APOLLO: A Proximity-Oriented, Low-Layer Orchestration Algorithm for Resources Optimization in Mist Computing

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Abstract. The fusion of satellite technologies with the Internet of Things (IoT) has propelled the evolution of mobile computing, ushering in novel communication paradigms and data management strategies. Within this landscape, the efficient management of computationally intensive tasks in satellite-enabled mist computing environments emerges as a critical challenge. These tasks, spanning from optimizing satellite communication to facilitating blockchain-based IoT processes, necessitate substantial computational resources and timely execution. To address this challenge, we introduce APOLLO, a novel low-layer orchestration algorithm explicitly tailored for satellite mist computing environments. APOLLO leverages proximity-driven decision-making and load balancing to optimize task deployment and performance. We assess APOLLO's efficacy across various configurations of mist layer devices while employing a round-robin principle for equitable task distribution among the close low-layer satellites. Our findings underscore APOLLO's promising outcomes in terms of reduced energy consumption, minimized end-to-end delay, and optimized network resource utilization, particularly in targeted scenarios. However, the evaluation also reveals avenues for refinement, notably in CPU utilization and slightly low tasks success rates. Our work contributes substantial insights into advancing task orchestration in satellite-enabled mist computing with more focus on energy and end-to-end sensitive applications, paving the way for more efficient, reliable, and sustainable satellite communication systems.

Keywords: Satellite Edge Computing · Task Management · Task Orchestration · Low-Layer Satellites communication · Energy-efficient Offloading · End-to-End Delay Reduction.

Added Material

The following additional content has been included in the journal paper format:

- An extended introduction section providing a more comprehensive overview of mist computing to better acquaint readers with the topic.
- Expansion of the related work section to include recent studies in the field of satellites communication.
- Introduction of a specific ratio and distribution of satellite types, along with an extended duration of testing (20 minutes of simulation time) to provide more robust results.
- Inclusion of testing for an additional scheme, namely, the pure randomized tasks distribution scheme, to evaluate its performance alongside our APOLLO scheme.
- Parametrization of our scheme to prioritize 30% of the closest mist satellites, based on previous research findings indicating its optimal performance.
- Interpretation of new results obtained from the extended testing duration and inclusion of additional scheme comparisons to provide deeper insights into the effectiveness of our approach.
- This is an extension from the previously presented outcome; that was presented in : WICON EAI 2023.

1 Introduction

Recent years have witnessed a profound evolution in mobile computing, propelled by the intersection of two pivotal trends: the burgeoning Internet of Things (IoT) and the emergence of 5G technology. This transformative shift steers the field away from traditional Mobile Cloud Computing towards Mobile Edge Computing (MEC), fostering a more decentralized approach [12, 1].

Concurrently, satellite communication, with a rich history spanning over four decades, experiences a resurgence [20]. Foundational work in this domain, encompassing pioneering concepts in satellite repeaters, orbital dynamics, and path-loss calculations, retains relevance today, particularly with the increasing integration of IoT in satellite-to-satellite communications.

The burgeoning demand for satellite-to-satellite IoT services is propelled by global enterprises and governments seeking to monitor and manage assets dispersed worldwide. Consequently, the satellite market experiences significant expansion, with operators now offering comprehensive IoT solutions leveraging satellite technology [6].

In this context, interest in edge computing within the satellite domain intensifies among diverse stakeholders, spanning mist devices, data centers, and cloud services, as illustrated in Fig. 1.

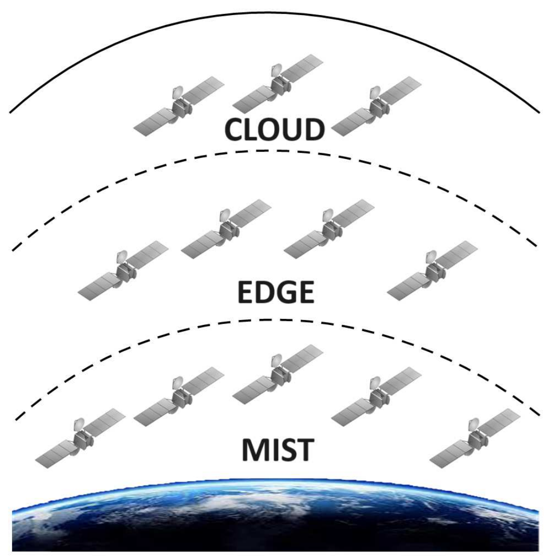


Fig. 1: The general satellite edge computing architecture.

In the dynamic landscape of mobile and satellite communications, the demand for handling "heavy computing tasks" emerges as a critical imperative. These tasks encompass a spectrum of compute-intensive operations, ranging from intricate calculations in optimizing satellite communication to the processing requirements of blockchain-based IoT frameworks. Within the realm of Unmanned Aerial Vehicles (UAVs), such tasks entail video preprocessing, pattern recognition, and feature extraction, necessitating substantial computational prowess [13]. Conversely, Yan et al. demonstrate that heavy computing arises during the mining process when integrating blockchain within IoT, demanding significant processing power [21]. Our research delves into the efficient management of these computationally intensive tasks within satellite-based mist computing environments, with the aim of optimizing energy consumption and ensuring timely task execution. This novel approach signifies a pivotal advancement towards accommodating heavy computing tasks and fostering a more efficient satellite-based mist computing paradigm.

Furthermore, the meticulous preservation of privacy and security assumes paramount importance in IT systems at large [2], with its significance magnified in the domain of satellite-based mist computing [3]. These foundational aspects underpin the success and reliability of the entire system. Neglecting robust privacy and security measures would expose the system to vulnerabilities, potentially leading to breaches by adversaries and malicious actors [8]. Such breaches could have dire consequences, undermining the efficacy and trustworthiness of the entire infrastructure. Hence, a vigilant and proactive approach to safeguarding privacy and security is indispensable, fortifying the foundations of satellite-based mist computing and ensuring its sustained success.

Moreover, the meticulous preservation of Quality of Service (QoS), encompassing essential factors such as latency and various types of delays, is indispensable. This necessity transcends general IT systems [5] and holds particular significance within satellite systems [6]. The seamless operation and performance of these systems hinge on consistently delivering QoS standards, underscoring the importance of maintaining and optimizing these aspects for sustained effectiveness.

In the rapidly evolving landscape of wireless communication systems, the transition from fifth-generation (5G) networks to the research focus on sixth-generation (6G) networks sets the stage for transformative advancements. With the technical roadmap for 6G networks already laid out, low earth orbit (LEO) satellite communication emerges as a pivotal component, poised to bridge the digital divide and provide ubiquitous access for mobile terminals [11].

One area of innovation lies in antenna design tailored for X-band satellite communication within cognitive radio networks. Leveraging graphene's unique properties, including high conductivity and mechanical flexibility, these antennas achieve reconfigurability in frequency, polarization, and radiation pattern. Operating within cognitive radio systems, graphene-based antennas enable real-time adjustments to antenna parameters, enhancing the efficiency and dependability of satellite communication systems [15].

Moreover, collaborative endeavors such as the Italian National project ITA NTN (Integrated Terrestrial and Non-Terrestrial Networks) are shaping the landscape of future communication networks. Funded under the EU initiative known as the Italian National Resilience and Restart Program, ITA NTN aims to integrate terrestrial and non-terrestrial network entities, including low-Earth orbit mega-constellations, High-Altitude Platforms (HAP), and unmanned aerial vehicles (UAVs). Envisioning a 6G-oriented scenario, ITA NTN aims to create a 3-dimensional (3D) wireless connectivity paradigm, highlighting the evolution from interoperable to fully integrated scenarios [14].

Yet, within the dynamic realm of satellite mist computing, the burgeoning potential of this paradigm is juxtaposed with the inherent challenge of devising orchestration algorithms tailored to meet specific application and scenario requirements. The intricate interplay among various factors, including energy efficiency, latency minimization, and resource optimization, underscores the ongoing need for exploration and refinement of orchestration strategies. As the demand for satellite-based edge computing escalates across diverse domains, spanning IoT deployments to remote sensing applications, the research community is spurred to develop innovative orchestration solutions capable of effectively addressing the unique demands posed by these varied use cases. This impetus to bridge the gap and furnish orchestration algorithms finely attuned to the intricacies of specific applications propels ongoing research endeavors within the satellite mist computing domain.

This paper significantly advances the field of satellite-based mist computing by introducing the following key elements:

1. **Novel Orchestration Algorithm:** Our research presents a pioneering orchestration algorithm, named APOLLO: A Proximity-Oriented, Low-Layer Orchestration (APOLLO) Algorithm for Resources Optimization in Mist Computing, specifically crafted for satellite-based mist computing environments. This algorithm prioritizes the selection of mist satellites based on proximity and load balancing, facilitating optimized task deployment.
2. **Optimized Parameter Configuration:** We fine-tuned our approach to prioritize the selection of mist-layer satellites based on proximity, selecting the closest 30% while also incorporating load balancing mechanisms to ensure equitable task distribution.
3. **Tailored Satellite Configuration:** We adopted a customized ratio of satellite numbers for cloud, edge datacenter, and mist satellites, set at 1, 2, and 50 respectively. This ratio can be used in real-life scenarios.
4. **Exploration of the Mist Layer:** Our study adds significant value by directing attention to the mist layer within satellite-based computing ecosystems. This exploration delves deeply into the complexities of task orchestration, particularly within the mist layer, elucidating the distinct challenges and opportunities inherent in this pivotal segment of computing infrastructure.

The subsequent sections of this paper are structured as follows:

In Section 2, we offer an overview of prior research in satellite-based mist computing. Section 3 delineates the system model, elaborating on the principal entities and components within our simulated environment. Our methodology, encompassing the development and description of our novel task orchestration algorithm, is outlined in Section 4. Section 5 details the simulation setup, environment, and ensuing results. Lastly, Section 6 encapsulates our conclusions drawn from the findings and explores potential directions for future research.

2 Related Work

A recent study conducted by Wang.F et al. [16] explores the capabilities of Low Earth Orbit (LEO) satellites within the context of satellite-based edge computing. LEO satellites, renowned for their expansive coverage and low latency, serve as valuable assets for delivering computing services to user access terminals. The investigation addresses resource allocation challenges in Edge Computing Satellites (ECS) stemming from diverse resource requirements and access planes. To tackle issues related to inter-satellite links (ISLs) and ECS resource scheduling, the study proposes a three-layer network architecture incorporating a software-defined networking (SDN) model. This model harnesses advanced algorithms for efficient resource allocation and ISL construction, including the Advanced K-means Algorithm (AKG) and a breadth-first-search-based spanning tree algorithm (BFST). Simulation results validate the feasibility and effectiveness of this dynamic resource scheduling approach, providing solutions to key challenges in satellite-based edge computing systems.

Zhang et al. investigate the critical integration of satellite and terrestrial networks within the realm of 6G wireless architectures [22]. These integrated networks ensure robust and secure connectivity across extensive geographic areas. The authors introduce the concept of double-edge intelligent integrated satellite and terrestrial networks (DILIGENT), emphasizing the imperative synergy between communication, storage, and computation capabilities within satellite and cellular networks. By leveraging multi-access edge computing technology and artificial intelligence (AI), the DILIGENT framework is meticulously crafted for systematic learning and adaptive network management. The article offers a comprehensive overview of academic research, standardization endeavors, and a detailed exploration of the DILIGENT architecture, highlighting its inherent advantages. Various strategies, including task offloading, content caching, and distribution, are scrutinized, with numerical results underscoring the superior performance of this network architecture compared to existing integrated networks.

Wang.Y et al. delve into the escalating significance of IoT within the information industry [18]. Edge computing emerges as a promising paradigm addressing challenges associated with network distance and the deployment of remote IoT devices. In scenarios where IoT devices are located in remote or challenging-to-access areas, reliance on satellite communication becomes imperative. However, conventional satellites often lack universal computing capabilities and are specialized. The proposed solution involves transforming traditional satellites into space edge computing nodes, enabling dynamic software loading, resource sharing, and coordinated services with the cloud. The article delineates the hardware structure and software architecture of such satellites and presents modeling and simulation results. Findings indicate that the space edge computing system exhibits superior performance, resulting in reduced time and energy consumption compared to traditional satellite constellations. Service quality is influenced by factors such as satellite quantity, performance, and task offloading strategies.

Gao et al. [9] focus on the role of satellite networks as complements to terrestrial networks, catering to the computing needs of IoT users in remote regions while acknowledging the inherent limitations of satellites, including constraints in computing power, storage, and energy. An innovative strategy involves decomposing IoT user computation tasks into segments, leveraging multiple satellites for collaborative processing to enhance the efficiency of satellite networks. Integrating Network Function Virtualization (NFV) technology with satellite edge computing represents a burgeoning area of interest. The paper introduces a potential game-based solution for Virtual Network Function (VNF) placement within satellite edge computing. The primary objective is to minimize deployment costs for individual user requests while maximizing the provision of computing services across the satellite network. This optimization problem is formulated as a potential game, employing a game-theoretical approach to maximize overall network benefits. The proposed decentralized resource allocation algorithm, known as the possible game-based resource allocation (PGRA), aims to find a Nash equilibrium to effectively address the VNF placement challenge. Experimental simulations validate the efficacy of the PGRA algorithm in solving the VNF placement problem within satellite edge computing.

One study by Wang et al. [4] focuses on enhancing data processing capabilities onboard satellites using edge computing. The proposed approach leverages deep learning techniques for low-light image enhancement, aiming to improve early detection and tracking accuracy. To overcome computational constraints, an edge-computing-enabled inference model is developed, featuring an encoder-decoder architecture with optimized illumination mapping. This model, deployed on Arm Cortex-M3 microcontrollers onboard satellite payloads, demonstrates significant acceleration compared to conventional convolution models while maintaining high-quality image processing. In a related context, another investigation by Zhang et al. [10] addresses the challenges of handling large volumes of Earth observation imagery data transmitted by Low Earth Orbit (LEO) satellites. The study proposes a satellite mobile edge computing (SMEC) framework to optimize image distribution and compression parameters, thereby minimizing energy consumption while maintaining real-time processing capabilities. Results indicate substantial improvements in system capacity and energy efficiency, particularly in scenarios involving real-time disaster detection and management.

Furthermore, Wang et al. [17] introduce a novel MEC fusion architecture based on low Earth orbit (LEO) satellites to extend computing services to users in geographically challenging regions. The study focuses on task assignment optimization in the task offloading process, proposing user-first matching game and edge service provider-first matching game algorithms based on game theory. Simulation experiments demonstrate the superiority of the proposed methods in reducing user delay and maximizing edge service provider benefits, highlighting the potential of satellite-enabled MEC solutions. Finally, Gao et al. [7] present a dense satellite-terrestrial integrated mobile-edge computing network (SATIMECN) architecture designed to meet the computing demands of next-generation networks. The study formulates an energy consumption minimization problem considering various factors such as task allocation, user-satellite association, and computation resource allocation. By employing Lyapunov optimization theory and decomposing the optimization problem into sub-problems, the proposed approach achieves a tradeoff between energy consumption and queue length while optimizing computation offloading efficiency in dense satellite networks.

3 System Model

Satellite mist computing encompasses several essential entities, each fulfilling distinct roles within the system as depicted in Fig. 2:

- **Mist Satellites:** These satellites constitute the mist layer and house a single host per satellite. Each host is equipped with a dedicated Virtual Machine (VM) where computational tasks are offloaded for processing.
- **Edge Satellites (Edge Datacenter Satellites):** Functioning as edge datacenters, these satellites possess enhanced processing capabilities. Each edge satellite comprises two hosts, each capable of accommodating two VMs. This architecture boosts computational capacity, particularly for more demanding tasks.
- **Cloud Satellites:** Situated at the highest layer, cloud satellites boast extensive computational resources. Each cloud satellite incorporates two hosts, each capable of running up to eight VMs simultaneously. This configuration facilitates extensive parallel processing and scalability.
- **Tasks:** These are computational workloads that require offloading for efficient processing. Tasks are initiated at various points within the system and are orchestrated to suitable VMs based on the specific requirements and constraints of the satellite mist computing environment.

4 Methodology

To assess the effectiveness of our proposed orchestration algorithm, which adopts the APOLLO algorithm within the mist layer, we integrated the algorithm into the satellite mist computing framework SatEdgeSim [19]. The algorithm aims to optimize task orchestration by strategically selecting VMs based on proximity, thereby achieving load balance and efficient resource utilization. This integration process involved incorporating the algorithm into the existing simulation environment, enabling a comprehensive evaluation of its impact on various performance metrics. Subsequently, the orchestration algorithm underwent rigorous

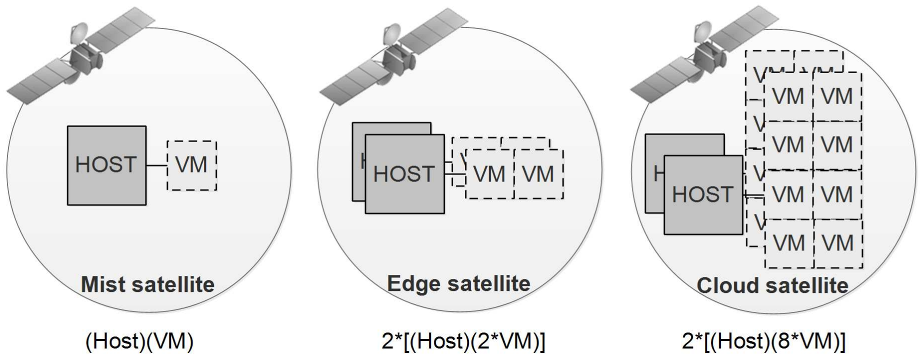


Fig. 2: The assumed types of satellites and their resources.

testing and comparison against other existing task orchestration approaches to provide insights into its effectiveness and applicability across different scenarios within the satellite mist computing paradigm.

4.1 Task Orchestration Algorithm Development

We developed a novel algorithm, referred to as APOLLO, aimed at optimizing task orchestration within the satellite mist computing framework. The pseudo-algorithm 1 is delineated below:

The APOLLO algorithm aims to efficiently orchestrate task offloading in a satellite-based mist computing environment. The following entities are integral to understanding the algorithm:

- **orchestrationHistory:** This is a data structure that maintains a historical record of task assignments to different VMs of the existing satellites.
- **satDevice.getType():** This method retrieves the type of the satellite device.
- **getDistance(satDevice, task.getSatDevice):** This function calculates the distance between a given mist satellite (*satDevice*) and the satellite device associated with the task to be offloaded (*task.getSatDevice*).
- **offloadingIsPossible(task, vmList.get(satelliteIndex)):** This function checks whether offloading the given task to a specific mist satellite (retrieved from *vmList* using *satelliteIndex*) is feasible.
- **satelliteDistances:** This list stores the calculated distances between the mist satellites and the satellite device associated with the task.
- **mistSatelliteIndices:** This list contains the indices of mist satellites eligible for task offloading.
- **vm:** This variable represents the selected mist satellite VM for task offloading.
- **k:** This variable determines the number of closest mist satellites to consider for task offloading. Its value is adjusted based on a percentage, in this build, is set to the 30% of the total number of mist satellites.

Algorithm 1 APOLLO

```
function APOLLO(task)
    Initialize empty lists satelliteDistances and mistSatelliteIndices
    for i in 0 to (orchestrationHistory - 1) do
        if satDevice.getType() == TYPES.mist_Device then
            //Calculate distance between mist satellite i and task's satellite device
            distance ← getDistance(satDevice, task.getSatDevice)/propagation_Speed
            Add distance to satelliteDistances
            Add i to mistSatelliteIndices
        end if
    end for
    Sort mistSatelliteIndices based on corresponding distances in satelliteDistances
    vm ← −1
    k ← 30 × mistSatelliteIndices.size() / 100
    for i in 0 to mistSatelliteIndices.size() do
        satelliteIndex ← mistSatelliteIndices.get(i)
        if offloadingIsPossible(task, vmList.get(satelliteIndex)) then
            if vm == −1 or orchestrationHistory.get(satelliteIndex).size() < orchestrationHistory.get(vm).size() then
                vm ← satelliteIndex
            end if
        end if
    end for
    return vm
end function
```

4.2 Used Metrics

In our study, we have meticulously selected various metrics to evaluate the performance of our newly developed orchestration algorithm, APOLLO, within the context of satellite mist computing. These metrics play a crucial role in understanding the system's behavior and assessing the efficacy of our solution within this unique computing environment.

Evaluation of VM CPU Utilization: We conducted an assessment of the mean CPU consumption of VMs to ensure they operated within optimal thresholds. This analysis was imperative for preventing resource overloads and enhancing the overall efficiency of the system.

Analysis of Average End-to-End Latency: We computed the average duration required to complete tasks from initiation to completion. This measure of end-to-end latency is crucial for assessing the effectiveness of our orchestration method in meeting stipulated deadlines and managing time-sensitive, compute-intensive tasks.

Measurement of Satellite Energy Consumption: We scrutinized the energy consumption of satellites during task processing, a vital aspect of our evaluation. This enabled us to quantify the sustainability and environmental impact of our orchestration algorithm.

Assessment of Task Success Rate: We evaluated the overall success rate of tasks executed using our orchestration technique. A high success rate signifies the reliability and effectiveness of our approach, while a low success rate could compromise the system's functionality.

Monitoring of Bandwidth Consumption: Throughout task execution, we monitored the consumption of bandwidth. This metric is pivotal for determining the required network capacity and identifying potential bottlenecks within the system.

Total Tasks Executed per Layer: We tallied the total number of tasks successfully executed at each layer of the satellite mist computing system. This metric offered a comprehensive overview of workload distribution and management across different system layers.

4.3 Task Orchestration Algorithms

This section delves into the diverse task orchestration algorithms explored in our research. Effective task orchestration is pivotal for enhancing resource efficiency within satellite mist computing. We compare different algorithms, including our proposed APOLLO algorithm, to evaluate their impact on different metrics, precisely: CPU utilization, end-to-end delay, energy consumption, and overall system reliability. This analysis sheds light on the strengths and weaknesses of each algorithm, guiding their applicability in diverse scenarios within the satellite mist computing paradigm.

RANDOM_VM: The RANDOM_VM scheme adopts a straightforward approach by randomly selecting satellite nodes for task offloading. This strategy contrasts with more nuanced selection algorithms, as it disregards factors such as workload distribution, resource availability, and task-specific attributes. Instead, tasks are assigned to satellites without any consideration for optimization or load balancing. While this approach may introduce variability in task execution times and resource utilization, it lacks the systematic approach of other schemes. In essence, RANDOM VM provides a baseline for comparison against more sophisticated task deployment strategies in satellite-based mist computing environments.

Round_Robin: The Round_Robin task deployment scheme selects satellite nodes with the fewest assigned tasks, promoting an evenly distributed computing workload. By prioritizing underutilized resources, it mitigates potential bottlenecks and alleviates strain on heavily loaded nodes. This strategy enhances system performance and task completion rates while minimizing the risk of overwhelming individual satellite nodes. In scenarios with diverse task requirements, this scheme offers a fair and practical approach to optimizing task deployment in satellite-based mist computing environments.

Trade_Off: The Trade_Off task deployment scheme employs a dynamic strategy to select the most suitable satellite node, balancing factors such as latency, energy consumption, and resource availability. This algorithm evaluates potential satellite nodes based on type (cloud or edge device), pending task count, CPU processing power, and task-specific attributes. By computing a weighted score for each candidate, the scheme ensures task allocation to the satellite with the most favorable trade-off among these factors. This approach improves task orchestration efficiency, optimizing satellite resource utilization in satellite-based mist computing environments.

WEIGHT_GREEDY (WG): The WEIGHT_GREEDY scheme is a sophisticated strategy tailored for satellite-based mist computing environments. It evaluates four critical performance indicators: transmission distance, CPU processing time, parallel task count, and equipment energy consumption. Notably, the scheme's effectiveness lies in its meticulous weighting of these indicators, with ratios fine-tuned to 6:6:5:3. This deliberate emphasis on factors related to task timeliness and minimal energy consumption ensures an optimal balance between low latency and minimal power consumption demands in satellite edge computing environments.

APOLLO: The APOLLO scheme strategically selects satellite nodes by delicately balancing considerations such as latency, energy consumption, and resource availability. Tailored specifically for deployment on mist layer devices within satellite-based mist computing environments, APOLLO prioritizes the efficient orchestration of tasks. This scheme achieves optimal equilibrium across these parameters by assessing candidate nodes based on various criteria, including node type, distance, pending tasks, and VM workload. By dynamically considering a percentage of the closest mist-type satellites and the load on VMs, APOLLO enhances orchestration efficiency, thereby optimizing satellite resource utilization. The emphasis on proximity-driven selection and load balancing mitigates resource bottlenecks, making it particularly well-suited for scenarios that prioritize energy efficiency and prompt task execution with minimal latency.

5 Results and Discussion

5.1 Simulation Environment

The simulations were conducted using the SatEdgeSim framework [19], utilizing a mobility dataset generated by the Satellite Tool Kit (STK). The key parameters for the simulation environment are summarized in Table 1.

Table 1: Simulation Environment Parameters

Parameter	**Value**
Number of Mist Satellites	500
Number of Edge Datacenter Satellites	20
Number of Cloud Satellites	10
Duration	1200 seconds
Task Generation Frequency	6 tasks per minute
Network Update Interval	1 second
Minimum Height	400.000 meters
Earth Radius	6.378.137 meters
Edge Devices Range	32.000.000 meters
Edge Datacenters Coverage	36.000.000 meters
Cloud Coverage	40.000.000 meters

5.2 Simulation Results

The simulation results were evaluated based on several key metrics. Each metric provides insights into the performance of different orchestration algorithms. The following sub-subsections discuss the outcomes of the simulation runs:

VM CPU Usage The analysis of VM CPU usage, as shown in Fig. 3, shows a usage across all schemes, including Random VM, Round Robin, and Trade-Off, exhibited consistently low levels. This can be attributed to these schemes predominantly relying on satellites with spare CPU capacity, particularly those equipped with dedicated CPUs like the upper-layer satellites. Consequently, the CPU usage remained minimal due to the efficient distribution of tasks across these less-utilized resources.

Following these schemes, the Weighted Greedy (WG) scheme demonstrated a moderate level of CPU usage. This can be attributed to its more sophisticated approach, which considers various performance indicators in task allocation. While still maintaining relatively low CPU usage compared to the APOLLO scheme, WG strikes a balance between task distribution and CPU utilization.

In contrast, our APOLLO scheme exhibited relatively higher CPU usage compared to the other schemes. This is primarily because APOLLO exclusively relies on the CPUs of lower-layer satellites, specifically those within the mist layer. As a result, the scheme's emphasis on proximity-based selection and load balancing led to higher CPU usage as tasks were concentrated on these lower-layer resources.

Overall, while APOLLO demonstrated higher CPU usage compared to other schemes, its approach prioritizing lower-layer satellite CPUs emphasizes proximity and load balancing, which are critical factors for optimizing resource utilization in satellite-based mist computing environments.

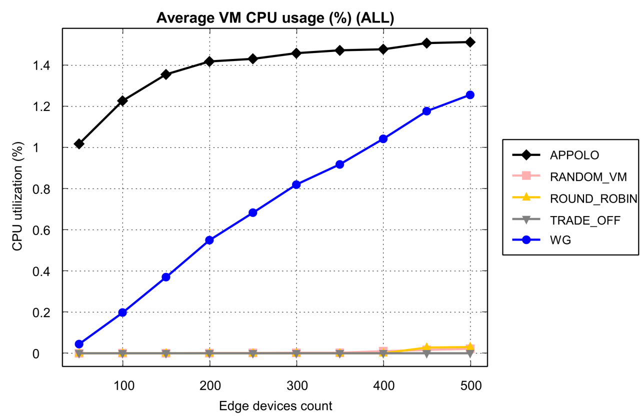


Fig. 3: The average CPU usage.

Average End-to-End Delay In terms of average end-to-end delay shown in Fig. 4, this metric is crucial for assessing latency-sensitive applications, varied across different orchestration schemes. The first three schemes, including Random VM, Round Robin, and Trade-Off, exhibited higher End-to-End Delay values. This outcome suggests that these schemes may not be suitable for applications requiring low latency due to their reliance on satellite nodes with longer communication paths or less-efficient task allocation strategies.

Following these schemes, the Weighted Greedy (WG) scheme demonstrated a moderate End-to-End Delay value. This indicates a more balanced approach compared to the earlier schemes, likely due to its consideration of multiple performance indicators in task allocation. While offering improved latency compared to the initial schemes, WG still falls short of achieving optimal latency levels.

In contrast, our APOLLO scheme yielded the lowest End-to-End Delay among all schemes, making it the most favorable for latency-sensitive applications. The scheme's reliance on nearby satellites from the mist layer facilitates shorter communication paths and more efficient task allocation. As a result, APOLLO excels in minimizing latency, offering optimal performance for applications that prioritize low End-to-End Delay.

Overall, the superior performance of the APOLLO scheme in minimizing End-to-End Delay underscores its effectiveness in achieving low-latency task execution. By leveraging close satellites from the mist layer, APOLLO ensures efficient communication and task allocation, making it highly suitable for latency-sensitive applications in satellite-based mist computing environments.

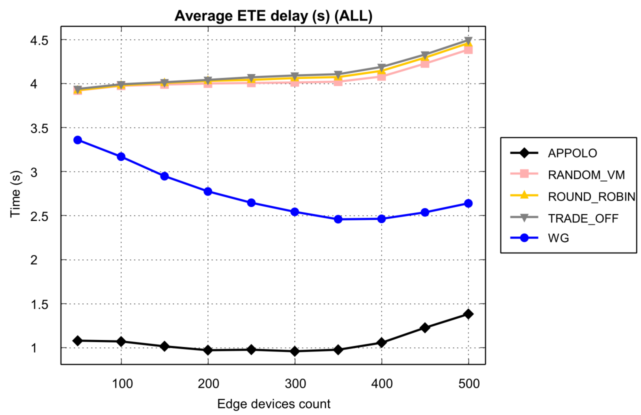


Fig. 4: The average end-to-end delay.

Satellites Energy Consumption Fig. 5 shows the assessment of Satellite Energy Consumption and revealed notable variations among different orchestration schemes. The initial three schemes, including Random VM, Round Robin, and Trade-Off, exhibited the highest energy consumption levels. This outcome indicates that these schemes may lead to excessive energy usage, likely due to their reliance on satellite nodes with longer communication distances or less-efficient task allocation strategies.

Following these schemes, the Weighted Greedy (WG) scheme demonstrated a more balanced energy consumption profile. By considering multiple factors in task allocation, including transmission distance and CPU processing time, WG achieves a more optimized use of satellite resources compared to the earlier schemes. However, despite this improvement, WG still consumes a relatively high amount of energy.

In contrast, our APOLLO scheme showcased the lowest Satellite Energy Consumption among all schemes, making it the most energy-efficient option. The scheme's reliance on nearby mist satellites, which do not involve long-range transmissions, contributes to reduced energy consumption. By minimizing the need for extensive data transmission and optimizing task allocation, APOLLO ensures efficient resource utilization while conserving energy.

Overall, the superior performance of the APOLLO scheme in minimizing Satellite Energy Consumption underscores its effectiveness in promoting energy efficiency in satellite-based mist computing environments. By leveraging close mist satellites and optimizing task allocation strategies, APOLLO offers a sustainable solution for reducing energy consumption and enhancing the overall efficiency of satellite operations.

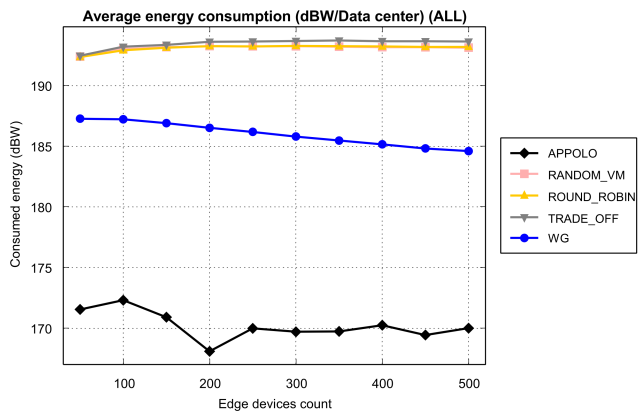


Fig. 5: The average energy consumption.

Bandwidth Usage The assessment of Bandwidth Usage shown in Fig. 6, revealed consistent trends across different orchestration schemes. The initial three schemes, including Random VM, Round Robin, and Trade-Off, demonstrated similar levels of bandwidth usage per task. These schemes achieved relatively low bandwidth consumption, indicating efficient utilization of network resources.

Following these schemes, the Weighted Greedy (WG) scheme exhibited moderate bandwidth usage per task. While WG considers multiple factors in task allocation to optimize resource utilization, its bandwidth usage remains within a reasonable range compared to the initial schemes.

In contrast, our APOLLO scheme showcased the highest bandwidth usage among all schemes. While this result may suggest relatively higher network utilization, it's important to note that the APOLLO scheme prioritizes proximity-based selection of mist satellites. As a result, tasks may be allocated to closer satellites, potentially reducing task completion times but leading to higher bandwidth consumption.

Although the bandwidth usage of the APOLLO scheme is comparatively higher, it's worth noting that this metric can be tailored and optimized based on specific application requirements and network conditions. By adjusting parameters and fine-tuning the orchestration strategy, it's possible to mitigate the impact of high bandwidth usage while still benefiting from the scheme's advantages in terms of task execution efficiency and low-latency performance.

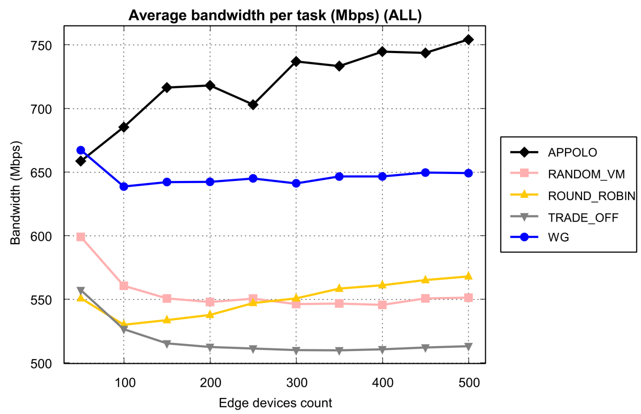
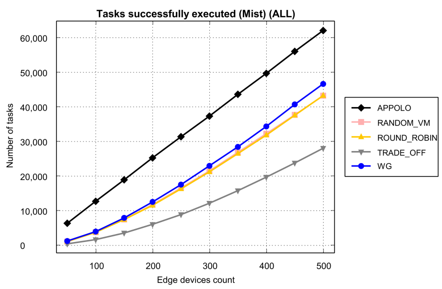


Fig. 6: The average bandwidth per task.

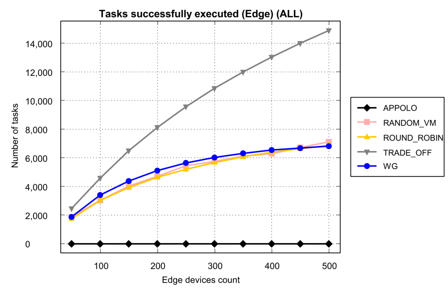
Successfully Executed Tasks As the results presented in Fig. 7a, Fig. 7b, Fig. 7c, and Fig. 7d, our APOLLO scheme operates exclusively within the mist layer, resulting in zero successfully executed tasks in the edge and cloud layers. This specificity is reflected in the scheme's high success rate for tasks executed within the mist layer. However, it's important to note that as the number of mist satellites increases, the success rate of APOLLO slightly declines. This decline can be attributed to the random augmentation of mist satellites, which may result in their dispersion across sparse locations, impacting the scheme's effectiveness.

Additionally, while the APOLLO scheme excels in the mist layer, the Trade-Off algorithm demonstrates better performance in the edge and cloud layers. This observation highlights the versatility of the Trade-Off algorithm, which may be better suited for distributing tasks across multiple layers in satellite-based mist computing environments.

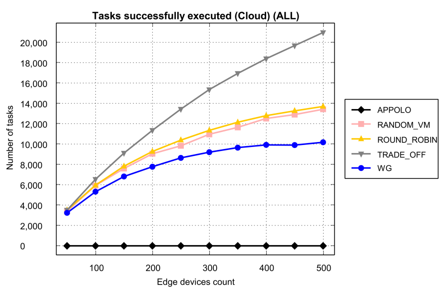
Overall, the performance of each scheme in terms of successfully executed tasks underscores the importance of considering the specific characteristics and requirements of different layers within the computing environment. While APOLLO excels in the mist layer, other algorithms may offer better performance in different layers, suggesting the need for tailored orchestration strategies to optimize task execution across the entire system.



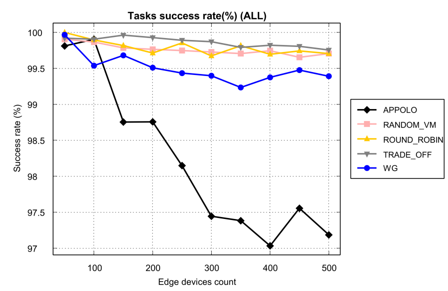
(a) Mist level successfully executed tasks.



(b) Edge level successfully executed tasks.



(c) Cloud level successfully executed tasks.



(d) Successfully executed tasks for all layers.

Fig. 7: Overall Task Execution

6 Conclusion and Future Work

In conclusion, our APOLLO scheme presents a promising solution for task orchestration in satellite-based mist computing environments. Through prioritizing proximity-based selection and load balancing, APOLLO effectively optimizes task deployment, resulting in superior energy efficiency and minimal end-to-end delays, especially in scenarios with a limited number of satellites.

However, it's important to acknowledge the scheme's limitations, particularly in terms of CPU and bandwidth usage. APOLLO's reliance on lower-layer mist satellites may lead to higher CPU utilization and bandwidth consumption compared to other schemes, particularly in environments with a larger number of satellites.

Furthermore, while APOLLO demonstrates strong performance in terms of successfully executed tasks, its effectiveness may diminish as the number of satellites increases. The scheme's dependency on a smaller number of mist satellites may pose challenges in scenarios where extensive satellite coverage is required.

In summary, APOLLO represents a valuable addition to the repertoire of task orchestration algorithms for satellite-based mist computing. Its strengths lie in energy efficiency, minimal end-to-end delays, and task success rates in environments with fewer satellites. However, considerations must be made for its performance in environments with higher satellite density and its impact on CPU and bandwidth utilization. Future research could focus on optimizing APOLLO's performance in diverse satellite deployment scenarios and addressing its limitations to further enhance its effectiveness and applicability in real-world settings.

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