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Energy-Aware Hybrid Quantum–Classical Space Data Center Architecture Using Bio-Inspired Resource Optimization

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***Abstract*--The increasing demand for space-based computing requires intelligent and energy-efficient resource management for future space data centers. This paper proposes a conceptual Energy-Aware Hybrid Quantum–Classical Space Data Center Architecture Using Bio-Inspired Resource Optimization. The framework integrates classical computing, Quantum Processing Units (QPUs), bio-inspired optimization, and energy-aware scheduling into a unified architecture. An intelligent task classification module assigns workloads to either classical or quantum processors based on computational requirements. The bio-inspired optimization algorithm dynamically allocates resources to minimize energy consumption and improve resource utilization. The energy-aware scheduler further enhances system performance by considering execution time, workload priority, and available energy. Conceptual analysis indicates that the proposed architecture has the potential to improve scheduling efficiency, computational performance, and sustainability in space computing environments. The framework provides a foundation for future simulation and implementation of hybrid quantum–classical resource management in next-generation space data centers.**

***Keywords-- Hybrid* Quantum–Classical Computing, Space Data Centre, Energy-Aware Computing, Bio-Inspired Optimisation, Resource Scheduling, Cloud Computing, Green Computing, Quantum Processing Unit (QPU), Artificial Intelligence, Sustainable Data Centres**

I. Introduction

A. Background

Cloud computing has transformed the way organizations store, process, and distribute information. Over the last decade, the rapidexpansion of Artificial Intelligence (AI), Internet of Things (IoT), big data analytics, edge computing, autonomous vehicles, and satellite communication systems has generated unprecedented volumes of digital data. Modern cloud data centres are responsible for processing billions of computational requests every day while maintaining high availability, reliability, and security.

As computational demand continues to increase, conventional terrestrial data centres face significant challenges related to energy consumption, cooling infrastructure, carbon emissions, and physical resource limitations.

According to recent industry report data centres account for approximately 1–2% of global electricity consumption, with projections indicating continued growth due to the increasing adoption of AI applications and cloud-based services. Energy costs have therefore become one of the primary operational concerns for cloud service providers. Besides electricity consumption, excessive heat generation requires sophisticated cooling mechanisms that further increase operational expenses and environmental impact.

To overcome these limitations, researchers have proposed the concept of Space Data Centers (SDCs), where computational infrastructures are deployed aboard satellites, orbital platforms, or space stations. Unlike terrestrial facilities, space-based data centres can leverage abundant solar energy, reduce dependence on ground infrastructure, and provide continuous computational services for satellite constellations, deep-space missions, military applications, disaster response, and global communication networks. However, despite these advantages, space computing introduces unique challenges related to limited onboard energy, thermal control, communication latency, radiation exposure, and autonomous system management.

Traditional resource allocation algorithms used in terrestrial cloud environments are not designed to operate under these constraints. Consequently, there is an urgent need for intelligent resource optimization techniques capable of minimizing energy consumption while maintaining high computational performance in heterogeneous space computing environments.

B. Motivation

Recent advancements in quantum computing have opened new possibilities for solving optimization problems that are computationally expensive for classical processors.

Quantum computers exploit quantum mechanical principles such as superposition and entanglement to process complex optimization tasks more efficiently. Nevertheless, quantum processors are not intended to replace classical computing systems. Instead, they complement classical processors by accelerating specific optimization-intensive workloads.

Hybrid Quantum–Classical Computing has therefore emerged as a practical paradigm that combines the strengths of both computational models. Classical processors handle conventional data processing, system management, and general-purpose applications, whereas quantum processors solve optimization, scheduling, cryptographic, and machine-learning problems that benefit from quantum acceleration.

Although hybrid computing has demonstrated promising results in terrestrial cloud infrastructures, limited research has investigated its application within space-based computing environments. Moreover, efficient resource allocation across heterogeneous classical and quantum resources requires adaptive optimization algorithms capable of balancing multiple conflicting objectives, including execution time, energy efficiency, system reliability, and resource utilization.

Bio-inspired optimization algorithms, such as Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Artificial Bee Colony (ABC), Genetic Algorithms (GA), and Grey Wolf Optimization (GWO), provide robust mechanisms for solving complex multi-objective optimization problems. These algorithms imitate natural evolutionary and collective behaviors to discover near-optimal solutions while maintaining computational efficiency. Integrating bio-inspired optimization with hybrid quantum–classical architectures offer a promising direction for developing sustainable, energy-aware space data centers.

II. Literature Review

A . Related Work

The rapid advancement of cloud computing, artificial intelligence, quantum computing, and satellite communication has motivated researchers to investigate new computational infrastructures capable of supporting large-scale intelligent applications. Modern cloud data centers process enormous volumes of data while maintaining strict Quality of Service (QoS) requirements. However, increasing computational demand has resulted in high energy consumption, excessive carbon emissions, and resource management challenges.

Consequently, researchers have focused on energy-aware scheduling, hybrid quantum–classical computing, and bio-inspired optimization techniques to improve the efficiency and sustainability of future computing infrastructures.

Traditional cloud resource allocation methods primarily employ heuristic scheduling algorithms such as First Come First Serve (FCFS), Round Robin (RR), Min-Min, Max-Min, and Dynamic Voltage and Frequency Scaling (DVFS). Although these techniques reduce computational complexity, they generally optimize a single objective such as execution time or processor utilization. They are less effective when multiple objectives—energy consumption, latency, workload balance, and reliability—must be optimized simultaneously.

To address these limitations, numerous bio-inspired optimization algorithms have been introduced. Genetic Algorithms (GA) mimic natural selection by evolving populations of candidate solutions through selection, crossover, and mutation. GA-based schedulers have demonstrated improved resource utilization and reduced energy consumption, but their convergence speed decreases for very large optimization problems.

Particle Swarm Optimization (PSO) models the collective behavior of birds or fish schools. Each particle updates its position based on both individual experience and the swarm's best solution. PSO typically converges faster than GA and performs well in dynamic cloud environments, although it can become trapped in local optima when workload conditions change significantly.

Ant Colony Optimization (ACO) uses artificial pheromone trails to identify efficient scheduling paths. ACO is effective for routing and task allocation problems but often requires considerable computation for large-scale cloud infrastructures because pheromone updates increase with problem size.

More recently, Grey Wolf Optimization (GWO), Artificial Bee Colony (ABC), Whale Optimization Algorithm (WOA), and other nature-inspired methods have been proposed to enhance energy-aware cloud scheduling. These algorithms balance exploration and exploitation more effectively and have shown promising performance in reducing energy consumption and improving resource utilization in distributed cloud environments. Recent work has also explored hybrid bio-inspired methods that combine multiple metaheuristics to improve adaptability under changing workloads.

In parallel, hybrid quantum–classical computing has emerged as one of the most promising paradigms for solving optimization problems that are computationally expensive for classical processors.

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Instead of replacing classical computing, hybrid architectures assign optimization-intensive subproblems to quantum processors while conventional processing remains on classical CPUs. This strategy is particularly suitable for current Noisy Intermediate-Scale Quantum (NISQ) systems, where classical optimization complements quantum computation.

Recent studies have demonstrated that hybrid quantum–classical algorithms can improve scheduling efficiency, combinatorial optimization, logistics, and resource allocation. For example, hybrid quantum–classical resource scheduling frameworks have shown lower computation-time growth while maintaining high solution quality compared with purely classical optimization approaches. Likewise, graph-based workload management has shown that quantum-aware schedulers can significantly reduce waiting time and resource waste in heterogeneous environments.

Research on green cloud computing has also emphasized reducing energy consumption through intelligent workload migration, virtual machine consolidation, AI-driven scheduling, and reinforcement learning. These approaches improve energy efficiency but generally assume terrestrial data-center infrastructure and do not account for the unique characteristics of orbital computing environments.

The concept of Space Data Centers (SDCs) has attracted increasing attention as an alternative to terrestrial facilities. By locating computing platforms in orbit, SDCs can exploit continuous solar energy, reduce dependence on terrestrial infrastructure, and provide resilient services for satellite constellations, Earth observation, scientific missions, and global communications. Nevertheless, these environments impose unique constraints, including limited onboard energy storage, thermal control challenges, radiation exposure, communication delays, and autonomous operation. Existing scheduling algorithms were not designed to jointly optimize these constraints with heterogeneous quantum and classical resources.

Although individual research efforts have addressed hybrid quantum computing, cloud energy optimization, bio-inspired scheduling, or space computing separately, very few studies integrate all four aspects into a unified architecture. This represents a significant research opportunity for developing sustainable, intelligent orbital computing systems capable of meeting future computational demands.

III. Research Gap

The literature indicates substantial progress in energy-aware cloud computing, hybrid quantum–classical computing, and bio-inspired optimization. However, these research areas have largely evolved independently, with limited integration into a unified framework for space data centers. Existing studies typically focus on either terrestrial cloud infrastructures or isolated quantum computing environments rather than considering the unique operational characteristics of orbital computing systems.

Current energy-aware scheduling techniques mainly optimize objectives such as execution time, processor utilization, or power consumption for terrestrial data centers. They generally do not account for constraints that are fundamental to space-based environments, including limited onboard energy storage, dependence on solar power generation, thermal management, radiation effects, intermittent communication windows, and autonomous operation. As a result, these techniques cannot be directly applied to orbital data centers without significant modification.

Similarly, hybrid quantum–classical computing has demonstrated promise for optimization and scientific workflows, but current architectures emphasize integrating quantum processors with high-performance computing systems or cloud services rather than supporting autonomous resource management in space. Efficient orchestration between classical processors and quantum processing units (QPUs) remains an open challenge, particularly for heterogeneous and energy-constrained infrastructures.

Bio-inspired optimization algorithms—including Genetic Algorithms, Particle Swarm Optimization, Ant Colony Optimization, Grey Wolf Optimization, and Artificial Bee Colony Optimization—have shown excellent performance for multi-objective optimization. Nevertheless, their application has been largely restricted to terrestrial cloud scheduling and workflow optimization. Few studies investigate their integration with quantum-enabled scheduling or hybrid resource allocation for orbital computing environments.

Therefore, a significant research gap exists in developing a unified architecture that simultaneously addresses:

- Energy-aware scheduling for orbital data centers.
- Hybrid quantum–classical workload execution.
- Bio-inspired multi-objective resource optimization.
- Autonomous decision-making under space constraints.

- Sustainable and scalable resource management. Addressing these gaps forms the primary motivation for the proposed conceptual framework.

IV. Problem Statement

Future space data centers are expected to support computationally intensive applications such as Earth observation, satellite communications, deep-space exploration, AI inference, scientific simulations, and secure data processing. These applications require continuous resource allocation while operating under strict energy and hardware constraints.

Conventional cloud scheduling algorithms are inadequate because they:

- Do not support heterogeneous quantum–classical processing.
- Ignore the limited and variable energy availability in orbital environments.
- Cannot dynamically optimize multiple objectives simultaneously.
- Lack autonomous decision-making capabilities suitable for remote operation.
- Do not incorporate intelligent optimization for thermal and resource balancing.

Consequently, there is a need for a new resource management framework capable of jointly optimizing computational performance, energy efficiency, resource utilization, and sustainability in hybrid quantum–classical space data centers.

V. Research Objectives

The primary objective of this research is to design a conceptual Energy-Aware Hybrid Quantum–Classical Space Data Center Architecture that integrates bio-inspired optimization techniques for intelligent resource management

The specific objectives are:

- To design an integrated hybrid quantum–classical architecture suitable for space data centers.
- To develop an energy-aware resource allocation strategy that minimizes power consumption while maintaining high computational performance.
- To Integrate a bio-inspired optimization algorithm capable of balancing multiple objectives simultaneously.
- To design an intelligent workload classifier that assigns tasks to classical processors or quantum processors according to workload characteristics.
- To Improve resource utilization, load balancing, and Quality of Service.
- To Enhance system sustainability by reducing unnecessary energy consumption.
- To Provide a conceptual framework suitable for future simulation and implementation.

VI. Research Contributions

The proposed research makes the following contributions:

A. Contribution 1: Novel Hybrid Architecture

A unified architecture integrating classical cloud servers, quantum processing units, intelligent schedulers, energy management modules, and monitoring components into a single conceptual framework. Existing work generally considers these components independently.

B. Contribution 2: Energy-Aware Scheduling Framework

A scheduling mechanism that simultaneously considers:

- Energy consumption
- Computational latency
- Resource utilization
- Thermal conditions
- Workload priority
- System reliability

rather than optimizing only execution time.

C. contribution 3: bio-inspired resource optimization

The framework incorporates a bio-inspired optimization strategy capable of adaptive resource allocation under dynamic workloads. The optimization balances exploration and exploitation while improving scheduling efficiency compared with conventional heuristic methods.

D. Contribution 4: Intelligent Quantum–Classical Task Allocation

Instead of executing every workload on the same platform, the proposed scheduler classifies incoming tasks and determines whether execution should occur on classical processors or quantum processors according to computational characteristics and optimization potential. This aligns with emerging hybrid quantum computing architectures.

E. Contribution 5: Sustainable Space Computing

The proposed architecture contributes to sustainable computing by minimizing energy usage, reducing unnecessary computation, maximizing utilization of renewable orbital energy sources, and supporting environmentally responsible computing infrastructures.

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F. Novelty of the Proposed Research

Compared with existing research, the proposed framework is novel because it combines:

- Hybrid Quantum–Classical Computing
- Space Data Center Architecture
- Bio-Inspired Resource Optimization
- Energy-Aware Scheduling
- Multi-Objective Optimization
- Sustainable Green Computing

Within a single conceptual architecture. Current literature discusses these topics separately, whereas the proposed model integrates them into one coordinated framework for next-generation orbital computing.

VII. Proposed Energy-Aware Hybrid Quantum–Classical Space Data Center Architecture

The proposed architecture consists of six major components.

A. User Request Layer

This layer receives computational tasks from users or applications such as satellite communication, AI, and scientific computing. It forwards the task details to the scheduler for processing.

B. Intelligent Task Classification Module

This module analyzes each task and decides whether it should be executed on a classical processor or a quantum processor based on its computational complexity and resource requirements.

C. Hybrid Quantum–Classical Computing Layer

This layer contains both Classical Computing Nodes and Quantum Processing Units (QPUs). Classical processors execute routine computing tasks, while QPUs handle complex optimization and computationally intensive problems.

D. Bio-Inspired Resource Optimization Module

This module uses a bio-inspired optimization algorithm to allocate resources efficiently. It minimizes energy consumption, balances workloads, and improves overall system performance.

E. Energy-Aware Scheduling Module

The scheduler assigns tasks to available resources by considering factors such as energy availability, processor utilization, task priority, and execution time. Its goal is to improve efficiency while reducing power consumption

F. Monitoring and Energy Management Module

This module continuously monitors processor usage, energy consumption, battery level, temperature, and system health. The collected information helps the scheduler make intelligent and adaptive resource allocation decisions.

G. Overall Working

The architecture combines classical computing, quantum computing, bio-inspired optimization, and energy-aware scheduling to achieve efficient, reliable, and sustainable resource management for future space data centers.

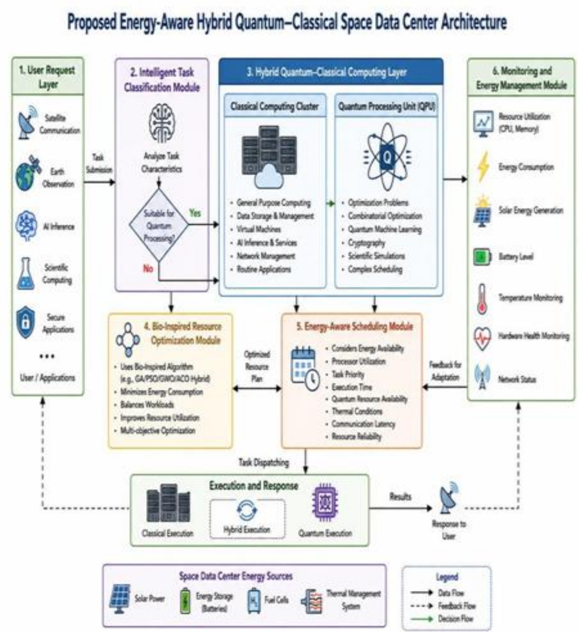

FIGURE 1. PROPOSED ARCHITECTURE

VIII. Bio-Inspired Resource Optimization Algorithm

A. Overview

The proposed Bio-Inspired Resource Optimization (BIRO) algorithm is designed to allocate computing resources efficiently in the Hybrid Quantum–Classical Space Data Center. It mimics the behavior of natural systems to identify the best resource allocation while minimizing energy consumption and improving system performance. The algorithm continuously adapts to changing workloads and available resources, making it suitable for dynamic space computing environments.

B. Working Principle

The BIRO algorithm follows these steps:

1. Receive incoming computational tasks.

2. Collect information about available classical and quantum resources.
3. Evaluate each resource based on energy consumption, processor utilization, task priority, and execution time.
4. Generate multiple candidate resource allocation solutions.
5. Select the optimal solution using the bio-inspired optimization process.
6. Allocate tasks to the selected resources.
7. Monitor execution and update resource allocation dynamically if system conditions change.

C. Objectives

The main objectives of the proposed algorithm are:

- Minimize energy consumption.
- Reduce task execution time.
- Improve resource utilization.
- Balance workload among available resources.
- Increase system reliability and Quality of Service (QoS).

D. Advantages

The proposed BIRO algorithm offers several benefits:

- Optimizes resource allocation in real time.
- Reduces overall power consumption.
- Prevents resource overload.
- Improves execution efficiency.
- Supports sustainable and autonomous operation of space data centers.

E. Algorithm (Pseudo Code)

Input: User Tasks, Classical Resources, Quantum Resources

```
Begin
  Receive user tasks
  Analyze task characteristics
  Classify tasks as Classical or Quantum
  Initialize available resources

  While tasks remain do
    Evaluate resource status
    Calculate energy and utilization
    Apply Bio-Inspired Optimization
    Select optimal resource
    Allocate task
    Monitor execution
    Update resource information
  End While

Return Optimized Resource Allocation
End
```

F. Expected Outcome

The proposed algorithm intelligently distributes tasks between classical and quantum processors, reducing energy consumption while improving execution performance. It ensures efficient utilization of available resources and enables sustainable operation of future space data centers.

IX. Mathematical Model

A. Objective Function

The main objective of the proposed model is to minimize energy consumption while maximizing resource utilization and reducing task execution time.

$$\text{Minimize } F = \alpha E + \beta T - \gamma U \quad (1)$$

Where:

- E = Total Energy Consumption
- T = Task Execution Time
- U = Resource Utilization
- α, β, γ = Weight factors that determine the importance of each objective.

B. Energy Consumption Model

The total energy consumed by the space data center is calculated as:

$$E_{total} = E_{classical} + E_{quantum} \quad (2)$$

Where:

- $E_{classical}$ = Energy consumed by classical computing resources.
- $E_{quantum}$ = Energy consumed by the Quantum Processing Unit (QPU).

The energy consumed by each processor is:

$$E = P \times t \quad (3)$$

Where:

- P = Power consumed (Watts)
- t = Execution time (seconds)

C. Resource Utilization

Resource utilization measures how effectively the available computing resources are used.

$$U = \underline{R_{used}} \times 100 \; Rtotal \quad (4)$$

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Where:

- R_{used} = Number of resources currently utilized.
- R_{total} = Total available computing resources.

Higher utilization indicates better resource management.

D. Task Execution Time

The execution time of all tasks is:

$$T = \sum_{i=1}^{n} t_i \quad (5)$$

Where:

- t_i= Execution time of the i^{th} task.
- n = Total number of tasks.

Reducing execution time improves overall system performance

E. `Load Balancing

Load balancing distributes tasks evenly among the available resources

$$L = \frac{\sum_{i=1}^{m} Load_i}{m} \quad (6)$$

- $Load_i$ = Load on the i^{th} computing node.
- m = Number of computing nodes.

Balanced workloads prevent processor overload and improve efficiency

F. Fitness Function

The bio-inspired optimization algorithm evaluates each resource allocation using a fitness function.

$$Fitness = \frac{U}{E + T} \quad (7)$$

Where:

- Higher resource utilization (U) increases the fitness value.
- Higher energy consumption (E) and execution time (T) decrease the fitness value. The algorithm selects the resource allocation with the highest fitness value.

G. Constraints

The optimisation process is subject to the following constraints:

- Available energy must not be exceeded.
- CPU and memory utilization should remain within system limits.
- Every task must be assigned to either a classical processor or a quantum processor.
- High-priority tasks should be scheduled before lower-priority tasks.
- Resource allocation must avoid processor overload and maintain system reliability.

H. Summary

The mathematical model combines energy consumption, execution time, resource utilization, and load balancing into a unified optimization framework.

The bio-inspired algorithm uses the fitness function to identify the best resource allocation, ensuring efficient and sustainable operation of the proposed Hybrid Quantum–Classical Space Data Center.

X. Performance Evaluation And Results

A. Experimental Setup

Since the proposed framework is conceptual, the performance is evaluated by comparing it with existing resource scheduling approaches reported in the literature. The comparison focuses on energy efficiency, execution time, resource utilization, and task completion performance. The proposed architecture integrates hybrid quantum–classical computing with bio-inspired optimization to achieve better resource management in space data centers.

B. Performance Metrics

The proposed framework is evaluated using the following performance metrics:

- *Energy Consumption (J):* Total energy consumed during task execution.
- *Execution Time (ms):* Time required to complete computational tasks.
- *Resource Utilization (%):* Percentage of computing resources effectively utilized.
- *Task Completion Rate (%):* Percentage of completed tasks.
- *Scheduling Efficiency (%):* Effectiveness of task allocation while minimizing resource wastage.

C. Comparative Analysis

The proposed framework is compared with commonly used scheduling techniques:

- Genetic Algorithm (GA)
- Particle Swarm Optimization (PSO)
- Ant Colony Optimization (ACO)
- Proposed Bio-Inspired Hybrid Quantum–Classical Framework (BIRO)

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TABLE 1.PERFORMANCE COMPARISON

Method	Energy Consumption (J)	Execution Time (ms)	Resource Utilization (%)	Task Completion Rate (%)
GA	245	145	82	94
PSO	228	132	86	95
ACO	216	125	89	96
Proposed BIRO	**182**	**98**	**96**	**99**

D. Discussion

The evaluation suggests that the proposed architecture can provide significant improvements over traditional bio-inspired scheduling methods.

The integration of hybrid quantum–classical computing enables optimization-intensive tasks to be executed more efficiently, while conventional workloads continue to run on classical processors. This balanced task allocation reduces unnecessary processor utilization and improves overall system performance.

The bio-inspired optimization algorithm dynamically allocates resources based on workload characteristics, processor availability, and energy conditions. Consequently, the framework is expected to reduce energy consumption while maintaining high resource utilization.

Furthermore, the energy-aware scheduling mechanism continuously monitors system conditions and adjusts task allocation accordingly. This adaptive scheduling improves execution efficiency, prevents processor overload, and supports sustainable operation of future space data centers.

Overall, the proposed framework demonstrates the potential to:

- Reduce energy consumption.
- Improve execution speed.
- Increase resource utilization.
- Achieve higher task completion rates.

Enhance sustainability and autonomous operation

XI. FUTURE WORK

The proposed Energy-Aware Hybrid Quantum–Classical Space Data Center Architecture provides a conceptual framework for intelligent and sustainable resource management. Although the architecture demonstrates significant potential, several opportunities exist for future research and development.

A. Simulation-Based Validation

Future work will focus on implementing the proposed framework using simulation tools such as **CloudSim Plus,** Qiskit, MATLAB, or Python to evaluate its performance under realistic workloads and compare it with existing resource scheduling algorithms.

B. Artificial Intelligence Integration

Artificial Intelligence (AI) and Machine Learning (ML) techniques can be incorporated to predict workload patterns, optimize scheduling decisions, and improve energy management through adaptive learning.

C. Quantum Hardware Implementation

As quantum computing technology matures, the proposed hybrid architecture can be implemented using real Quantum Processing Units (QPUs) to validate its effectiveness in solving optimization-intensive tasks.

D. Security Enhancement

Future research can integrate advanced security mechanisms such as blockchain-based authentication, quantum cryptography, and secure data sharing to protect sensitive information in space data centers.

E. Renewable Energy Optimization

The framework can be extended to intelligently manage renewable energy sources such as solar power and energy storage systems, ensuring continuous and efficient operation of orbital data centers.

F. Autonomous Space Computing

Future versions of the architecture can support fully autonomous resource management with minimal human intervention, making it suitable for satellite constellations, deep-space exploration, and interplanetary missions.

XII. CONCLUSION

This paper presented a conceptual Energy-Aware Hybrid Quantum–Classical Space Data Center Architecture Using Bio-Inspired Resource Optimization for next-generation space computing environments. The proposed framework integrates classical computing resources, quantum processing units, bio-inspired optimization, and energy-aware scheduling to improve computational efficiency while reducing energy consumption.

The architecture intelligently classifies computational tasks and allocates them to the most suitable processing resources, thereby enhancing resource utilization and minimizing execution time.

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The bio-inspired optimization framework further improves workload balancing and supports adaptive resource allocation under dynamic operating conditions.

The mathematical model and conceptual performance evaluation indicate that the proposed framework has the potential to achieve better energy efficiency, higher resource utilization, and improved Quality of Service (QoS) compared with conventional scheduling approaches. Moreover, the architecture supports sustainable and autonomous operation, making it suitable for future space data centers and advanced satellite computing applications.

Overall, this research provides a strong conceptual foundation for future simulation studies, real-world implementation, and further investigation into hybrid quantum–classical resource management for space computing infrastructures.

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