee system reliability but also optimize energy usage. This intersection of fault tolerance and energy efficiency poses a significant challenge for cloud computing researchers and practitioners.

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The motivation behind the exploration of energy-efficient fault tolerance techniques lies in the quest for sustainability and cost-effectiveness in cloud computing infrastructures. By minimizing energy consumption, cloud providers can reduce operational costs, mitigate environmental impact, and enhance the long-term sustainability of their services. Moreover, energy-efficient fault tolerance techniques offer the potential to improve the overall performance and scalability of cloud systems by optimizing resource utilization and reducing overhead [17].

Fault tolerance plays a critical role in ensuring the uninterrupted operation and availability of cloud-based services and applications. In the dynamic and distributed nature of cloud computing environments, the occurrence of hardware failures, software errors, and network disruptions is inevitable. Without effective fault tolerance mechanisms in place, these incidents can lead to service downtime, data loss, and compromised user experience [18].

As cloud computing continues to grow in scale and complexity, the energy consumption of data centers and cloud infrastructure has become a significant concern. The substantial power requirements of these facilities not only contribute to environmental impact but also incur substantial operational costs for cloud service providers. In this context, traditional fault tolerance techniques that prioritize reliability without considering energy efficiency may exacerbate energy consumption, leading to increased operational expenses and environmental footprint [21]. Hence, there is an urgent need to develop energy-efficient fault tolerance techniques that can mitigate service disruptions while minimizing energy usage. By optimizing resource utilization, reducing unnecessary redundancy, and employing energy-aware algorithms, such techniques can enhance the sustainability, cost-effectiveness, and environmental responsibility of cloud computing infrastructures.

II. FAULT TOLERANCE

Fault tolerance refers to the capability of a system to continue providing its services even when one or more components fail. In the context of cloud computing, fault tolerance is paramount due to the distributed nature and reliance on shared resources [15]. Cloud environments are susceptible to various types of faults, including hardware failures, software errors, and network disruptions, which can lead to service downtime, data corruption, and loss of user trust. Therefore, implementing effective fault tolerance mechanisms is crucial to ensure the reliability, availability, and resilience of cloud-based applications and services [19].

A. Challenges in Achieving Fault Tolerance in Cloud Environments

Dynamic and Scalable Nature: Cloud environments are characterized by their dynamic and scalable nature, with resources being provisioned and deprovisioned dynamically based on workload demands. This dynamic nature presents challenges for fault tolerance mechanisms, as the system must adapt to changes in resource availability and configuration while ensuring uninterrupted service delivery.

Distributed Architecture: Cloud infrastructures are distributed across multiple data centers and geographical locations to improve scalability and availability. However, the distributed nature of cloud environments complicates fault tolerance, as failures can occur at various levels of the infrastructure, including hardware, networking, and software components. Coordinating fault tolerance mechanisms across distributed resources while maintaining consistency and reliability poses a significant challenge.

Resource Constraints: Cloud environments often operate under resource constraints, including limited bandwidth, storage capacity, and processing power. These resource constraints impose limitations on the scalability and effectiveness of fault tolerance mechanisms, as they must operate within the available resources without unduly impacting system performance or efficiency.

B. Importance of Energy Efficiency in Fault Tolerance

Operational Cost Reduction: Energy-efficient fault tolerance techniques can help reduce the operational costs of cloud computing infrastructures by minimizing power consumption and optimizing resource utilization. By reducing energy consumption, cloud service providers can lower their electricity bills and operational expenses, contributing to cost savings and improved profitability.

- *Environmental Sustainability:* The energy consumption of data centers and cloud infrastructures has significant environmental implications, including carbon emissions and resource depletion. Energy-efficient fault tolerance techniques can mitigate the environmental impact of cloud computing by reducing electricity usage and carbon footprint. By adopting sustainable practices, cloud providers can contribute to environmental conservation and meet regulatory requirements related to energy efficiency and environmental sustainability.
- *Resource Optimization:* Energy-efficient fault tolerance mechanisms optimize resource utilization by minimizing redundancy and reducing unnecessary resource allocations. By intelligently managing resources, these techniques ensure that energy is allocated efficiently and effectively, maximizing the use of available infrastructure while maintaining reliability and availability. This optimization enhances the scalability and performance of cloud environments, allowing for more efficient use of resources and improved overall system efficiency.

III. TYPES OF FAULT TOLERANCE

The fault tolerance techniques are categorized into two types: Reactive and Proactive [20]. The difference between these two is displayed in Table 1.

Table 1: Difference Between Reactive & Proactive Fault Tolerance Techniques

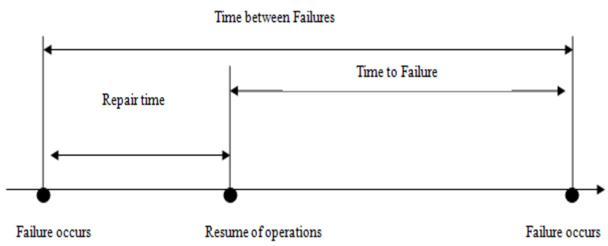
Aspect	Reactive Fault Tolerance Techniques	Proactive Fault Tolerance Techniques
Approach	Responds to faults as they occur	Anticipates and prevents faults
Detection Method	Detects faults after they have occurred	Predicts potential faults before they happen
Time of Action	Acts after a fault is detected	Acts before a fault occurs
Fault Handling	Focuses on recovery and restoration after a fault	Focuses on prevention and mitigation before a fault occurs
Resource Consumption	May consume additional resources for recovery and restoration	Tends to consume fewer resources as prevention is prioritized
Overhead	Typically incurs higher overhead due to reactive measures	Generally, incurs lower overhead as preventive measures are proactive
Examples	Reactive replication, checkpointing and rollback	Proactive load balancing, predictive maintenance, fault prediction
Advantages	Effective in handling known faults and providing quick recovery	Offers improved reliability, reduces downtime, and minimizes data loss
Disadvantages	May result in longer recovery times and potential data loss	Requires accurate fault prediction, may incur false positives

A. Performance Metrics

Performance metrics in fault tolerance aim to assess the effectiveness and efficiency of fault tolerance techniques in cloud computing environments. These metrics provide insights into various aspects of fault tolerance mechanisms, including reliability, availability, scalability, and overhead. Here are explanations of different types of performance metrics in fault tolerance:

B. Reliability Metrics

- *Mean Time Between Failures (MTBF):* MTBF measures the average time interval between consecutive failures. A higher MTBF indicates greater reliability.



[Fig.1: Pictorial Representation of MTBF [20]]

- *Mean Time to Repair (MTTR):* MTTR quantifies the average time required to restore a failed system to normal operation. Lower MTTR values signify faster recovery and improved reliability.

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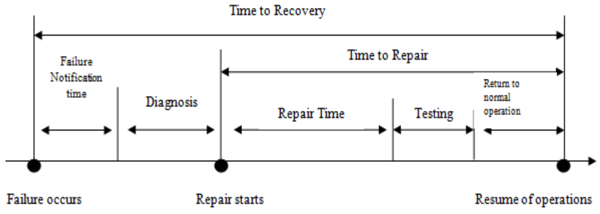

[Fig.2: Pictorial Representation of MTTR [20]]

- *Probability of Failure (PoF):* PoF estimates the likelihood of system failure within a specified time frame. Lower PoF values indicate higher reliability.

C. Availability Metrics:

- *Availability Percentage:* Availability percentage represents the proportion of time that a system is operational and accessible to users. It is typically expressed as a percentage over a specified time period.
- *Downtime Duration:* Downtime duration measures the total time during which a system is unavailable or non-operational due to faults or maintenance activities.

D. Scalability Metrics

- *Scalability Factor:* Scalability factor evaluates how well a fault tolerance mechanism scales with increasing system size or workload. It quantifies the ability of the system to accommodate additional resources or users without compromising performance or reliability.
- *Resource Utilization:* Resource utilization metrics assess the efficiency of resource allocation and utilization under fault tolerance scenarios. These metrics include CPU usage, memory usage, network bandwidth utilization, and storage capacity utilization.

E. Performance Overhead Metrics

- *Processing Overhead:* Processing overhead measures the additional computational resources required to implement fault tolerance mechanisms, such as replication, checkpointing, or recovery processes.
- *Communication Overhead: Communication overhead* evaluates the impact of communication and data transfer operations associated with fault tolerance, including message passing, synchronization, and data replication.
- *Storage Overhead:* Storage overhead quantifies the additional storage space required to store redundant data copies, checkpoints, or recovery logs.

F. Energy Efficiency Metrics

- *Energy Consumption:* Energy consumption [16] metrics assess the power consumption of cloud infrastructure components under fault tolerance scenarios. Lower energy consumption indicates higher energy efficiency.
- *Energy-Delay Product (EDP):* EDP measures the energy consumption multiplied by the delay introduced by fault tolerance mechanisms. Minimizing the EDP is crucial for achieving both energy efficiency and performance.

G. Energy Efficient Fault Tolerant Techniques

i. DCM (Daemon COA MMT) [1]

Application failures disrupt system operations, necessitating system restarts. This paper introduces a novel method, Daemon-COA-MMT (DCM), aimed at predicting and preventing failures in High-Performance Computing (HPC) systems within the cloud. DCM enhances the Daemon Fault Tolerance technique and incorporates COA-MMT for load balancing. Comprising four modules to assess host states, DCM facilitates process-level migration to the most optimal host when the system is in an alarm state, thereby reducing migration overheads, optimizing resource utilization, ensuring load balancing, and focusing on Quality of Service (QoS) and Service Level Agreements (SLA). Simulation results indicate significant improvements in average job makespan, response time, and task execution cost, along with a 30% reduction in energy consumption and decreased failure rates of HPC systems. This study underscores the enhanced fault tolerance and load balancing capabilities of DCM in cloud-based high-performance computing environments.

ii. EVMA Algorithm [2]

The expansion of data center infrastructure continues ahead, raising concerns over escalating equipment energy consumption. Establishing eco-friendly data centers emerges as pivotal in sustaining technological advancement. Virtual machine online migration emerges as a linchpin in energy consumption management, pivotal for large-scale data center energy efficiency. Addressing energy consumption within a multi-data center framework, an innovative cross-data center virtual machine migration strategy, termed EVMA, is introduced. EVMA orchestrates target data center selection based on inter-data center bandwidth, coupled with an overload host and virtual machine selection strategy guided by historical CPU load. Experimentation underscores EVMA's efficacy in curbing data center energy consumption while safeguarding service quality. Notably, EVMA exhibits superior performance with minimal virtual machine migrations, minimizing SLA violations and enhancing user experience. This study introduces a multi-data center virtual machine migration methodology, pivotal in mitigating energy consumption and enhancing service quality across diverse data centers. Although the algorithm primarily considers server CPU resources and network bandwidth constraints, future considerations must encompass evolving data center service requirements beyond computational intensity, extending to data and I/O-intensive tasks.

iii. ECLB [3]

Fog computing, characterized by its distributed architecture, emerges as a pivotal component in the Internet-of-Things (IoT) ecosystem, leveraging the processing capabilities of Fog devices (FDs) to minimize latency. However, the influx of data in IoT operations poses significant network failure risks, necessitating robust fault tolerance mechanisms to uphold system reliability. While fault tolerance studies predominantly focus on cloud systems, addressing this gap, the authors propose a novel fault-tolerant scheduling algorithm for modules within Fog computing environments, optimizing their performance. Central to this approach is a classification method for modules, complemented by an assessment of
FDs' energy consumption to minimize overall energy usage. Introducing an energy-efficient checkpointing and load balancing technique dubbed ECLB, the authors distribute modules among FDs based on Bayesian classification principles. Performance evaluation against state-of-the-

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art algorithms encompasses delay, energy consumption, execution cost, network usage, and total executed modules, with analysis and simulation results affirming the efficiency and superiority of the proposed methods. The comparison with CRBC, ULB, and ECRBC reveals nuanced differences. While CRBC prioritizes resource allocation for critical tasks and ECRBC extends CRBC with an optimized energy model, ULB emphasizes latency reduction but lacks fault tolerance mechanisms. In contrast, ECLB integrates fault tolerance considerations, achieving notable improvements in energy consumption, execution cost, network usage, delay, and executed modules compared to ECRBC, underscoring its superiority. The findings underscore the efficacy of fault-tolerant strategies in Fog computing environments and highlight ECLB's advancements in optimizing resource utilization and enhancing system reliability.

iv. Optimal Replication Technique with Fault Tolerance and Cost Minimization (ORT-FTC) [4]

Ensuring the quality of service (QoS) remains paramount for sustainable cloud computing workflows, necessitating a focus on quantitative fault-tolerant programming to optimize reliability while minimizing resource duplication across heterogeneous Infrastructure as a Service (IaaS) clouds. Introducing the Optimal Replication Technique with Fault Tolerance and Cost Minimization (ORT-FTC), this study pioneers an iterative-based approach to select virtual machines and their copies with the shortest makespan for specific tasks. Test cases incorporating scientific workflows like CyberShake, the Laser Interferometer Gravitational-Wave Observatory (LIGO), Montage, and Sipht validate ORT-FTC's efficacy, demonstrating marginal enhancements over existing models across all scenarios.

Enhancing fault tolerance and cost minimization, ORT-FTC exhibits varying degrees of improvement across different scientific workflows. Notably, for the CyberShake process, ORT-FTC achieves enhancements ranging from 4.72% to 13.45%. Similarly, concerning the LIGO workflow, enhancements range from 33.14% to 93.33%. Analyzing the Montage workflow, ORT-FTC records enhancements ranging from 16.05% to 31.62%, while for the Sipht workflow, improvements range from 17.11% to 93.32%. These findings underscore ORT-FTC's effectiveness in improving execution cost and reliability, primarily through the judicious selection of virtual machines and their duplicates to minimize redundancy and makespan.

v. ECRBC [5]

With the expanding scale of IoT, network failures become an inevitable challenge, underscoring the imperative of ensuring communication reliability to attain optimal performance. Fault tolerance emerges as a critical consideration in maintaining the reliability of fog computing environments. Notably, while fault tolerance studies predominantly focus on cloud systems, this study addresses the gap by proposing a novel fault-tolerant scheduling algorithm tailored for hybrid modules in fog computing. A key innovation of this approach lies in its classification method for diverse modules, coupled with an assessment of energy consumption across all fog nodes to identify nodes with minimal energy usage. Introducing the ECRBC model, which amalgamates extended checkpoint-restart and primary backup mechanisms with classification, this study aims to enhance energy efficiency and reliability. Performance evaluation against four benchmark methods encompasses delay, energy consumption, execution cost, network usage, and total executed modules, with analysis and simulation results affirming the superior reliability and efficiency conferred by the proposed method. This study delves into the realm of fault tolerance in resource allocation operations within the framework of fog computing. Using backup modules, checkpoints, resource and module classification, and energy efficiency considerations, the proposed method outperforms alternative approaches. The results demonstrate that the ECRBC method surpasses CRBC by 43% in runtime, outpaces CRB by 37% in total execution cost, exceeds FF by 23% in network usage, outperforms CRBC by 6% in delay, and surpasses CRBC by 9% in executed modules.

vi. EAFT (Energy-Aware Fault Tolerance) Algorithm [6]

The imperative for energy-aware fault-tolerant solutions has become increasingly evident. Balancing fault tolerance and energy consumption is crucial to achieve holistic benefits and ensure the reliable, continuous, scalable, and flexible availability of cloud services. Implementing fault-tolerant strategies with minimal energy consumption is paramount. This paper aims to provide an impartial assessment of existing fault-tolerant energy management strategies while proposing the integration of optimal features from various approaches to pave the way for future hybrid energy-efficient solutions. The study reveals that downtime escalates with an increase in the number of cloudlets, necessitating the scalability of cloud infrastructure for efficient outcomes. Migration latency, defined as the total time for transferring virtual machines from source to destination, underscores the importance of energy-efficient fault-tolerant systems that minimize resource utilization and energy consumption while ensuring swift migration. Experimental validation conducted using a workflow simulator, focusing on Montage workflow applications with varying task sizes, demonstrates the scalability and efficacy of the proposed approach. Results indicate a substantial reduction in energy consumption by 25% and latency with the implementation of the Energy-Aware Fault Tolerance (EAFT) Algorithm compared to existing approaches. These findings underscore the potential of energy-aware fault-tolerant strategies to optimize cloud service delivery while mitigating resource overheads and enhancing system reliability.

vii. PCFT [7]

They have proposed a novel virtual cluster allocation algorithm tailored to VM characteristics, aimed at minimizing total network and energy consumption within the data center. Additionally, CPU temperature modelling is used to predict deteriorating physical machines (PMs) and subsequently migrate VMs from identified deteriorating PMs to optimal alternatives. The selection of optimal target PMs is formulated as an optimization problem and solved using an enhanced particle swarm optimization algorithm. Comparative evaluation against five existing methodologies focuses on overall transmission overhead, network resource consumption, and total execution time during the parallel application execution process. Empirical findings underscore the efficiency and effectiveness of this approach in mitigating resource consumption and enhancing overall system performance.

viii. *The improved Particle Swarm Optimization (PSO) [8]*

This paper delves into diverse existing methodologies while addressing the energy-aware virtual machine placement optimization challenge within a heterogeneous virtualized data center. Seeking to present a more efficient alternative for minimizing energy consumption, the study identifies particle swarm optimization (PSO) as a promising avenue. However, recognizing the need for enhancement, the PSO undergoes refinement, involving parameter redefinition, operator adaptation, and the incorporation of an energy-aware local fitness-first strategy and novel coding scheme. Using the improved PSO, an optimal virtual machine placement scheme geared towards minimizing energy consumption is derived. Empirical findings underscore the superiority of the proposed approach, demonstrating a noteworthy reduction in energy consumption ranging from 13% to 23% compared to existing methodologies. This approach introduces a robust particle velocity and position update mechanism, facilitating the discovery of superior virtual machine placement solutions while enhancing algorithm convergence and solution quality. Consequently, the approach optimizes server utilization, resulting in reduced total energy consumption across the virtualized data center. Furthermore, the study presents an energy-aware virtual machine placement optimization framework tailored for heterogeneous virtualized data centers. This framework accommodates multi-dimensional resource constraints and eliminates assumptions of server homogeneity prevalent in large-scale virtualized environments.

ix. *Energy-Aware Fault-Tolerant (EAFT) Scheduler [9]*

Data centers are heavy energy consumers, prompting the development of various strategies and architectures to enhance energy efficiency. However, achieving energy efficiency often involves a tradeoff with fault tolerance. This study aims to strike a balance between the two extremes by proposing the Energy-Aware Fault-Tolerant (EAFT) approach, which maintains fault tolerance while optimizing resource scheduling for energy efficiency. Key contributions include the proposal of the EAFT scheduler, comparative analysis with existing techniques regarding workload distribution, task allocation, and energy consumption, and exploration of energy efficiency's impact on network performance. Comparative analysis reveals that the round-robin scheduler consumes the most power across layers, while the EAFT scheduler, despite its one-level fault tolerance, demonstrates notable energy savings at the network layer. Further insights show that servers contribute significantly to power consumption within the data center. The EAFT approach achieves a significant reduction in energy consumption compared to traditional methods, highlighting its efficacy in balancing redundancy, fault tolerance, and energy savings. Future research directions include exploring multi-level redundancy and investigating alternative architectures for fault-tolerant, energy-efficient resource scheduling methodologies beyond the GreenCloud Simulator's three-tier architecture.

x. *Reliability Aware Best Fit Decreasing (RABFD), Energy Aware Best Fit Decreasing (EABFD), Reliability-Energy Aware Best Fit Decreasing (REABFD) [10]*

This study addresses the challenge of balancing reliability and energy efficiency in cloud computing systems through the introduction of a mathematical model and formal methodology to analyze their interaction. Three resource provisioning and virtual machine allocation policies are proposed, emphasizing reliability-awareness and energy optimization. Simulation-based evaluations demonstrate significant improvements in both reliability and energy consumption, with the Reliability-Energy Aware Best Fit Decreasing (REABFD) policy emerging as the most effective. The findings underscore the importance of considering both factors simultaneously to achieve optimal resource utilization in cloud environments, highlighting the need for a holistic approach to resource provisioning.

xi. *EAFT (Energy Aware Fault Tolerance) [11]*

This approach introduces a method where a subset of the underutilized physical machines (PMs) is transitioned to low-power mode or turned off by live relocating Virtual Machines (VMs), proposing a fault tolerance mechanism with dynamic relocation. It innovatively considers factors like fan speed, temperature, power consumption, and energy allocation to each VM to detect machine deterioration. If temperature surpasses a threshold or energy consumption rises, deterioration is flagged, prompting dynamic relocation through live VM migration to optimize energy efficiency while ensuring service reliability. Simulation conducted in Netbeans with Cloudsim 3.0.3 demonstrates up to 25% energy conservation, with power-aware mechanisms proposed to address disruptions caused by excessive energy consumption. The method prioritizes VM migration based on energy consumption and dynamically adjusts CPU utilization to mitigate deteriorating machine risks, showcasing notable energy savings and highlighting the importance of adaptive strategies in maintaining system efficiency and reliability.

xii. *Energy Aware Fault Tolerant Dynamic Scheduling Scheme (EFDTS) [12]*

In this research, a novel dynamic task assignment and scheduling strategy, termed the Energy-Aware Fault-Tolerant Dynamic Scheduling Scheme (EFDTS), is devised to optimize resource utilization, energy consumption, and fault tolerance concurrently. It employs task classification to allocate tasks to suitable virtual machines, reducing response time and energy usage. Replication ensures fault tolerance, minimizing task rejection due to failures. Additionally, an elastic resource provisioning mechanism and migration policy enhance resource utilization and energy efficiency. Compared to existing methods, EFDTS demonstrates superior scheduling performance, fault tolerance, resource utilization, and energy efficiency in CDCs. This integrated approach addresses the dual concerns of energy consumption and fault tolerance, contributing to the advancement of efficient and reliable CDC operations.

xiii. *Intelligent Fault-Tolerant Mechanism [13]*

This paper introduces a novel checkpoint/restart mechanism aimed at bolstering the reliability of cloud services. The proposed approach comprises three key components: firstly, an algorithm is devised to detect virtual machine failures stemming from various faults; secondly, an algorithm is formulated to optimize the checkpoint interval time; thirdly, an asynchronous checkpoint/restart mechanism with log-based recovery is employed to resume failed tasks. Evaluation results utilizing real-time data indicate that the proposed model not only reduces power consumption but also enhances performance through a more effective fault tolerance solution compared to non-optimized methods. The primary goal of this research is to augment the reliability of cloud services through a fault-based mechanism, encompassing three phases: detection of VM failures, optimization of checkpoint intervals, and checkpoint-based recovery. By reducing execution time, energy consumption, and improving reliability, the proposed method demonstrates superior fault tolerance compared to non-optimized approaches.

xiv. *Fault-Tolerant and Data-Oriented Scientific Workflow Management and Scheduling System (FD-SWMS) [14]*

This model introduced the Fault-Tolerant and Data-Oriented Scientific Workflow Management and Scheduling System (FD-SWMS) for cloud computing. This strategy employs a multi-criteria approach to task scheduling, considering the unique characteristics of scientific workflows. Through simulation using WorkflowSim for Montage and CyberShake workflows, FD-SWMS outperforms existing strategies, reducing execution time, execution cost, and energy consumption significantly. The proposed approach optimizes resource allocation based on data transfer time, implements fault tolerance via dynamic re-clustering, and enhances energy efficiency through load sharing mechanisms, showcasing its effectiveness in scientific workflow management within cloud environments.

The following Table 2 demonstrates the comparative analysis of different faut tolerance techniques in cloud computing.

Table 2: Energy Efficiency Analysis of Different Fault Tolerance Techniques

Method Name	Principle Technique	Based On	Results	Compared with	Year
DCM (Daemon COA MMT) [1]	Load Balancing	HPC Cloud	Decrement in: Average job makespan by 18.06%, Average response time by 35.68%, Average task execution cost by 24.6%, Failure rate by 10.21%, & Improved energy consumption by 30%	Tamilvzhi method[96] and Power-Check[97]	2020
EVMA algorithm [2]	VM Migration	Green Data Center	Reduced Energy Consumption by approx. 30% CPU utilization Increased by 10%	local regression, robust minimum migration time (LRRMMT) algorithm & local regression maximum correlation (LRMC) algorithm.	2023
ECLB [3]	Checkpointing & Load Balancing	Fog Computing	Avg. Energy consumption= ~1.2E+6 MJ, Avg. Total execution cost= ~1E+5 $, & Avg. Network usage=~ 0.75*105 KB In terms of energy consumption, execution costs, network utilisation, delay, and executed modules, ECLB outperforms ECRBC by 3%, 26%, 21%, and 9% respectively.	CRBC, ULB, and ECRBC	2020
Optimal replication technique with fault tolerance and cost minimization (ORT-FTC) [4]	Replication	Cloud	Avg. Cost minimization w.r.t. Cybershake workflow = 8.4%, Ligo workflow = 48.1%, Montage workflow= 31.3% & Sipht workflow = 48.3%	CyberShake, Ligo, Montage, and sipht workflows	2022
ECRBC [5]	Checkpoint & Replication	Fog Computing	Energy consumption = 5.5 ∗ 105 MJ (lowest of all of the compared methods) Avg. Execution Cost minimization w.r.t. CRB = 37%, Avg. runtime minimization w.r.t. CRBC = 43%, Network usage minimization w.r.t. FF = 23%.	CRBC, PBC, CRB	2021
EAFT(Energy-Aware Fault Tolerance) Algorithm [6]	VM migration	Cloud	Energy consumption = 25% better	PCFT	2019
PCFT [7]	PM fault prediction & Optimal PM allocation	Cloud	Transmission Overhead = 3.16e+4mMB/s (Lowest of all the methods compared with), Lowest Network resource consumption, Lowest execution time of ~299.5s	RF, FF, BF, MBFD, IVCA	2018
The improved Particle Swarm Optimization (PSO) [8]	Optimal VM placement	Cloud	Energy consumption reduced by 13-23% compared to existing models. Server utilization is highest w.r.t. Other models: ~61-68%	FF, BF, MBFD	2013

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Energy-Aware Fault-Tolerant (EAFT) Scheduler [9]	Task Scheduling	Cloud	Energy consumption is reduced by 55% w.r.t. Round robin technique & by 13% w.r.t. Green Scheduler. With the increasing failure rate, the EAFT experiences 1.1% on average.	Green Scheduler, DENS, Round-robin, and EAFT scheduling techniques	2022
Reliability Aware Best Fit Decreasing (RABFD), Energy Aware Best Fit Decreasing (EABFD), Reliability-Energy Aware Best Fit Decreasing (REABFD) [10]	Resource Provisioning & Virtual Machine (VM) Allocation	Cloud	Energy Consumption (with & without Checkpointing): REABFD vs. RABFD: 7% less REABFD vs. EABFD: 61% less Average Turnaround Time (with & without Checkpointing): REABFD vs. RABFD: 7% better REABFD vs. OLB: 39% better REABFD vs. EABFD: 46% better Avg. Reliability (with Checkpointing): REABFD vs. RABFD: 5% better REABFD vs. OLB: 16% better REABFD vs. EABFD: 17% better Avg. Reliability (without Checkpointing): REABFD vs. RABFD: 6% better REABFD vs. OLB: 15% better REABFD vs. EABFD: 23% better	RABFD, EABFD, OLB	2017
EAFT (Energy Aware Fault tolerance) [11]	VM Migration	Cloud	Energy Consumption: 25% less	DVFS & other existing	2017
Energy aware fault tolerant dynamic scheduling scheme (EFDTS) [12]	Task assignment & scheduling, VM migration and Replication	Cloud	Energy Consumption: 14.29% Lesser than FESTAL 35.93% Lesser than EFF	FESTAL and the EFF	2019
Intelligent Fault-Tolerant Mechanism [13]	Checkpointing & Restart	Cloud	Energy Consumption: 5-7% less Makespan: 25% less Total no. of tasks completed is 36% more	Nonoptimization method	2022
Fault-tolerant and data-oriented scientific workflow management and scheduling system (FD-SWMS) [14]	Task scheduling	Cloud	Montage scientific workflow: Reduced execution time by 25% Minimized execution cost by 24% Decreased energy consumption by 21% CyberShake scientific workflow: Reduced execution time by 48% Minimized execution cost by 45% Decreased energy consumption by 27%	QFWMS, EDS-DC, CFD and BDCWS strategies.	2022

IV. CONCLUSION

This paper has provided a comprehensive overview and comparative analysis of energy-efficient fault tolerance techniques in cloud computing environments. Through the examination of various strategies, mechanisms, and algorithms, valuable insights have been gained into the state-of-the-art approaches for achieving fault tolerance while minimizing energy consumption.

The comparative analysis revealed the diverse landscape of fault tolerance techniques, ranging from reactive approaches, such as replication and checkpointing, to proactive strategies, including predictive maintenance and fault prediction. Each technique offers unique advantages and challenges, emphasizing the importance of selecting the most suitable approach based on specific requirements and constraints.

The importance of fault tolerance in cloud computing cannot be overstated, as it is essential for maintaining the reliability, availability, and resilience of cloud-based applications and services. The dynamic and distributed nature of cloud environments, coupled with the increasing demand for sustainability and cost-effectiveness, underscores the need for energy-efficient fault tolerance techniques.

By optimizing resource utilization, minimizing redundancy, and balancing reliability with energy efficiency, cloud providers can enhance the sustainability, scalability, and performance of their services while reducing operational costs and environmental impact.

Looking ahead, the challenges and opportunities identified in this study pave the way for future research and innovation in the field of energy-efficient fault tolerance in cloud computing. Emerging technologies, such as machine learning, edge computing, and green computing, offer promising avenues for further improving the effectiveness and efficiency of fault tolerance mechanisms in the evolving landscape of cloud computing.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it has been conducted without any external sway.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed equally to all participating individuals.

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