Space Data Center Networks - Latency and PUE

Ayodele A Periola
Electrical, Electronic and Computer Engineering
Cape Peninsula University of Technology
Cape Town, Western Cape, South Africa
periolaa@cput.ac.za

Abstract

Abstract – Landlock locations with limited water resources cannot host computing platforms to ensure content access. Subscribers at such locations access internet content via accessing distant terrestrial data centers. This involves forwarding between numerous internet exchange points leading to high latency. The use of space-based data centers (SBDCs) reduces dependence on terrestrial power grid and enables landlocked region subscribers to reduce this latency. This is because of reduced interaction between internet exchange points. SBDCs also requires a ground segment to enable information transfer to terrestrial networks for final subscriber access. It is important to ensure good performance for power usage effectiveness (PUE). The research addresses the challenge of designing a multiple hop multiple satellite architecture for enabling low latency content access from SBDCs. It proposes architecture where each ground station has a solar powered modular data centre and a standalone cooling system. Architecture reduces the overhead thereby enhancing the PUE. Analysis shows that using the proposed approach reduces the latency by up to 5% and enhances the PUE by up to 17.7%. .

Keywords

Space Data Centers, Water, PUE, Landlocked, Latency.

ACM Reference Format:
Ayodele A Periola. 2025. Space Data Center Networks - Latency and PUE. In *2025 International Conference on Artificial Intelligence, Big Data, Computing and Data Communication Systems (icABCD 2025), November 26–27, 2025, Cape Town, South Africa.* ACM, New York, NY, USA, 7 pages. https://doi.org/10.1145/3759023.3759093

1 Introduction

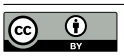
The realization of hyper-connectivity in future generation networks is an important [6, 7, 9, 17]. Hyper-connectivity implies continued session continuity for subscribers connected to communication networks. This is an important objective to be achieved for subscribers connected to cloud platforms integrated networks. Cloud platform integrated platform integrated networks enable subscribers to access content from terrestrial and non-terrestrial data centers.

Non-terrestrial data centers can be sited in the stratosphere [1, 11, 12], underwater environment [13, 16, 18, 20], and in space [3, 10]. Computing platforms in these locations have environment-friendly operation. This is because they have low water usage in comparison to terrestrial data centers. The deployment of stratosphere-based data centers (STBCs) and space-based data centers (SBDCs) is beneficial for developing countries with an increasing population. This is because of the low land footprint.

The use of SBDCs is most appropriate in landlocked high population scenarios where low to zero land footprint is required. Examples of countries in this regard are Burkina Faso, Ethiopia, and Mali Therefore, it is important to investigate the ability of SBDCs to provide long connectivity sessions. SBDCs should support hyper-connectivity using SBDCs in seventh generation (7G) communication networks.

The research contribution is the investigation of the ability of SBDCs to support hyper-connectivity in the 7G context. SBDCs provide cloud data coverage in a location with low water footprint and low development in aviation infrastructure. In this consideration, the ability of a constellation of SBDCs to provide hyper-connectivity in landlocked regions. In addition, the use of SBDCs in a manner that enables the realization of hyper-connectivity requires the design of a supporting ground infrastructure. The conduct of research in a manner that involves using multiple SBDCs as satellites is at a nascent stage and has not received significant research attention as seen in [3, 10].The research in [3] is seminal and focuses on the use of small satellites, not large structures as envisaged in the SBDC. A network architecture where data centres are present in space and ground segment is presented here thereby extending [3] where data processing occurs in the space segment only via the micro datacenter. The research makes the following contributions:

(1) First, it proposes a network architecture that supports the execution of multiple–hops and multiple satellites (MHMS) with focus on the role of SBDCs constellations to provide data coverage and footprint alongside hyper-connectivity within the context of 7G. The MHMS is realized in a satellite constellation with satellites having intersatellite links and capable of executing data forwarding. Data forwarding can be realized via either intersatellite link or via the ground station. The network architecture is designed for use in areas with the profile of high population (necessitating low to zero land footprint), low to zero water footprint, and low to zero marginal aviation infrastructure within a developing context. The MHMS network architecture is executed within the context of a ground station as s service. The ground station as a service is provided by computing platform service provider operating a green modular data center (GMDC).
(2) Second, the research presents a framework enabling the use of SBDCs provisioning data transport and storage services to both satellites in the low earth orbit and ground stations (in the ground segment). The ground segment hosts a terrestrial network that interfaces with the GMDC. The GMDC hosts



This work is licensed under a Creative Commons Attribution 4.0 International License.
icABCD 2025, Cape Town, South Africa
© 2025 Copyright held by the owner/author(s).
ACM ISBN 979-8-4007-1427-6/25/11
https://doi.org/10.1145/3759023.3759093

power entities benefiting from the use of solar energy and nuclear energy. In the designed and supporting energy system, nuclear energy enables the realization of power provisioning considering the occurrence of variability in the harnessing of solar energy. The ground segment aspect is executed by the GMDC that supports data forwarding to other low earth orbiting satellites. In this way, the GMDC participates in the forwarding of data. The data is forwarded through a multi-constellation. The large multi-constellation comprises small satellites. These small satellites are in low earth orbit. They provide internet connectivity. The execution of this functionality enables the realization of hyper-connectivity (with minimal interference).

(3) Third, the research formulates and investigates the performance of the proposed MHMS and GMDC integrated network. The performance metrics are the power usage effectiveness (PUE), and the latency. The PUE is formulated for a case where the concerned region hosts multiple terrestrial data centers (existing approach) in comparison to using GMDCs. The latency is formulated for the existing case and proposed case. In this context, the existing case is when data access is executed via remote terrestrial data center access.

The rest of the presentation is organized as follows. Section 2 presents the proposed network architecture with a focus on the space and ground segments in the MHMS network. This section also presents the power subsystem enabling the use of nuclear energy as a supporting power source to the MHMS's ground segment. Section 3 formulates the performance model. Section 4 investigates performance evaluation and simulation. Section 5 is the conclusion.

2 Proposed Network Architecture

The proposed network architecture is discussed in this section. The network architecture has two aspects, i.e., the space segment and ground segment. The space segment comprises SBDC constellations and satellites. The SBDC constellation is based on the medium earth orbit. It does not use the orbital resources of the low earth orbit. The reason for the use of the medium earth orbit is its reduced orbital congestion compared to the low earth orbit. The satellites considered are in the low earth orbit. These satellites execute applications such as earth observations and broadband communications. However, these satellites have the capability to host inter-satellite links. Such satellites are technologically feasible as seen in [2, 5, 15].

The ground segment comprises ground stations in the desired location. The ground stations execute two roles. They enable accessing information by subscribers from the cloud via the in-orbit SBDC. The ground station also enables data forwarding between the SBDCs and other satellites. Such satellites are in the low earth orbit and do not have intersatellite links. The ground station has a modular data center enabling the temporary storage and processing of data. Data storage and processing by the ground station is realized via the modular data center. The modular data center is powered via solar power. In the considered context, there are multiple modular data centers alongside ground stations. The use of modular data centers is beneficial for the satellite network operator because it enables the realization of computing systems at low cost. This is because modular data centers have lower capital and operational costs than conventional terrestrial data centers. The availability of multiple modular data centers, and ground stations across the desired location increases the meaningful communication duration. In this case, each ground station has an associated modular data center. The sources of power in this case are solar (as primary) and nuclear (as secondary). Nano nuclear modular plants (NNMPs) are used to supplement the power provided by the solar system with relation to enabling GMDC operation. This is essential when there is no solar radiation incident and battery power is depleted. Its use as a backup is suitable when the GMDC is located in regions without grid coverage, and a supporting backup power source is required.

NNMPs are nuclear plants (smaller than small modular reactors) being used for modular data center operation. They are not intended to replace the small modular reactors. Instead, they meet the appeal of another type of end user. Being smaller, they can be used by application service providers with significant capital constraints. The use of a single modular reactor instead of an NNMP array is also feasible. In this case, the single modular reactor capability is shared across multiple ground entities.

The ground station integrated with a modular data center utilizing solar and nuclear power sources is called the green modular data center (GMDC). The GMDC comprises the: (i) Communication Subsystem, (ii) Computing Subsystem, and (iv) Power Subsystem.

The communication subsystem executes the functions of receiving data from the SBDC and forwarding the data to the user via the terrestrial wireless network. GMDC–Terrestrial wireless network transmission is realized via wired media using high speed fibre optic cable. In addition, communication subsystems enable data forwarding between SBDC (medium earth orbit) and satellites (in the low earth orbit). This enables the execution of an SBDC to satellite hop. In addition, the GMDC forwards a request for data access by a user received from the terrestrial wireless network base station. The request is forwarded to the SBDC to enable data access on the download. The entities in the communications system are the GMDC–forwarding entity (GFE), GMDC–uploading entity (GUE), and GMDC - downloading entity (GDE). The relations between the GFE, GDE, and GUE are shown in Figure 1. The role of the GMDC in a forwarding role is shown in Figure 2.

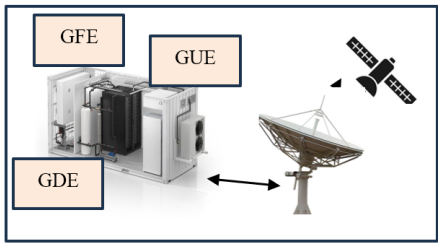


Figure 1: Relations between GMDC (showing GFE, GUE, GDE), ground segment and space segment.

The computing system comprises the modular data center associated with the GMDC. It executes the functionalities of data storage and algorithm processing. In addition, the computing system enables the temporary storage of content files. These files are

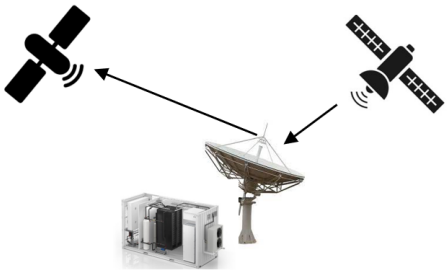


Figure 2: GMDC forwarding data between satellites in an MHMS context.

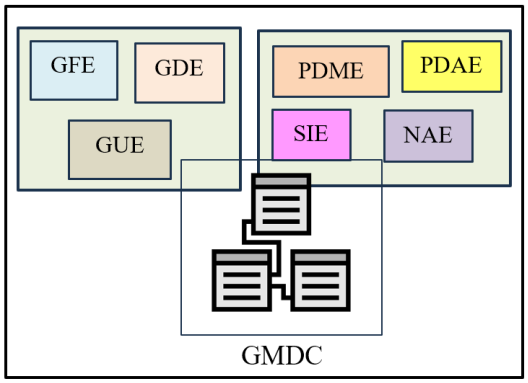


Figure 3: Relations between communication and power system related entities for the GMDC.

temporarily stored aboard the modular data center prior to forwarding to the terrestrial wireless network for subscriber access later. The core component of the computing system is the modular data center. In the concerned architecture, multiple modular data centers are associated with a ground station. This is necessary to ensure the storage and processing of a significant amount of data.

The power system enables the provision of power to enable the operation of the communication and computing subsystems. The functioning of the power system utilizes computational resources in the computing system. The entities in the power system are the: (i) Power Demand monitoring entity (PDME), (ii) Solar input entity (SIE), (iii) Power deficit analysis entity (PDAE), and (iv) nuclear activation entity (NAE). The PDME, SIE, PDAE and NAE are cyber-entities associated with the power system and hosted aboard the GMDC. The PDME monitors the power consumption of the ground station and modular data center. It determines the power demand of the modular data center and the ground station. The SIE monitors the amount of power accessible via a battery pool. The battery pool is charged via the deployed solar panel arrays. In addition, the PDAE determines the difference between the PDME and the SIE in evaluating the occurrence and amount of power deficit. The NAE enables the selective activation and deactivation of NNMPs.

GMDC hosts communication system and power system entities. The entities associated with the communication system are the GFE, GPE, and GUE. The power system entities are the PDME, SIE, PDAE, and NAE. GMDC's computational resources enable system related data acquisition and execution of related processing for these entities. GMDC's hosted entities are in Figure 3. In Figure 3, communication system and power system related entities are on the left, and right, respectively.

3 Performance Formulation

The performance model of the proposed solution and presented network architecture is presented. The discussion is divided into two aspects. The first aspect focuses on the formulation of the latency. The second aspect focuses on the formulation of the PUE.

3.1 Performance Formulation – Latency

The latency is formulated for the existing scenario and proposed scenario. The existing scenario is one in which the subscriber accesses cloud-based content from a distant terrestrial data center. In this scenario, the content is accessed via a series of internet exchange points. The proposed scenario is one in which the SBDCs enable the provisioning of data access to the subscribers in the remote location benefitting from the proposed architecture. Let α denote the set of internet exchange points between the subscriber in the remote region and the computing platform hosting the content whose access is desired by the subscriber.

$$\alpha = \{\alpha_1, \alpha_2, \ldots, \alpha_A\} \tag{1}$$

The latency associated with the ath internet exchange point, $\alpha_a, \alpha_a \in \alpha$ at the yth epoch $t_y, t_y \in t, t = \{t_1, t_2, \ldots, t_Y\}$ is denoted as $L(\alpha_a, t_y)$. The latency is derived as a ratio of the amount of associated data $\beta(\alpha_a, t_y)$, and the link throughput, $\theta(\alpha_a, t_y)$. The data size of the content requested by the bth subscriber $\vartheta_b, \vartheta_b \in \vartheta, \vartheta = \{\vartheta_1, \vartheta_2, \vartheta_3, \ldots, \vartheta_B\}$ at the epoch t_y is given as $\Upsilon(\vartheta_b, t_y)$. The data size $\beta(\alpha_a, t_y)$ is significantly greater than the data size $\Upsilon(\vartheta_b, t_y)$ i.e., $\beta(\alpha_a, t_y) \gg \Upsilon(\vartheta_b, t_y)$. This is because the data conveyed by the internet exchange points comprises the data requests for a significant number of subscribers. The terrestrial wireless network downlink speed associated with the bth subscriber ϑ_b at the epoch t_y is denoted as $\phi(\vartheta_b, t_y)$. The latency in the existing case, L_1 is formulated as:

$$L_1 = \sum_{y=1}^{Y} \left(\sum_{a=1}^{A} \left(\frac{\beta(\alpha_a, t_y)}{\theta(\alpha_a, t_y)} \right) + \sum_{b=1}^{B} \left(\frac{\Upsilon(\vartheta_b, t_y)}{\phi(\vartheta_b, t_y)} \right) \right) \tag{2}$$

In the proposed case, the data downloaded i.e., transferred from the SBDC to the ground station. Let the set of SBDCs be denoted as Γ such that:

$$\Gamma = \{\Gamma_1, \Gamma_2, \ldots, \Gamma_C\} \tag{3}$$

The amount of data transmitted from the c^{th}SBDC, $\Gamma_c, \Gamma_c \in \Gamma$ to the ground station at the epoch t_y is denoted $\Upsilon(\Gamma_c, t_y)$. It should also be noted that $\Upsilon(\Gamma_c, t_y) \gg \Upsilon(\vartheta_b, t_y)$. This is applicable as the SBDC's amount of forwarded data comprises the data applicable for multiple subscribers. In this case, the associated link speed is denoted $\phi(\Gamma_c, t_y)$. The latency is obtained as a ratio of the data size to the network latency. In this case, it is obtained as a sum of the

latency associated with SBDC and subscriber related data access. The latency after incorporating SBDCs, L_2 is formulated as:

$$L_2 = \left(\frac{\Upsilon\left(\Gamma_c, t_y\right)}{\phi\left(\Gamma_c, t_y\right)}\right) + \sum_{y=1}^{Y}\left(\sum_{b=1}^{B}\left(\frac{\Upsilon\left(\vartheta_b, t_y\right)}{\phi\left(\vartheta_b, t_y\right)}\right)\right) \tag{4}$$

The latency presented in (4) does not consider the exchange of data between SBDCs in meeting subscriber's data access demands. The latency L_3 given the exchange of data between SBDCs is formulated as:

$$L_3 = \sum_{y=1}^{Y}\left(\sum_{c=1}^{c}\left(\frac{Y\left(\Gamma_c, t_y\right)}{\phi\left(\Gamma_c, t_y\right)}\right) + \sum_{b=1}^{B}\left(\frac{Y\left(\vartheta_b, t_y\right)}{\phi\left(\vartheta_b, t_y\right)}\right)\right) \tag{5}$$

3.2 Performance Formulation - PUE

The performance formulation in this section focuses on the PUE. The existing case considers the use of large-scale terrestrial data centers. In this scenario, terrestrial data centers are hosted in the concerned location and execute the function of the arrays of modular data centers. In the proposed case, arrays of modular data centers are logically considered. The set of servers in the terrestrial data centers is denoted as ψ_1 such that:

$$\psi_1 = \left\{\psi_1^1, \psi_1^2, \psi_1^3, \ldots, \psi_1^D\right\} \tag{6}$$

The power spent in operating and cooling the dth server, $\psi_1^d, \psi_1^d \in \psi_1$ at the epoch t_y are denoted $P_1\left(\psi_1^d, t_y\right)$, and $P_2\left(\psi_1^d, t_y\right)$, respectively. The PUE is given as a ratio of the total mini data center operational power to the power used by servers in the mini data center. The PUE in existing case, θ_1 is:

$$\theta_1 = \sum_{y=1}^{Y}\sum_{d=1}^{D}\left(\frac{P_1\left(\psi_1^d, t_y\right) + P_2\left(\psi_1^d, t_y\right) + \Omega}{P_1\left(\psi_1^d, t_y\right)}\right) \tag{7}$$

Where Ω is the additional amount of energy consumed by the cooling system in the course of its operation.
In the formulation, each GMDC hosts only a single server without reliance on centralized cooling. Instead, it relies on decentralized cooling. The parameters associated with the set of servers still hold true i.e., the server operational power is also denoted and applicable as $P_1\left(\psi_1^d, t_y\right)$. However, the cooling power spent in this case is denoted as $P_2'\left(\psi_1^d, t_y\right)$. In this case, the PUE, θ_2 is:

$$\theta_2 = \sum_{y=1}^{Y}\sum_{d=1}^{D}\left(\frac{P_1\left(\psi_1^d, t_y\right) + P_2'\left(\psi_1^d, t_y\right)}{P_1\left(\psi_1^d, t_y\right)}\right) \tag{8}$$

The term, Ω is not present in (8) as the proposed case utilizes decentralized cooling.

4 Performance Evauation

The performance evaluation is presented in this section. The discussion in this section has two aspects. The first aspect investigates the latency arising in the existing and proposed case. The second aspect focuses on investigating the PUE in the existing case and proposed case.

4.1 Performance Evaluation – Latency

The performance evaluation is done via MATLAB using the parameters in Table 1. The results obtained for the case of the existing case, proposed case, and proposed case with MHMS are in Figure 4, Figure 5, and Figure 6, respectively. The simulation parameters in Table 1 consider that the internet exchange point has a maximum link speed of 34.7 Gbps, and maximum transported data size of 1.96 GB. These values are feasible considering that the internet exchange point utilizes high speed fibre optic link. In addition, a data size of 1.96GB is feasible. This is feasible if an internet exchange point handles data for a significant number of subscribers. In the case of the terrestrial wireless network, the network link has a capacity in the order Mbps which is feasible [4, 14]. The SBDC utilizes free space optical links thereby achieving link speed of up to the order of Gbps which is feasible as seen in [8, 19].

Table 1: Latency - Performance Evaluation Parameters

S/N	Parameter	Value
1	Total Number of Internet Exchange Points	15
2	Minimum Internet Exchange Point Data	36.7 MB
3	Mean Internet Exchange Point Data	1 GB
4	Maximum Internet Exchange Point Data	1.96 GB
5	Minimum Internet Exchange Point Link	1.41 Gbps
6	Mean Internet Exchange Point Link	17.8 Gbps
7	Maximum Internet Exchange Point Link	34.7 Gbps
8	Total Number of Subscribers	300
9	Minimum Subscriber Requested Data	0.18 MB
10	Mean Subscriber Requested Data	36.7 MB
11	Maximum Subscriber Requested Data	74.9 MB
12	Minimum Subscriber Download Speed	2.1 Mbps
13	Minimum Subscriber Download Speed	2.1 Mbps
14	Mean Subscriber Download Speed	617.2 Mbps
15	Maximum Subscriber Download Speed	1.25 Gbps
16	Minimum SBDC Data Transfer	20.6 MB
17	Mean SBDC Data Transfer	1.495 GB
18	Maximum SBDC Data Transfer	2.358 GB
19	Minimum SBDC Link Speed	448.2 Mbps
20	Mean SBDC Link Speed	26.9 Gbps
21	Maximum SBDC Link Speed	67.04 Gbps

The results presented in Figure 4 show that the longest latency associated with accessing data arises with the existing case shown in Figure 4. In this case, it can be seen that the total latency increases with the number of subscribers reaching a maximum of total latency of 2500 seconds. In the proposed case, the use of the proposed approach results in a reduced latency with the maximum total latency being approximately 58 seconds. Furthermore, the consideration of the MHMS results in a slight increase in the total latency. In this case, the total MHMS associated latency is approximately 60 seconds. Further analysis of results shows that using the proposed approach (without MHMS) instead of the existing approach reduces latency by an average of 62.3%, 40.4%, and 37.8% for 10 subscribers, 200 subscribers and 300 subscribers, respectively. This is for the results in Figure 5.

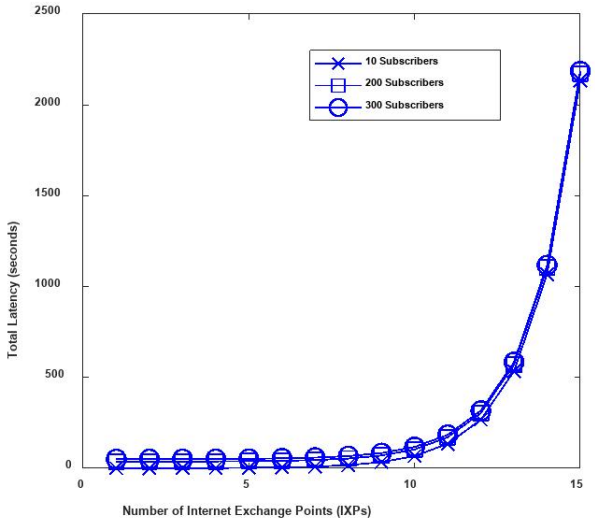


Figure 4: Performance Analysis showing the total latency given the use of the existing approach.

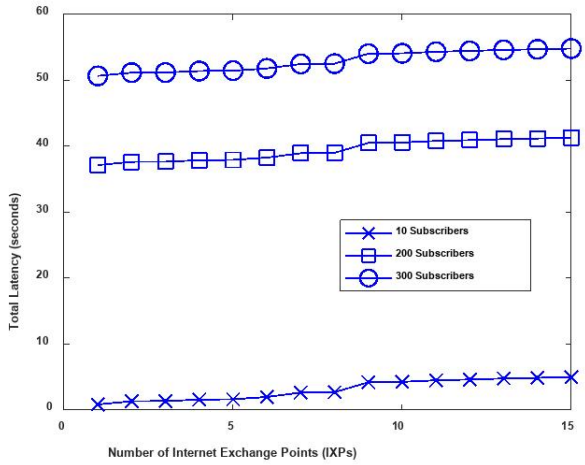


Figure 5: Performance Analysis showing the total latency given the use of the proposed approach (without the MHMS)

The use of the proposed approach (with MHMS) instead of the existing approach reduces latency by an average of 57.6%, 39.4%, and 37% for 10 subscribers, 200 subscribers, and 300 subscribers, respectively. This explanation is for the results presented in Figure 6. The inclusion of the MHMS consideration in the proposed approach increases the total latency by an average of 45.1%, 4.3%, and 3.3%, respectively. The use of the proposed approach (with MHMS) instead of the existing approach reduces latency by an average of 57.6%, 39.4%, and 37% for 10 subscribers, 200 subscribers, and 300 subscribers, respectively. In addition, the inclusion of the MHMS consideration in the proposed approach increases the total latency by an average of 45.1%, 4.3%, and 3.3%, respectively.

Therefore, the request of content requiring the use of either multiple hops in the space segment or ground – space segment relations results in an increased latency. However, a comparison of the results in Figure 5 and Figure 6 shows that the increment in the latency is only slight. It can be inferred that the use of high-speed links (free space optical or high-capacity radio links) enables the realization of low latency for MHMS content forwarding communication systems.

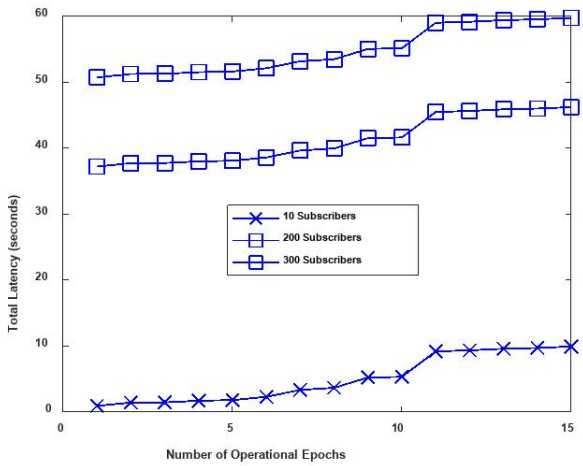


Figure 6: Performance Analysis showing the total latency given the use of the proposed approach (including the MHMS).

4.2 Performance Evaluation – PUE

The PUE related investigation and performance evaluation is done for non-energy intensive servers with energy consumption at a maximum less than half a kilowatt. The simulation parameters are in Table 2. In this case, the servers have a varying power consumption due to the processing of a changing workload. In this case, the maximum server power consumption does not exceed a kilowatt even when a high workload is being processed. Furthermore, the investigation is done for high server utilization in a warm climate requiring significant cooling. In this case, the maximum proportion of the energy used for cooling is 34.6%. The performance evaluation parameters concerned are presented in Table 2. In the case of the proposed approach, a decentralization factor is introduced to evaluate the cooling power of each server or modular data center unit. The maximum decentralization factor is 41.1 %. This implies that decentralization factor is not highly sophisticated being that it does not coordinate cooling for multiple modular data centers. Such a cooling system can also be realized feasibly due to the moderate (and not high level) of sophistication. A high decentralization factor implies increasing use of ground station specific cooling systems. Each GMDC has its own cooling system with reduced inter-connection between cooling systems. The decentralization factor cannot exceed 100%. A case where the decentralization factor exceeds 100% is one where the proposed approach's cooling systems have communicating entities. This introduces overhead,

a drawback associated with the existing approach i.e., the use of centrally cooling systems for terrestrial server farms. The decentralization factor cannot have a zero as well. A value of zero implies that the cooling system has ideal performance with an operating system enabling the realization of an ideal PUE. In addition, the PUE related results are presented in Figure 7. Results show that the PUE is enhanced (lower figure is better) by the proposed solution being used instead of the existing approach by an average of 15.5%.

Table 2: PUE – Evaluation and Simulation Results

S/N	Parameter	Value
1	Number of Servers	20
2	Maximum Server Power Consumption	448.1 W
3	Minimum Server Power Consumption	9.31 W
4	Mean Server Power Consumption	281.8 W
5	Maximum Proportion of Power spent in Cooling	34.6%
6	Minimum Proportion of Power spent in Cooling	2.5%
7	Mean Proportion of Power spent in Cooling	23.4%
8	Maximum Decentralization Factor	41.1%
9	Minimum Decentralization Factor	5.53%
10	Mean Decentralization Factor	25.3%

Performance evaluation also aims to investigate the PUE given the use of servers with high power consumption. In this case, the amount of power expended on server cooling also increases. This is because the cooling power is deemed a proportion of the total power provided for operation. The results in Figure 8 show that the PUE increases with an increase in server power. Given high power servers, additional and more cooling capabilities are required. Hence, the decentralization factor is increased by a maximum of 8.76 %. However, the cooling systems are not significantly interconnected and have no supporting communication mechanism.

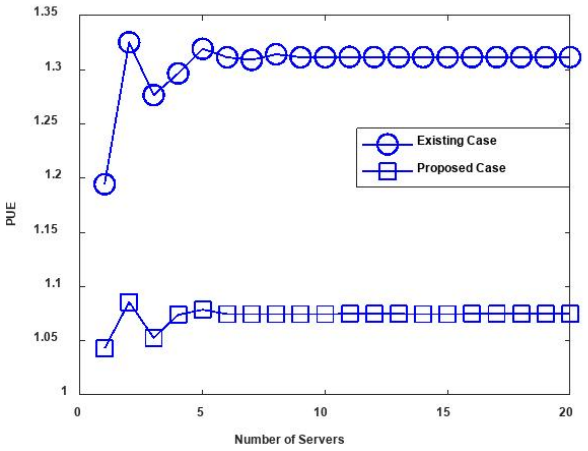


Figure 7: PUE – Performance Evaluation Results.

The identities of the existing case (being one of the conventional terrestrial data centers), and proposed case (being one of the GMDC associated with each ground station) still hold true. The performance evaluation parameters and values are in Table 3, and the results are presented in Figure 8.

Table 3: PUE – Evaluation Parameters: Increase in Server Power

S/N	Parameter	Value
1	Number of Servers	20
2	Maximum Server Power Consumption	806.6 W
3	Minimum Server Power Consumption	85.3 W
4	Mean Server Power Consumption	429.3 W
5	Maximum Proportion of Power spent in Cooling	75.7%
6	Minimum Proportion of Power spent in Cooling	2.84%
7	Mean Proportion of Power spent in Cooling	33.59%
8	Maximum Decentralization Factor	44.7%
9	Minimum Decentralization Factor	1.98%
10	Mean Decentralization Factor	24.6%

The results in Figure 8 also show that the PUE has slightly increased, implying that the use of high-power servers requiring more cooling worsens the PUE. Further analysis shows that the use of the proposed approach instead of the existing case enhances the PUE by an average of 17.74%. Therefore, it can be inferred that the use of higher power servers with enhanced workload execution capacity results in an increased PUE figure (resulting in worsening PUE).

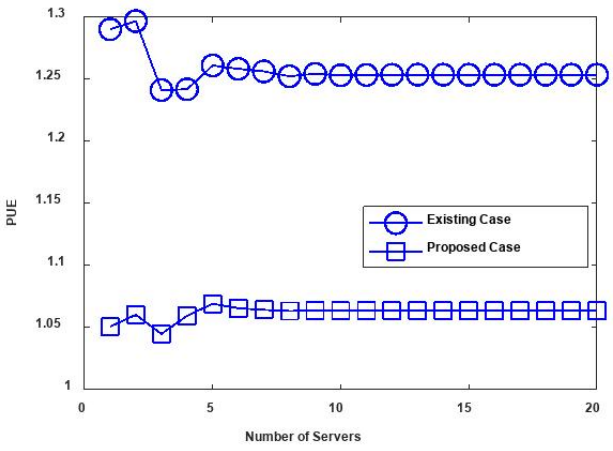


Figure 8: PUE – Performance Evaluation Results for case of increased server power.

Analysis shows that the PUE improvement degrades with an increasing decentralization factor. The PUE is enhanced by an average of 9.98%, 6.99%, 6.40%, 3.09 %, and -56.6 given a maximum

decentralization factor of 100.9%, 102%, 139% , 247.9% and 337.4%, respectively. A negative improvement implies that the proposed approach does not enhance PUE due to the high level of interconnectedness. This arises because of the use of a significant amount of energy intended for operating the cooling system is used for exchanging control signaling messages to enable cooling system configuration.

5 CONCLUSION

The research analyses latency and performance usage effectiveness in a computing network with space-based data centers (SBDCs) as the computing platform component. SBDCs increase computing platform network coverage and footprint. This is beneficial to landlocked locations without significant capability to ensure the sustained provision of water for cooling computing platforms. In the proposed research, computing platforms (terrestrial-based or space-based) host internet accessible content. In the proposed SBDC network, ground stations have their own sustainably operated modular data centers. The use of SBDCs for the considered location type is found to reduce the latency in comparison to accessing content via a network with multiple internet exchange points interacting during content forwarding. In addition, the use of modular data centers being operated singly instead of servers deployed in the manner utilized in existing terrestrial data centers also reduces operational and inter-connectivity associated overhead. This reduction in overhead is found to enhance power usage effectiveness. The use of the proposed approach reduces the latency by at least 4% and up to 56%. The use of the proposed computing system integrated into the ground segment enhances power usage effectiveness by up to 17.7%. Future work will focus on conducting a techno-economic analysis of integrating modular data centers to realize data processing in a multi-hop multi-satellite network scenario. In addition, future work will address the space mission planning aspects of SBDC as the presented approach focuses on the integration of SBDCs in communication networks.

Acknowledgments

The authors acknowledge their indebtedness to the Department of Electrical, Electronic and Computer Engineering, and F'SATI of the Cape Peninsula University of Technology.

References

[1] W. Abderrahim, O. Amin, and B. Shihada. 2024. Data Center-Enabled High Altitude Platforms: A Green Computing Alternative. *IEEE Transactions on Mobile Computing* (2024), 1–14. doi:10.1109/tmc.2023.3316204

[2] D. N. Amanor, W. W. Edmonson, and F. Afghah. 2018. Intersatellite Communication System Based on Visible Light. *IEEE Trans. Aerospace Electron. Systems* 54, 6 (2018), 2888–2899. doi:10.1109/taes.2018.2832938

[3] N. Bleier, M. H. Mubarik, G. R. Swenson, and R. Kumar. 2023. Space Microdatacenters. In *Proceedings of the ACM.* doi:10.1145/3613424.3614271

[4] J. Garcia, S. Sundberg, G. Caso, and A. Brunstrom. 2023. Multi-Timescale Evaluation of Starlink Throughput. In *KTH Publication Database DiVA (KTH Royal Institute of Technology).* 31–36. doi:10.1145/3614204.3616108

[5] L. Kosmidis, M. M. Trompouki, M. Solé, A. Á. Suárez, and J. Wolf. 2024. Towards a Qualifiable Space Cloud Approach. In *2024 IEEE 10th International Conference on Space Mission Challenges for Information Technology (SMC-IT).* 109–114. doi:10.1109/SMC-IT61443.2024.00019

[6] H. Lee et al. 2023. Towards 6G hyper-connectivity: Vision, challenges, and key enabling technologies. *Journal of Communications and Networks* (2023), 1–11. doi:10.23919/jcn.2023.000006

[7] A. Martínez-Gutiérrez, J. Díez-González, P. Verde, R. Ferrero-Guillén, and H. Perez. 2023. Hyperconnectivity Proposal for Smart Manufacturing. *IEEE Access* 11 (2023), 70947–70959. doi:10.1109/access.2023.3294308

[8] N. Mohan et al. 2024. A Multifaceted Look at Starlink Performance. In *WWW '24: Proceedings of the ACM Web Conference 2024*, Vol. 12. 2723–2734. doi:10.1145/3589334.3645328

[9] A. Ojo. 2019. Next Generation Government - Hyperconnected, Smart and Augmented. In *IFIP Advances in Information and Communication Technology*. 285–294. doi:10.1007/978-3-030-28464-0_25

[10] A. Periola, A. A. Alonge, and K. A. Ogudo. 2023. Space-Based Data Centers and Cooling: Feasibility Analysis via Multi-Criteria and Query Search for Water-Bearing Asteroids Showing Novel Underlying Regular and Symmetric Patterns. *Symmetry* 15, 7 (2023), 1326–1326. doi:10.3390/sym15071326

[11] A. A. Periola. 2020. Aerial computing—security from missile threats and enhancing PUE. *Aerospace Systems* 3, 4 (2020), 327–342. doi:10.1007/s42401-020-00064-9

[12] A. A. Periola. 2023. Power Usage Effectiveness in Stratosphere Based Computing Platforms: Re-evaluation and Need to Re-establish Performance Benefits via an Intelligent Light Server Selection Architecture. *Wireless Personal Communications* 132, 2 (2023), 1577–1591. doi:10.1007/s11277-023-10676-x

[13] A. A. Periola, A. A. Alonge, and K. A. Ogudo. 2024. Ocean warming events resilience capability in underwater computing platforms. *Scientific Reports* 14, 1 (2024). doi:10.1038/s41598-024-54050-8

[14] R. Radhakrishnan, W. W. Edmonson, F. Afghah, R. M. Rodriguez-Osorio, F. Pinto, and S. C. Burleigh. 2016. Survey of Inter-Satellite Communication for Small Satellite Systems: Physical Layer to Network Layer View. *IEEE Communications Surveys Tutorials* 18, 4 (2016), 2442–2473. doi:10.1109/COMST.2016.2564990

[15] S. Saha and K. Dasala. 2024. Terahertz Inter-Small-Satellite Communications via Angularly Dispersive Antennas. In *2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz).* 1–2. doi:10.1109/irmmw-thz60956.2024.10697904

[16] J. Sheldon et al. 2024. AquaSonic: Acoustic Manipulation of Underwater Data Center Operations and Resource Management. In *2024 IEEE Symposium on Security and Privacy (SP).* 331–349. doi:10.1109/sp54263.2024.00201

[17] R. Sil and R. Chatterjee. 2023. Evolution of Next-Generation Communication Technology. In *5G and Beyond*, B. Bhushan, S. K. Sharma, R. Kumar, and I. Priyadarshini (Eds.). Springer, Singapore, 1–17. doi:10.1007/978-981-99-3668-7_1

[18] T. Sutherland and G. Bopp. 2023. The Pacific futures of subsea data centers. *New Media & Society* 25, 2 (2023), 345–360. doi:10.1177/14614448221149944

[19] S. M. Walsh et al. 2022. Demonstration of 100 Gbps coherent free-space optical communications at LEO tracking rates. *Scientific Reports* 12, 1 (2022), 18345. doi:10.1038/s41598-022-22027-0

[20] Y. Wu, J. Ren, C. Jiang, and J. Ye. 2025. Evaluation Scheme of Environmental Impact of Underwater Data Centers Based on GIS. In *Lecture Notes in Electrical Engineering*. 471–478. doi:10.1007/978-981-96-2798-1_51