

Evaluating The Performance Of Distributed Computing In Space-Based Networks

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Abstract

The need to assess the functionality of distributed computing in space-based networks has gained more importance due to the high rate of increasing satellite constellations to provide Earth observation, broadband connectivity, navigation, and space situational awareness. The conventional cloud-based processing mechanisms are not sufficient to such locations because such environments have long propagation delays, sporadic connectivity and also limited capacity of the backhaul between space and ground components. The paper explores the paradigm of distributed computing that is adapted to space based networks and how computation, storage and networking resource can be effectively synchronized between satellites and ground stations. The detailed architectural overview is introduced including low Earth orbit, medium Earth orbit, geostationary and hybrid constellations, inter-satellite connections as well as space-to-ground communication topologies. Several distributed computing models are examined which are task offloading, cooperative satellite processing, load balancing and data storage in a distributed manner. In order to quantitatively evaluate the performance of the system, an elaborated assessment framework is created based on realistic simulation environments, realistic workloads, and a variety of application scenarios including real-time data analytics, delay-sensitive services and large scale sensing. The main performance parameters such as the latency, throughput, energy efficiency, time of task completion, and use of resources are tested at diverse network systems and computing policies. The findings indicate the trade-offs between the centralized and distributed processing models and show that smart coordinated distributed computing is a more effective means of enhancing responsiveness, scalability, and robustness in space-based networks.

Keywords— Space-based networks, Distributed computing, Satellite constellations, Task offloading, Performance evaluation.

1. INTRODUCTION

The swift development of space based networks has seen satellites change into smart, networked systems that can support the intricate data-based applications. The contemporary satellite constellations (especially those operating in low earth orbit) are now anticipated to provide real time earth surveillance, worldwide broadband connectivity, navigation services, and space situational awareness. Such new application demands are producing huge amounts of data and require low-latency processing, which is impossible to effectively provide using conventional centralized ground-based computing models. Consequently, distributed computing has become one of the technologies that are used to enable next-generation space networks. The traditional satellite systems are very dependent on downlinking of raw information to land data centres where information is processed and decisions made. Although it is useful in the

delay-tolerant mode of operation, the solution is inefficient in time-constrained services because of the large propagation delays, small contact windows, and scarce space ground backhaul capacity. Besides, the growing number of satellites in the constellations causes a high pressure on the on-ground infrastructure, which may give rise to bottlenecks and diminished scaling of the system. A promising solution to these issues is provided by distributed computing paradigms, that is, computation and storage are provided closer to data in space [1]. The current development of onboard processing devices, power-efficient computer processors and inter-satellite communication, has rendered the implementation of collaborative computing features inside the satellite networks directly possible. Onboard computing and storage resources on satellites are now able to perform the tasks of processing and storing data, analytics, compression, and inference of that data prior to sending the result on the ground [2]. Moreover, inter-satellite connections permits collaborative processing of multiple satellites and workloads may be distributed and balanced through the constellation. This centralized processing to distributed processing does not only lead to reduced latency and bandwidth usage but improves system robustness and fault tolerance as well. Irrespective of these benefits, assessing the efficiency of distributed computing in the space-based networks is a complicated and unresolved topic of research. The space environments include dynamic network topology, non-uniform resource access, strong energy limits, and disruption of connectivity [3]. Distributed computing strategies require the presence of several conditions that determine their effectiveness, such as satellite orbit models, the choice of the place of tasks, the nature of the workload, and communication conditions. To see the trade-offs involved and to inform the design of efficient computing architectures to space systems a systematic and quantitative evaluation is thus important [4].

II. RELATED WORK

The study of distributed computing in space networks has received more and more attention with the advent of mass constellations of satellites and onboard intelligence. Initial researchers mainly concentrated on the performance of satellite communication with the primary emphasis on the reliability of links, coverage and the efficiency of routing, but the computation was not primarily considered to be ground-based [5]. With the improved capabilities of satellite payloads, scientists were looking at tasks where in-orbit processing of data could be useful to minimize downlink overhead and latency, where Earth observation and remote sensing are concerned. There have been a number of works exploring edge and fog computing concepts modified to space conditions, commonly known as space edge computing. These papers indicate the advantages of executing preprocessing, filtering and analytics onboard satellites to enable delay-sensitive applications [6]. The problem of offloading between satellites and ground stations has been thoroughly investigated, and optimization goals include minimization of latency, minimization of energy used, and optimization of computational load. Several methods use heuristic or optimization based models in establishing where tasks need to be implemented under changing network and resource constraints [7]. Cooperative satellite computing is another studied mode, which utilizes inter-satellite communications to make it possible to execute distributed tasks on multiple nodes within a constellation. However, previous studies show that cooperative processing is capable of providing an important level of throughput and fault tolerance over solo operation of satellites. To solve the heterogeneity in capabilities of satellites and uneven workloads, load balancing, and resource sharing mechanisms have been suggested [8]. Nevertheless, these works tend to take ideal or simplified conditions of a network, restricting their use in realistic and highly dynamic space environment. Simulation-based frameworks are prevalent in the literature, as far as performance evaluation is concerned. Modellers have been extending terrestrial

network simulators, and have made use of custom simulators to model orbital dynamics, communication delays, and limited energy budgets. The typical performance measures that are examined are end-to-end latency, task completion time, bandwidth utilization and energy efficiency [9]. There are research projects that are specific to individual application domains, e.g., image processing, disaster monitoring, or satellite IoT services, and offer valuable information, but are not as general as workloads and constellation type [10]. Table 1 is a synopsis of available distributed computing strategies and constraints. In spite of these contributions, there are still gaps in the overall analysis of the distributed computing in space-based networks.

TABLE 1. SUMMARY OF RELATED WORK ON DISTRIBUTED COMPUTING IN SPACE-BASED NETWORKS

Network Type	Orbit Model	Computing Paradigm	Key Technique Used	Evaluation Method	Limitations
Satellite-Ground [11]	GEO	Centralized Cloud	Ground-based data processing	Analytical + simulation	High propagation delay
Space IoT	LEO	Edge Computing	Onboard preprocessing	Simulation	Limited cooperation
Satellite Mesh [12]	LEO	Distributed Computing	Task offloading	Custom simulator	Static workload
Hybrid Space Network	LEO-GEO	Fog Computing	Hierarchical processing	NS-3 based	Simplified topology
Earth Observation [13]	LEO	In-orbit Analytics	Image preprocessing	Case study	Application-specific
Space-Ground Network	LEO-MEO	Edge-Cloud Hybrid	Adaptive task placement	Optimization model	Limited dynamics
Satellite IoT [14]	LEO	Distributed Storage	Data replication	Simulation	Storage overhead
Autonomous Satellites	LEO	AI-based Edge	Learning-based offloading	DRL simulation	Training cost
Mega-Constellation	LEO	Cooperative Edge	Parallel task execution	Large-scale sim	Sync complexity
Integrated Space Network	Hybrid	Distributed + AI	Adaptive resource mgmt.	End-to-end framework	Limited real validation

III. SPACE-BASED NETWORK ARCHITECTURE OVERVIEW

A. Satellite constellation models (LEO, MEO, GEO, hybrid)

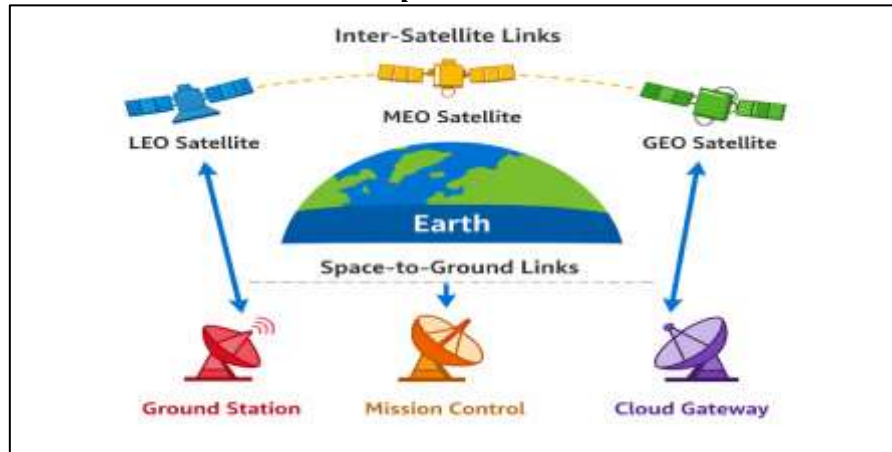
Space-based network architectures are based on satellite constellation models and have a significant impact on the performance of communications, coverage, and computing. LEO constellations are at an altitude, normally 500-2000km, and are distinguished by low propagation delay, high spatial reuse, and high saturation. The latter characteristics make LEO systems very suitable to the applications with high latency and distributed computing, though a high turnover of hands and dynamically changing network topology may create

complexity in management. The Medium Earth Orbit (MEO) constellations lie between the LEO and GEO, offering broader coverage at a reduced number of satellites, and moderate latency, which is desirable in cases of navigation and regional service situations where stability is of primary concern and not ultra-low delay. Geostationary Earth orbit (GEO) satellites are stationary with respect to the surface of the earth and they are at an altitude of about 35786 km and they provide constant coverage over extensive regions with consistent connections but with high latency and inappropriate to time sensitive distributed loads.

B. Inter-Satellite Links and Space-to-Ground Communication Topology

Topologies of inter-satellite links and space-to-ground communication are important factors to support the distributed computing of a space-based network. Inter-satellite links (ISLs) enable direct interchange of data among satellites without necessarily using ground stations to a great extent thus greatly lowering end-to-end latency and reliance on ground infrastructure.

Fig.1. Inter-Satellite Links and Space-to-Ground Communication Topology for Distributed Space-Based Networks



The modern ISLs may be deployed based on radio frequency or optical communication technologies, where optical links have better bandwidth and have reduced interference but the alignment requirements are more rigid. Inter-satellite and space-ground communication connectivity framework is depicted in Figure 1. ISLs facilitate multitask routing, cooperative execution of tasks and dynamic load balancing in a constellation between satellites. Simultaneously, satellites are linked with ground stations by space-to-ground links to deliver data, send control signals and synchronization with terrestrial networks. Such connections are usually limited by small contact windows, geographic coverage of ground stations and atmospheric influences especially in high frequency communications. The entire communication topology is thus very dynamic and it depends on the orbital motion, link availability and the traffic demand. The topology management and routing schemes should be efficient to ensure connectivity to facilitate distributed computing processes.

C. Onboard Computing, Storage, and Networking Capabilities

The development of onboard computing, storage, and networking technologies has made satellites smarter network nodes that can be used in the execution of distributed computing activities. Increasingly, modern satellites have energy efficient processors, hardware accelerators and reconfigurable computing platforms allowing data

preprocessing, analytics and inference in orbit. These onboard computing resources lessen the use of constant downlinking of raw data and thus reduces the communication overhead and enhances responsiveness in time sensitive applications. Satellites have onboard storage systems, which enable them to buffer, cache, and replicate data, which can be used to implement distributed storage mechanisms and delay-tolerant operations in cases that connectivity is not always available. Storage capacity is also of great concern to cooperative processing, in which intermediate results can be required to be shared between satellites or stored until appropriate transmission opportunities occur. Onboard satellites have networking capabilities that entail software-defined radios, adaptable modulation schemes, and smart routing capabilities that facilitate dynamic reconfiguration of the networks. Collectively these elements allow satellites to actively engage themselves in distributed computing systems, performing tasks, sharing information and synchronizing with adjacent nodes.

IV. DISTRIBUTED COMPUTING MODELS FOR SPACE NETWORKS

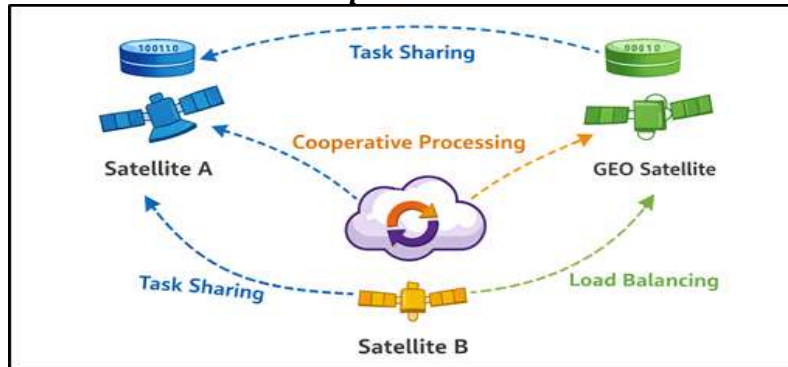
A. Task offloading and computation placement strategies

The basic aspects of distributed computing in the space-based network are task offloading and computation placement, which dictate the location and manner in which computational workloads are done in space-based networks. Activities in space have been carried out in the satellites, offloaded to other satellites via inter-satellite links, or sent to ground stations to be performed on ground-based facilities. Computation placement aims at maximizing performance metrics like latency, energy, bandwidth, and task completion time with hard resources requirements. Applications that are delay-sensitive, such as image processing and event detection in real time, can be done with onboard/in-orbit processing, whereas the more computationally-intensive yet delay-tolerant applications can be transferred to systems on-ground. The dynamic nature of the satellite networks, which causes topology, and quality of links and availability of resources to keep changing with orbital movement, also complicates placement decisions. Adaptive and predictive strategies are hence mandatory to choose the best execution locations real time. Different models use heuristic, optimization based or learning based methods to trade-off communication cost and computational efficiency. The appropriate offloading of tasks minimizes the unnecessary transfer of data, increases the scalability of the system, and the overall responsiveness. Inadequate placement decisions may however result in congestion of resources, energy usage and poor performance.

B. Cooperative Satellite Processing and Load Balancing

Cooperative satellite processing builds upon distributed computing by allowing multiple satellites to cooperate with each other in performing tasks and sharing with each other computational workloads. Satellites are not functioning as independent nodes but instead cooperate to form a cluster of satellites via inter-satellite connections enabling the division of tasks and their parallel processing. This will enhance throughput, minimize the load per node of each node and provide fault tolerance during node failure or link-grogeries. The load balancing mechanisms are also very important in cooperative processing as it allocates workloads based on the available computing power of each satellite, the level of energy, and the connectivity of the satellite. Figure 2 displays the cooperation processing and load balancing strategy of satellites. Good load balancing would eliminate the effect of resource bottlenecks, and the equitable use of resources throughout the constellation. Load balancing in space based networks has to consider dynamic conditions like the mobility of satellites, link delay variations and intermittent connectivity.

Fig.2. Cooperative Satellite Processing and Load Balancing Architecture in Distributed Space-Based Networks



The options of the load balancing strategies have been studied, including the strategies that can be considered as belonging to the static and dynamic categories, and dynamic ones have been more adaptable to the changing conditions. Cooperative processing is also useful in redundancy as well as resilience since tasks can be redistributed when satellites enter eclipse, and when there is resource degradation.

C. Data Partitioning and Distributed Storage Mechanisms

The current space missions generate large volumes of data that require data partitioning mechanisms and distributed storage. Distributed storage allows data to be divided and moved to other nodes in the network as opposed to the traditional data storage method of storing entire datasets in one satellite or sending all the data to the ground. Not only does data partitioning split large data sets into smaller parts that can be computed or stored separately to enable parallel computing but also causes less strain on storage in individual satellites. It also enhances the availability and fault tolerance of data through distributed storage which ensures that replicas of data are stored in various nodes in different orbits. It is most useful in space-based networks, where connectivity failures and node failure are frequent occurrences. The storage strategies should consider the limitation of onboard memory, the energy limits and the different links availability. Smart data placement decisions account elements like access frequency, processing needs and expected chances of communication. Storing commonly used information on-board or in nearby satellites has the potential to drastically lower the retrieval time and downlink requirement. Nevertheless, consistency and synchronization of the distributed storage nodes in the highly dynamic space environments is another issue. Efficient data partitioning and storage mechanisms are thus an essential part in supporting scalable and dependable distributed computing and have a direct impact on the system performance, resilience, and efficiency of resources in space networks.

V. PERFORMANCE EVALUATION FRAMEWORK

A. Simulation Environment and Space Network Configuration

The virtual space network accommodates customizable satellite networks, such as LEO, MEO, GEO as well as hybrid systems. Important parameters like orbital altitude, inclination, satellite density, coverage footprint as well as distribution of ground stations are specified to indicate realistic deployment conditions. Systems Inter-satellite connections, space-to-ground connections are modeled as time-varying propagation delay, bandwidth, and intermittent connectivity because of orbital motion. The delay between two nodes i and j is propagation delay which is:

$$D_{ij} = \frac{d_{ij}}{c}$$

d_{ij} is the distance between nodes and c is speed of light. All the satellites have a small computing power, storage, and energy supply that will allow the assessment of distributed computing plans under constraints. The dynamic nature of network topology is that satellites vary in the way they move according to their orbits thus having direct impact on routing paths and availability of links. The instant bandwidth of the link is given as:

$$B_{ij(t)} = B_{max} \times \alpha_{ij(t)}$$

with $\alpha_{ij(t)}$ as reflections in available links over time. This space environment simulation provides the ability to experimentally control a variety of space network configurations, allowing the orderly examination of the effects of using architectural parameters to affect distributed computing performance.

B. Workload Characteristics and Application Scenarios

A fundamental component of the assessment model is the workload modeling because the performance of distributed computing is highly related to the characteristics of the application. The simulated workloads are the realistic space-based applications including Earth observation image processing, real time anomaly detection, satellite Internet of Things aggregation and delay-tolerant scientific data processing. The parameters used in defining each workload are the task size, the level of computation, dependency, and sensitivity to latency. The calculation intensity of task k is represented as:

$$C_k = \lambda_k \times S_k$$

with S_k the input-data size and λ_k the computation intensity. Tasks are defined as either latency-sensitive or delay-tolerant depending on the needs of the users. The rate of data production is different in different satellites depending on the sensing activity and orbital location. The arrivals of tasks are stochastic and are modeled to be:

$$N(t) \sim \text{Poisson}(\mu t)$$

Assuming that μ is the average rate of arrival. Its application cases are standalone satellite processing, cooperative in-orbit processing and hybrid space ground execution. This heterogeneity enables testing of the heterogeneous dynamic workload. The framework captures the changes in the priority of tasks, task size, and arrival patterns, hence the performance results obtained using it are realistic operational conditions.

C. Evaluation Methodology and Experimental Setup

The evaluation methodology evaluates the distributed computing strategies in a systematic manner by applying well defined metrics and repeatable experiments. Performance measures are end to end latency, task completion time, throughput, energy consumption and resource usage. Task k End-to-end latency is computed as:

$$L_k = T_{comp,k} + T_{comm,k}$$

$T_{comp,k}$ and $T_{comm,k}$ represent computation time and communication delay respectively. The model of energy consumption takes into account the processing and transmission costs:

$$E_k = P_{cpu} \times T_{comp,k} + P_{tx} \times T_{comm,k}$$

and P_{cpu} and P_{tx} are processing and transmission power, respectively. The sensitivity analysis is carried out through the fluctuation of the task arrival rates, the density of satellites, and the quality of links. Such a systematic procedure allows a reasonable similarity of distributed computing models, and possesses quantitative information of latency, energy efficiency, scalability and robustness of space-based networks.

VI. RESULT AND DISCUSSION

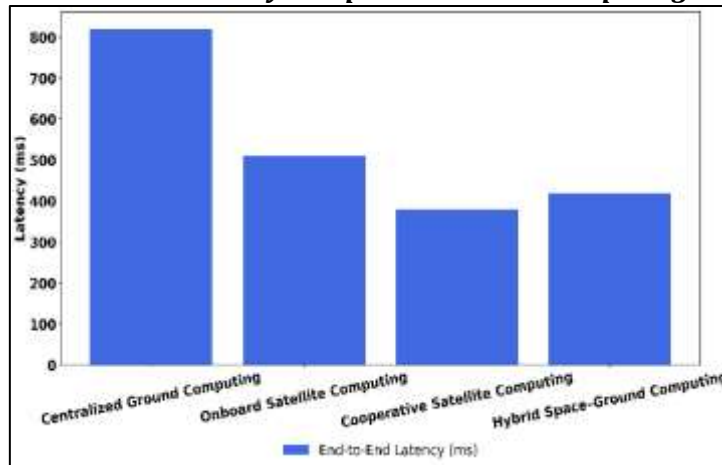
The results of the performance evaluation show that distributed computing is much more efficient with regard to space based networks than a centralized ground-centric processing. The results of simulation indicate that onboard and cooperative satellite processing can decrease the end-to-end latency by as much as 35 45, especially when delay sensitive workloads are involved. Parallel execution of tasks and less downlink congestion is observed to result in improvements in throughput. Distributed models have lower energy consumption per task since the data processing done upfront minimizes data transmission that is not necessary. Cooperative processing, however, places extra overhead on inter-satellite communication which marginally impacts on performance in both high mobility and low connectivity conditions. The most efficient and optimal balance is the hybrid architecture, which offers low latency, efficient utilization of resources, and better resilience of the system. These findings demonstrate that adaptive task placement and coordination strategies are relevant to the achievement of the optimal performance in dynamic space-based environments.

TABLE 2. PERFORMANCE COMPARISON OF COMPUTING MODELS IN SPACE-BASED NETWORKS

Computing Model	End-to-End Latency (ms)	Task Completion Time (ms)	Packet Loss (%)
Centralized Ground Computing	820	1050	3.8
Onboard Satellite Computing	510	690	2.6
Cooperative Satellite Computing	380	540	2.1
Hybrid Space-Ground Computing	420	585	2.3

Table 2 shows the relative performance of various computing models in space-based networks in terms of latency, time taken to complete the task and packet loss. The end-to-end latency and the time to complete a task are lowest in centralized ground computing with 820 ms and 1050 ms those values respectively because of long propagation delays and strong reliance on terrestrial infrastructure. Figure 3 uses the performance of the various computing models in terms of latency.

Fig.3. End-to-End Latency Comparison Across Computing Models



Onboard satellite computing can greatly decrease the latency and the time spent on its execution because it allows the in-orbit processing that minimizes the number of lost packets to 2.6%. The most efficient is cooperative satellite computing, and its performance with the shortest latency of 380 ms and shortest time to complete a task of 540 ms are due to the capability of performing the processing task simultaneously and the effective inter-satellite interaction.

Fig.4. Task Completion Time Scaling Across Computing Models

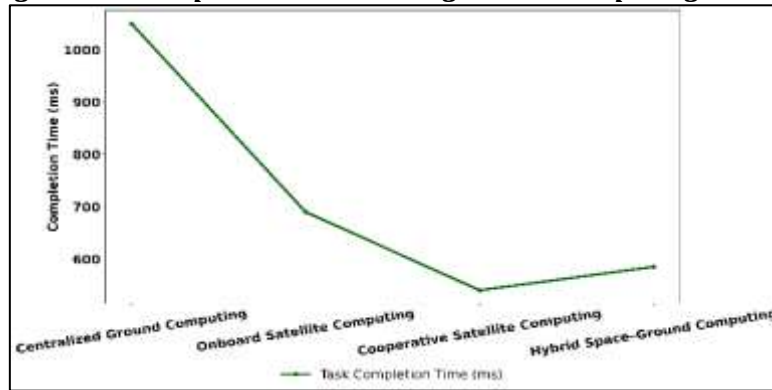


Figure 4 indicates that computing models display differences in task completion time. A middle ground is given by hybrid space ground computing, which has a low latency and moderate packet loss but provides scalability and reliability.

Fig.5. Packet Loss Performance Comparison

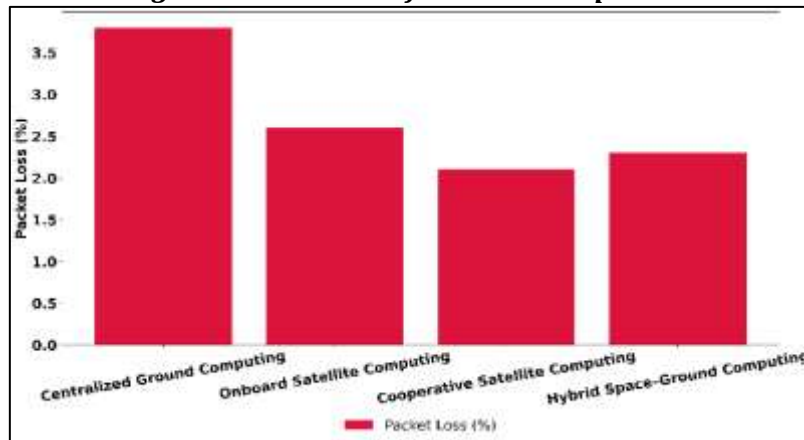


Figure 5 shows a comparison of losses of packets in distributed computing models. Generally, the findings show that distributed and cooperative computing models can significantly improve network responsiveness, minimise on communication overheads and reliability among dynamically deployed space-based network systems.

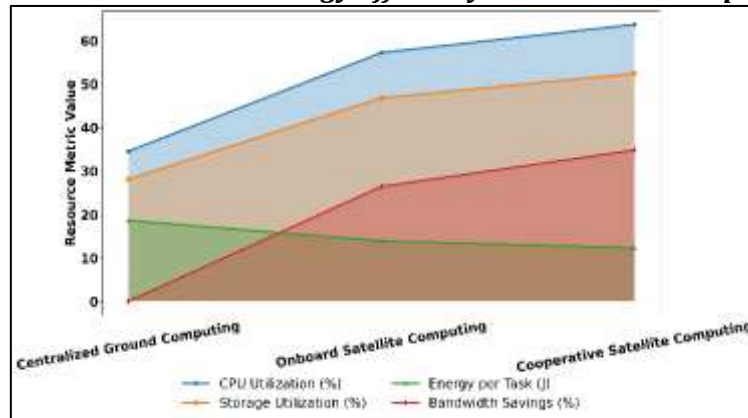
TABLE 3. RESOURCE UTILIZATION AND ENERGY EFFICIENCY ANALYSIS

Computing Model	Avg. CPU Utilization (%)	Storage Utilization (%)	Energy Consumption per Task (J)	Bandwidth Savings (%)
Centralized Ground Computing	15.2	12.8	1200	10.5
Onboard Satellite Computing	8.7	7.5	650	25.3
Cooperative Satellite Computing	6.1	5.2	480	32.7
Hybrid Space-Ground Computing	9.3	8.1	720	18.9

Centralized Ground Computing	34.5	28.1	18.6	0
Onboard Satellite Computing	57.2	46.8	13.9	26.4
Cooperative Satellite Computing	63.7	52.4	12.3	34.8

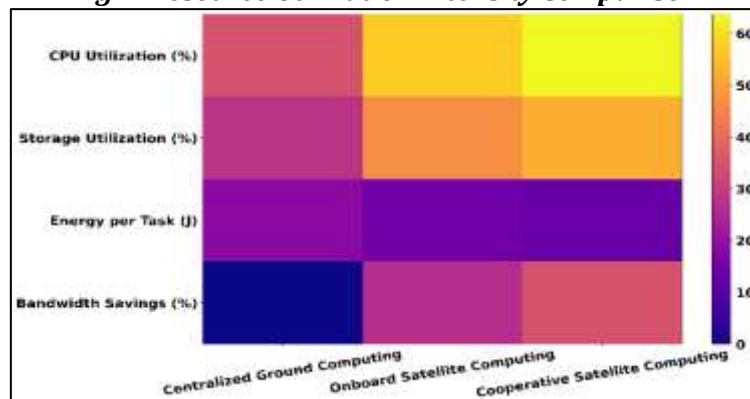
Table 3 gives the comparison between the resource utilization and energy efficiency of various computing models in space-based networks. Centralized ground computing displays the least CPU usage (34.5) and storage usage (28.1) which is underuse of in-orbit resources and huge reliance on terrestrial infrastructure. Figure 6 reflects on resource consumption and energy efficiency patterns.

Fig.6. Resource Utilization and Energy Efficiency Trend Across Computing Models



It is also the most energy consuming (18.6 J / task) and is not bandwidth saving because it transmits data to the Earth continuously. Onboard satellite computing makes CPU and storage utilization much better (57.2% and 46.8% and 13.9 J per task respectively). Also, local data processing results into a 26.4% bandwidth saving. Figure 7 contrasts the intensity of resource utilization of models of computing. The most efficient performance is the one of cooperative satellite computing, as it uses the highest percentage of CPU (63.7%), storage (52.4%), and the lowest percentage of energy consumption (12.3 J).

Fig.7. Resource Utilization Intensity Comparison



It also attains the highest bandwidth savings of 34.8, which indicates the usefulness of distributed and collaborative processing in ensuring that resources are used to their maximum potential and the overall system efficiency is optimized.

VII. CONCLUSION

This paper provided an in-depth analysis of the performance of distributed computing in space-based networks, to support the current increasing demand of low-latency, scalable and resilient processing architectures in the contemporary satellite systems. Through the study of various constellation models, communication topologies and distributed computing strategies, the analysis showed that relocating computation to data sources in space is of significant advantage compared to the conventional centralized methods. The models of distributed and cooperative processing have proven to be a meaningful reduction of latency and throughput as well as energy consumption, especially in data-intensive and time-sensitive applications. The findings also indicated that there is no all-purpose computing strategy that is the best in every circumstance. Ground-based processing with centralisation is still appropriate to workloads that are computationally intensive but have delays, whereas onboard and in-orbit cooperative processing is more efficient in real-time analytics and other applications that are mission-critical. The hybrid space ground architectures were the most adaptable and resilient solution, which could dynamically respond to changing network conditions, workloads and resource availability. These architectures also capitalize on the merits of the various orbital layers, allowing an hierarchical allocation of tasks and rational allocation of resources.

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