Perspectives on Tier Classification of Underwater Computing Platforms

A.A. Periola
Department of Electrical, Electronic and Computer Engineering
Cape Peninsula University of Technology
periolaa@cput.ac.za

A.A. Alonge
Department of Electrical and Electronics Engineering Technology
University of Johannesburg
aalonge@uj.ac.za

K.A Ogudo
Department of Electrical and Electronics Engineering Technology
University of Johannesburg
kingsleyo@uj.ac.za

Abstract— **Underwater data centers have been recognized to be suitable future computing platforms due to the benefits of low cooling. In addition, underwater computing platforms reduce content access latency for coastal subscribers. The performance of underwater data centers is influenced by different system configuration parameters and different events such as ocean warming that occurs in the underwater environment. In addition, the capabilities of different underwater computing platforms to keep functioning given the occurrence of ocean warming events should also be considered. This challenge can be addressed by defining a tiering system for underwater computing platforms. The presented research proposes a four-tier system for underwater computing platforms. The four-tier system describes the different capabilities and operational contexts of underwater computing platforms enabling their continued functionality in the event of the occurrence of marine heat waves and ocean warming events.**

Keywords – Computing Platforms; Underwater Data centers; Ocean Warming; Reservoir Capability; Data Center Tiers

I. INTRODUCTION

Cloud computing platforms (CCPs) are envisioned to play an important role in future communication networks like the sixth-generation (6G) and seventh-generation (7G) networks [1 – 4]. The future of CCPs is expected to deliver power-efficient [5] and environment-friendly operations [7]. CCPs should also support low-latency content access as nodes in communication networks [7–8].

CCPs have improved power efficiency and environment-friendly operation when placed in the underwater environment. This is because accessible free cold water is useful for free cooling benefits [9–11]. These benefits have been shown to be derivable in real-life underwater-based CCPs [12–13].

An important challenge that is identified to influence the use of underwater CCPs (UCCPs) in 6G and 7G networks is that of ocean warming. Ocean warming describes the gradual increase in ocean temperature and has been observed to occur over time [14–15]. The discussion in [16] proposes the incorporation of reservoirs to ensure UCCP functioning continuity in the event of marine heat waves and ocean warming occurrence. The discussion in [16] proposes the incorporation of reservoirs to ensure UCCP functioning continuity in the event of marine heatwave occurrence.

The discussion in [16] demonstrates that the inclusion of reservoirs in the UCCP enhances its operational duration. The discussion in [16] considers two reservoir contexts. These are coupled reservoir contexts and decoupled reservoir contexts. In the coupled reservoir context, the UCCP hosts the reservoir. The decoupled reservoir context is one in which the UCCP and reservoir are separate. Reservoirs in both contexts complement each other and jointly enhance UCCP operational duration.

However, the discussion in [16] has not considered UCCP Reservoir relations from a service provisioning perspective. This is important as UCCPs will be deployed by different kinds of computing platform service providers (CPSPs) with varying reservoir capabilities in different maritime resources. Each maritime resource also has dynamic ocean warming effects. In considering the different contexts and parameters, it is important to define different tiers for UCCPs. This has been done for terrestrial data centers in [17]. However, a Tier classification has not been done for UCCPs.

Nevertheless, it is important to develop a tier rating of UCCPs to define the expected performance level and UCCP capabilities in different scenarios. This is because of the diversity in the capability of UCCPs and similar systems. The research presented in [18] presents results enabling researchers to infer that the heterogeneity in the computing payload, cooling system composition and workload (tasks) influences the functioning duration of an emulated UCCP.

The main contribution of this paper is the development of a Tier classification of UCCPs. The Tier classification is done considering the UCCP operational duration and associated factors such as reservoir capabilities as the main criteria. In addition, the UCCP operational duration is defined considering its ability to function in 6G and 7G communication networks. Four tiers of UCCPs have been considered and proposed. These are Tier 1, Tier 2, Tier 3, and Tier 4. The Tier classification is deemed important to consider the need to execute data exchange with external networks. The classification also considers the need to consider different CPSP capabilities and the non–ideal functionality of reservoir and associated computing entities. The research also proposes the integration of each UCCP Tier with external networks.

Furthermore, the presented research examines the role of manned and unmanned maintenance operations in the proposed Tier UCCP classification.

The use of UCCPs is expected to occur across different players with varying capabilities. This is because of their varying access to resources and performance expectations. The asymmetry in resource and performance expectations has not been considered in existing work [9 – 13]. The discussion in existing work [9–13] has focused on identifying the low operational cost benefit and performance description. The discussion in [16] proposes the use of reservoirs to ensure long-term functioning in the event of marine heatwave occurrence. However, the adoption of UCCPs by entities having varying capabilities and service expectations is yet to receive research consideration. This can be done by presenting a perspective on different tiers of UCCPs and is the goal of the research.

The rest of the research is organized as follows. Section II discusses the proposed Tier UCCP classification. Section III focuses on the context of manned and unmanned operations in the proposed UCCP Tier classification. Section IV presents the integration of UCCP Tiers in the framework of the third-generation partnership project (3GPP) release 17 [19]. The discussion here presents the integration of a Tiered UCCP system in the fifth generation (5G) network. 5G network is considered because of the non–coverage of 6G and 7G in the existing 3GPP technical specifications. Section V is the conclusion.

II. UCCP TIER CLASSIFICATION

The discussion in this section presents and discusses the capabilities of the proposed UCCP tiers. The tier classification is considered for the cases of severe marine heat waves and ocean warming incidences, and that of mild marine heat waves and ocean warming incidences. A maritime resource i.e., a given region of the ocean is deemed to experience either severe or mild ocean warming incidence via the observation of the variation of its associated temperature. This characterization is

2023 IEEE AFRICON | 979-8-3503-3621-4/23/$31.00 ©2023 IEEE | DOI: 10.1109/AFRICON55910.2023.10293568

979-979-8-3503-3621-4/23/$31.00 ©2023 IEEE

done by a municipal authority or the CPSP prior to the deployment of the UCCP.

The UCCP differs from the existing case of the terrestrial data center in the manner of cooling. This difference arises in two aspects. In the first aspect, the proposed UCCP benefits from free cooling. This offers an operational benefit in terms of reducing the operating cost in comparison to existing terrestrial data centers. The second aspect is also pertaining to the realization of the cooling. In the existing terrestrial data centers, the cloud computing platform has access to the coolant and does not explore to determine the suitability of the coolant. This is because existing terrestrial data centers have a cooling system and associated components. However, the case of the UCCP is different as underwater computing platforms can explore the suitability of different ocean regions for obtaining cold water to ensure the cooling of the UCCPs.

Hence, the UCCP benefits from intelligent coolant exploration systems in the underwater environment. This is not applicable to realize cooling in the existing terrestrial data center where the coolants and cooling system components are made available prior to cloud computing platform operation.

The discussion in this section has two aspects. The first aspect focuses on Tier specifications for the case of severe marine heat waves and ocean warming incidence. The second aspect focuses on the Tier specifications for the case of mild marine heat waves and ocean warming incidence.

A. Tier Specifications – Severe Warming Incidences

The UCCP Tier classification considers the availability of computing platforms hosted in the marine plane as a core performance parameter. The availability criterion is significantly influenced by the occurrence of marine heat waves, ocean warming alongside the capability of the reservoir. In addition, the tier classification considers the occurrence of reservoir failure due to non–ideal functionality.

There are four UCCP Tiers in the order of increasing availability. These are Tier 4–UCCP, Tier 3–UCCP, Tier 2–UCCP, and Tier 1–UCCP. The tiers Tier 4 – UCCP, Tier 3 – UCCP, Tier 2 – UCCP, and Tier 1 – UCCP are referred to as Tier 4, Tier 3, Tier 2, and Tier 1, respectively. Tier 4 have the highest availability while Tier 1 have the lowest availability.

Tier 4 can communicate with terrestrial data centers and stratosphere-based data centers. The need to incorporate support for connection with aerial systems (unmanned) is recognized in Section 4.2.14 of the 3GPP Release 17 [19]. The context in this case considers terrestrial–aerial system connections and not underwater–aerial plane connectivity. In Tier 4, the underwater–aerial plane connectivity is realized via the sequence of underwater–terrestrial connectivity and terrestrial–aerial connectivity.

In addition, Tier 4 hosts a significant number of servers and has an onboard communication system. The servers enable the storage and execution of algorithms i.e., workloads from different subscribers and applications. In this regard, system performance is critical aboard Tier 4. Tier 4 incorporates reservoir redundancy capabilities.

Reservoir redundancy should be considered to accommodate the failure of the computing systems and entities associated with the reservoir. The occurrence of non–functionality in this case results in the inability of the reservoir to deliver cold water for the purposes of server payload cooling Reservoir redundancy is the provisioning of extra reservoirs considering the occurrence of long-duration marine heat waves and ocean warming events. The provisioning of additional reservoirs enables the continued functioning of Tier 4 when a given and utilized reservoir becomes faulty.

From the perspective of implementation, Tier 4 is suitable for CPSP with significant capital and technology resources. The concerned CPSPs target the provisioning of latency-sensitive (critical) and non–latency sensitive (non–critical) data and networked applications. In the Tier 4 specification, the redundancy configuration for the reservoir is $2N$ and follows the specification of the redundancy for existing terrestrial data centers [21].

In addition, Tier 4 incorporates intelligent robust reservoir functionality capability. This capability enables the deactivation and activation of faulty (active) reservoirs and redundant reservoirs, respectively. In the context of Tier 4, the underwater data center incorporates sensors that monitor the ocean environment and acquire temperature-related data. This is done with the aim of detecting the onset of ocean warming and the occurrence of marine heat waves. The detection enables the switching from the faulty reservoir to the active (but previously redundant) reservoir. In Tier 4, the implied reservoir switching is proactively executed.

The architecture for the Tier 4 showing the components and subsystems is presented in Figure 1.

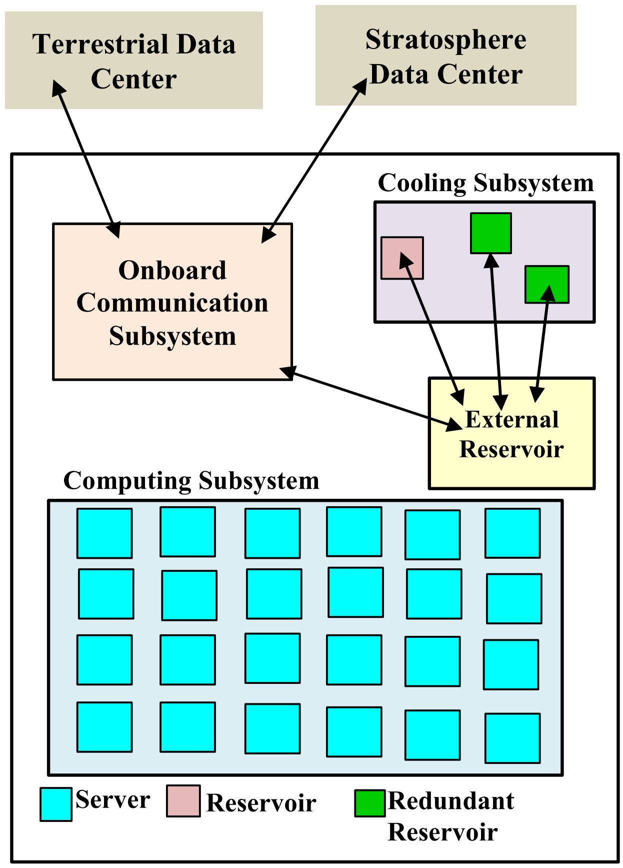

Figure 1: Architecture showing components and subsystems in the Tier 4 UCCP.

Tier 3 is like Tier 4 in communicating with the terrestrial and stratosphere-based data centers. In addition, the Tier 3–UCCP incorporates the intelligent robust reservoir functionality capability. However, the redundancy configuration in Tier 3 is the N following the pattern of redundancy provisioning in existing terrestrial data centers [21]. However, the reservoir switching context in Tier 3 is simpler than that in the case of Tier 4. This is because the implicit redundant reservoir selection makes the selection decision from fewer redundant reservoirs in Tier 3 in comparison to Tier 4.

Tier 3 is suitable for a CPSP with lesser resources than that considered for the case of Tier 4. Tier 3 also has a lesser operational duration than Tier 4 given the same severity of ocean warming and marine heat waves in the same maritime resource i.e., the ocean. An architecture for the Tier 3 data center is presented in Figure 2.

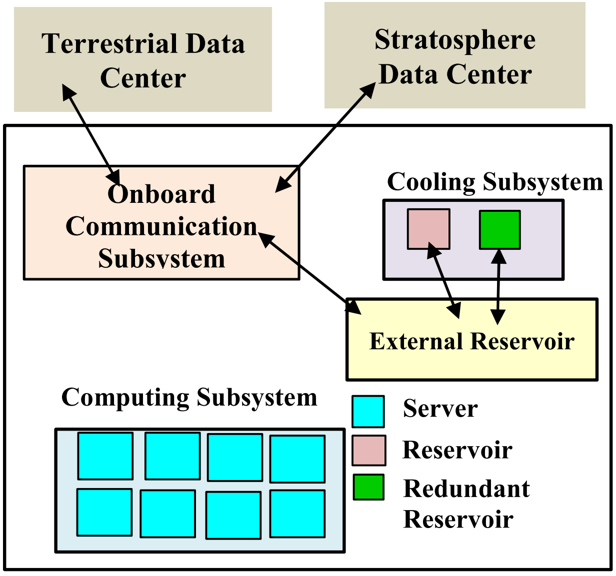

Figure 2: Architecture showing components and subsystems in the Tier 3 UCCP.

Tier 3 and Tier 4 are suitable for the case of a CPSP with significant capital and technological resources. In addition, they have a long functional duration due to the use of redundant reservoirs. They also benefit from the reservoir as a service system such as in [16].

From the perspective of operational power sources, Tier 4 and Tier 3 utilize underwater renewable energy sources and the conventional terrestrial grid. Examples of underwater renewable energy sources being considered are wave renewable energy and tidal renewable energy.

Such a synergy provides Tier 4 and Tier 3 with sufficient power sources to ensure a long functional duration. Renewable energy sources are combined with the grid due to the high level of variability in underwater renewable energy sources. However, this combination is done in a manner that does not cause environment-friendly operations. This is realized by ensuring that the energy input into the grid arises from renewable energy farms i.e., solar farms, onshore wind farms, and offshore wind farms.

B. Tier Specifications – Mild Warming Incidences

The Tier 1 and Tier 2 specifications are intended to be used in the context of mild warming incidences for the concerned maritime resources. Tier 2 incorporates a single reservoir with a non–redundant pair. It also benefits from the presence of the reservoir as a service context. Tier 2 communicates with the terrestrial data center via a shore-based gateway. It does not communicate or engage in the exchange of data with the stratosphere-based data center. Hence, it does not incorporate support for data communications with unmanned aerial systems as indicated in the specifications of Section 4.2.14 of the 3GPP Release 17. In addition, Tier 2 does not incorporate the intelligent robust reservoir capability. This is because it does not have the need to execute an implicit process of reservoir selection. Tier 2 also has a smaller number of servers in comparison to Tier 3 and Tier 4.

In addition, Tier 2 is deployed in a maritime resource with a smaller area in comparison to Tier 3 and Tier 4. Furthermore, it has lower availability than Tier 3 and Tier 4. Hence, it is suitable for non–critical applications that do not require all round access. Tier 1 has only one reservoir, does not incorporate redundancy, and connects only to the terrestrial data center.

Tier 2 and Tier 1 utilize only underwater renewable energy sources. The inclusion of a source from the grid has not been considered as the capital constrained CPSP is not able to execute power links from the grid to the underwater environment. In addition, the concerned CPSP is not able to engage in the installation of its own renewable energy farm in the onshore and offshore environments. The CPSP is also unable to acquire and purchase energy from these energy farms.

Tier 1 and Tier 2 are intended for use by CPSPs with constraints on capital and technological resources. Hence, the non-inclusion of the intelligent reservoir robust functionality in Tier 1 and Tier 2. Furthermore, Tier 1 does not utilize the reservoir as a service capability since the concerned CPSP is not able to afford the services being delivered by the reservoir service provider. The capabilities of each UCCP Tier classification are presented in Table 1.

Table 1: UCCP Tier Classification and Capabilities

Capability	Tier 4	Tier 3	Tier 2	Tier 1
Redundancy Configuration	2N	N	1	None
Benefits from Reservoir as a Service	Yes	Yes	Yes	No
Capital and Technology constraints	No	No	Yes	Yes
Severe warming incidence operation	Yes	Yes	No	No
Mild warming incidence operation	No	No	Yes	Yes
Communicates with terrestrial Data centers	Yes	Yes	Yes	Yes
Communicates with stratosphere data centers	Yes	Yes	Yes	No
Use of underwater renewable energy sources	Yes	Yes	Yes	Yes
Use of solar power farms	No	No	Yes	Yes
Use of onshore wind energy farms	No	No	Yes	Yes
Use of offshore wind energy farms	No	No	Yes	Yes

III. UCCP–TIER RELATED OPERATIONS

The UCCP hosts multiple servers aboard a chamber in the underwater environment. The different UCCP tiers have different service specifications and roles in the computing and communication network. In addition, the use and definition of UCCP Tiers require the conduct of maintenance and addressing the resolution of different faults aboard the UCCP.

Existing considerations on the deployment and use of UCCPs assume that they benefit from advances in artificial intelligence and exhibit autonomous capability. The exhibition of autonomous capability makes the UCCPs capable of self–healing, repair, and configuration. However, this has not considered that the ocean floor is a hostile environment.

In this regard, it is important to consider different faults that may arise in view of the consideration of marine heat waves and ocean warming events. The occurrence of ocean warming can stimulate the mass migration of sea animals to ocean regions with lower temperatures as seen in [22]. The occurrence of such a migration implies that the UCCPs in each region are subject to increased collision with sea animals.

The mass migration of sea animals to a given ocean region poses a threat to reservoirs in ocean regions where ocean warming incidence arises. This is because reservoirs store a high volume of water which becomes attractive to sea animals needing a low temperature. This increases the collision to active reservoirs, redundant reservoirs, and the pods storing cold water in the reservoir as a service context from mass migrating sea animals. This also applies to sea animals that cluster around the reservoirs and concerned pods in search of a cold environment. The test of the prototype by Microsoft Natick recognizes that such clustering is not harmful to the UCCP as seen in [9]. However, this has not been considered in a context arising from sea animal migration due to the occurrence of ocean warming.

The emergence of increased collision can lead to a case where certain reservoirs comprising active and redundant reservoirs become damaged. Hence, it is important to consider the case where a manned inspection of reservoirs for damage and subsequent repair is required.

The role of the reservoir is critical in the Tier 2, Tier 3, and Tier 4. The damage to the reservoir due to the reasons identified is challenging to fix in an autonomous manner. This is because the reservoir is an electromechanical system with significant mechanical components. Therefore, the resolution of faults associated with the reservoir in a manner that does not result in the interruption of UCCP functionality should be done in a manned fashion.

A manned repair has high costs and is unsuitable for CPSPs with severe capital constraints. Hence, UCCPs in this category i.e., Tier 2 and Tier 1 should be placed in an ocean region with low frequencies of sea animal migration.

Tier 4 and Tier 3 UCCPs benefit extensively from reservoirs and pods for the realization of server cooling. Damage to these reservoirs and pods reduces the ability of redundancy to ensure UCCP service continuity. In addition, the CPSPs utilizing Tier 4 and Tier 3 UCCPs are not subject to significant capital and technology constraints. Hence, they n afford the manned repair of damaged reservoirs to active and redundant reservoirs in the underwater environment during an epoch of ocean warming.

Therefore, the Tier 4 and Tier 3 UCCPs achieve long operational duration and can engage in data communications with terrestrial data centers and stratosphere data centers via the UCCP's onboard communication system.

The use of UCCPs is recognized to reduce the latency associated with accessing communications and networked applications by coastal subscribers. Hence, the repair of faulty reservoirs in a manner that ensures the non–interruption of services and applications such as online gaming, multimedia content streaming, and high-speed multimedia content downloads. Service delivery to subscribers desiring non–interruption of these services makes use of either Tier 4 UCCPs or Tier 3 UCCPs.

In the case of Tier 2 and Tier 1 UCCPs, faulty reservoirs are fixed by removing the UCCP from the underwater environment. This approach is being considered as Tier 2 and Tier 1 UCCPs are intended for use in capital and technology-constrained contexts. This is also deemed feasible as Tier 2 and Tier 1 UCCPs host a lesser number of servers than Tier 4 and Tier 3 UCCPs.

IV. UCCP TIER INTEGRATION

The proposed Tier 1, Tier 2, Tier 3, and Tier 4 UCCPs play an important role as computing platforms supporting mobile edge computing and aerial communication entities in Sections 4.2.13 and 4.2.14 in of the 3GPP Release 17, respectively. The specifications and expectations for 6G networks are expected in 3GPP Release 21 which isn't available [23]. This is because 3GPP's latest standards are in 3GPP Release 18.

The discussion [24] recognizes that UCCPs will interact with communication networks. However, integration into the available network standards has not been provided in [24]. Therefore, there is a need to describe the integration of Tier 1, Tier 2, Tier 3, and Tier 4 data centers into the standard of communication networks. In this regard, the integration with the wireless network's standards specified in the 3GPP Release 17 is presented. This is considered important to address the issues and concerns associated with ensuring session continuity in communication networks. An important concern is that of executing handover. This should be addressed to ensure seamless session continuity to accommodate user mobility. It is also important to address this challenge as different categories of entities are being increasingly interested in UCCPs [25-27].

The 3GPP Release 17 incorporates support for non–terrestrial networks. However, this non – terrestrial support only considers the case of satellite networks and the siting of cloud computing platforms in the marine plane and its associated environment. Hence, the consideration of the role of the UCCPs in 3GPP Release 17 is important.

In the context of a communication network, the execution of different handover procedures within the marine plane; and between the marine plane and terrestrial plane as well as those involving the stratosphere should be considered.

The handover between UCCPs of different tier classifications can occur within the marine environment. This becomes necessary when ocean warming is being observed at the site of a given UCCP (with a lower Tiering) while ocean warming is not being observed to occur at the ocean region hosting another UCCP (with a higher Tiering). In this case, the workload migration is executed to ensure service continuity. This handover procedure occurs between computing platforms in the underwater environment and is called the horizontal underwater handover.

Handover can also be executed between the UCCPs of a given tier and terrestrial networks. It is recognized that the Tier 4 and Tier 3 UCCPs execute data exchange with stratosphere based UCCPs. However, this data exchange occurs via terrestrial-based network entities or cloud computing platforms.

The specifications for the mobile edge computing platforms and user equipment relations can be found in 3GPP TS 23.548 v17.5.0 Stage 2 Release 17 [28-29]. The discussion in [28] focuses on the relations enabling the discovery, attachment, and re-discovery of the edge computing node by the subscriber in the mobile network. These functionalities are also beneficial to the definition of the role of the UCCPs when integrated into the 5G network.

In the communication network incorporating the UCCP, UCCPs engage in high-speed communications and are linked with each other via optic fiber cables. The shore-based gateway that is connected to the terrestrial data center constitutes the edge node in this consideration. Each UCCP in our consideration needs to develop an awareness of the edge node to enable the forwarding of data. This becomes necessary when the execution of the horizontal handover procedure is unsuccessful due to the occurrence of long-duration marine heat waves and ocean warming events at all locations in the concerned maritime resource.

The execution of a horizontal handover procedure involves the analysis of the occurrence of ocean warming and the computing workload associated with UCCPs. This analysis is important and is executed by the UCCP discovery and handover function (UDHF). The UDHF is executed by an autonomous underwater vehicle (AUV) that is linked to multiple UCCPs (across all tiers). The UDHF also enables the determination of the online and offline status of a given UCCP. In this case, the occurrence of ocean warming alongside the event of reservoir damage in a manner that results in the inability of redundancy to ensure UCCP continued functioning causes the UCCP to transition to the offline status.

In addition, the UDHF hosts entities enabling the execution of operation, administration, and management functionalities. These entities provide the concerned CPSP with health status and associated information at a terrestrial platform via the shore-based gateway. A network architecture showing these relations is presented in Figure 3. The flowchart showing the execution of the UDHF is in Figure 4. The UDHF functionality inclusive of the handover is executed by the marine gateway entity which hosts the concerned AUV.

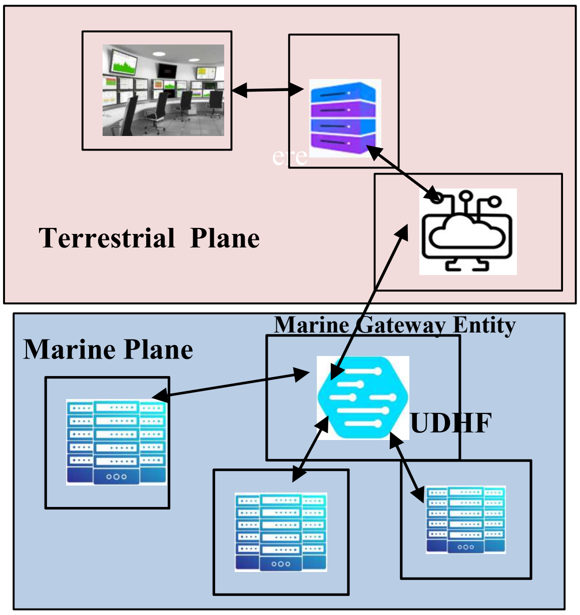

Figure 3: Relations between entities in the marine plane and physical plane in the proposed integration.

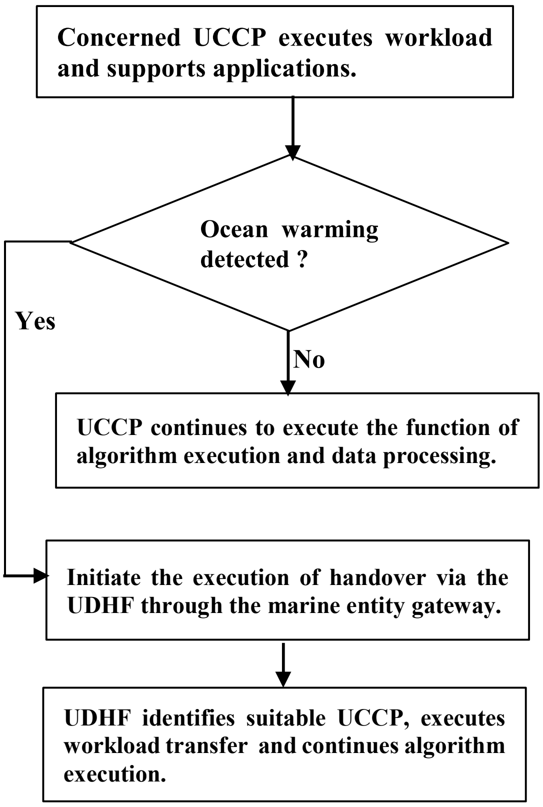

Figure 4: Flowchart showing the sequence in UDHF.

The discussion in the presented research has focused on the description of the tier of UCCPs in presenting a tiering system. The proposed Tiering system focuses on the different categories of UCCPs and their performance capabilities. However, discussion has not been made on quantifying the performance of the UCCPs in view of their operational parameters. This has been done in suitable existing work and can be found in [17, 19].

V. CONCLUSION

The presented research addresses the challenge of developing a tiering system for underwater computing platforms. The development of this tiering system is necessitated due to the need to consider the different contexts, capabilities, and operations of underwater computing platforms in ensuring their continuity of operation given the occurrence of marine heat waves and ocean warming events. Four tiers of underwater computing platforms intended for operation in the case of a severe and mild case of ocean warming events have been considered. These are Tier 1, Tier 2, Tier 3, and Tier 4 underwater computing platforms. The Tier 1 and Tier 2 underwater computing platforms are designed to execute data storage, algorithm execution, and communication node functionalities in maritime resources i.e., ocean regions having a mild case of marine heat waves and ocean warming events. The Tier 3 and Tier 4 underwater computing platforms execute the functionalities of data storage, algorithm execution, and communication node in ocean regions experiencing severe cases of marine heat waves and ocean warming events.

ACKNOWLEDGMENT

The support of the Department of Electrical, Electronic and Computer Engineering, Cape Peninsula University of Technology and the Department of Electrical and Electronic Engineering Technology of the University of Johannesburg is highly acknowledged.

REFERENCES

[1] L. Ismail and R. Buyya, "Artificial Intelligence Applications and Self-Learning 6G Networks for Smart Cities Digital Ecosystems: Taxonomy, Challenges, and Future Directions," Sensors, vol. 22, no. 15, p. 5750, Aug. 2022, doi: 10.3390/s22155750.

[2] S. A. Abdel Hakeem, H. H. Hussein, and H. Kim, "Vision and research directions of 6G technologies and applications," Journal of King Saud University - Computer and Information Sciences, Mar. 2022, doi: 10.1016/j.jksuci.2022.03.019.

[3] A. I. Salameh and M. El Tarhuni, "From 5G to 6G—Challenges, Technologies, and Applications," Future Internet, vol. 14, no. 4, p. 117, Apr. 2022, doi: 10.3390/fi14040117.

[4] K. B. Letaief, Y. Shi, J. Lu, and J. Lu, "Edge Artificial Intelligence for 6G: Vision, Enabling Technologies, and Applications," IEEE Journal on Selected Areas in Communications, vol. 40, no. 1, pp. 5–36, Jan. 2022, doi: 10.1109/jsac.2021.3126076.

[5] P. Mishra, M. Sivaram, M. Arvindhan, A. Daniel, and R. Ranjan, "Energy-Efficient Cloud Computing Techniques for Next Generation," Hybrid Intelligent Approaches for Smart Energy, pp. 49–66, Sep. 2022, doi: 10.1002/9781119821878.ch3.

[6] S. Sharma and C. Rana, "The Scope of Energy Efficient Techniques in Cloud Computing," *2022 10th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions) (ICRITO)*, 2022, pp. 1-4, doi: 10.1109/ICRITO56286.2022.9965129.

[7] M. Banafaa et al., "6G Mobile Communication Technology: Requirements, Targets, Applications, Challenges, Advantages, and Opportunities," Alexandria Engineering Journal, Sep. 2022, doi: 10.1016/j.aej.2022.08.017.

[8] P. N. Srinivasu, M. F. Ijaz, J. Shafi, M. Wozniak, and R. Sujatha, "6G Driven Fast Computational Networking Framework for Healthcare Applications," IEEE Access, pp. 1–1, 2022, doi: 10.1109/access.2022.3203061.

[9] "Want an Energy-Efficient Data Center? Build It Underwater," IEEE Spectrum, Feb. 21, 2017. https://spectrum.ieee.org/want-an-energyefficient-data-center-build-it-underwater (accessed Aug. 05, 2022).

[10] Z.-H. Hu, Y.-X. Zheng, and Y.-G. Wang, "Packing computing servers into the vessel of an underwater data center considering cooling efficiency," Applied Energy, vol. 314, p. 118986, May 2022, doi: 10.1016/j.apenergy.2022.118986.

[11] B. Cutler, S. Fowers, J. Kramer and E. Peterson, "Dunking the data center," in *IEEE Spectrum*, vol. 54, no. 3, pp. 26-31, March 2017, doi: 10.1109/MSPEC.2017.7864753.

[12] J. Roach, "Microsoft finds underwater datacenters are reliable, practical and use energy sustainably," Innovation Stories, Sep. 14, 2020. https://news.microsoft.com/innovation-stories/project-natick-underwater-datacenter/

[13] https://natick.research.microsoft.com/

[14] D. Laffoley and J. M. Baxter, Eds., Explaining Ocean Warming: Causes, scale, effects, and consequences. IUCN, International Union for Conservation of Nature, 2016. doi: 10.2305/iucn.ch.2016.08.en.

[15] L. Cheng et al., "Past and future ocean warming," Nature Reviews Earth & Environment, pp. 1–19, Oct. 2022, doi: 10.1038/s43017-022-00345-1.

[16] E. García, S. Clemente, C. López, J. S. McAlister, and J. C. Hernández, "Ocean warming modulates the effects of limited food availability on Paracentrotus lividus larval development," Marine Biology, vol. 162, pp.

7, pp. 1463–1472, Jun. 2015, doi: 10.1007/s00227-015-2682-0.

[17] A. A. Periola, A. A. Alonge, and K. A. Ogudo, "Heat Wave Resilient Systems Architecture for Underwater Data Centers," Scientific Reports, vol. 12, no. 1, Oct. 2022, doi: 10.1038/s41598-022-21293-2.

[18] M. Manganelli, A. Soldati, L. Martirano, and S. Ramakrishna, "Strategies for Improving the Sustainability of Data Centers via Energy Mix, Energy Conservation, and Circular Energy," Sustainability, vol. 13, no. 11, p. 6114, May 2021, doi: 10.3390/su13116114.

[19] AA Periola,S.O.Adegbola, and R.I.Salawu, 'Computing systems in a pseudo–marine operational environment: design and initial test results', The Proceedings of the Nigerian Academy of Science, Vol. 14, No.2, 2021, pp. 45 – 60.

[20] 3GPP, ' ETSI TS 123 501 V17.4.0 (2022-05)– 5G; System architecture for the 5G System (5GS) (3GPP TS 23.501 version 17.4.0 Release 17)', 2022,https://www.etsi.org/deliver/etsi_ts/123500_123599/123501/17.04.00_60/ts_123501v170400p.pdf

[21] 3GPP, 'ETSI TS 123 501 V17.4.0 (2022-05) – 5G; System architecture for the 5G System (5GS) (3GPP TS 23.501 version 17.4.0 Release 17)', https://www.etsi.org/deliver/etsi_ts/123500_123599/123501/17.04.00_60/ts_123501v170400p.pdf

[22] https://phoenixnap.com/blog/data-center-tiers-classification

[23] C. Chaudhary, A. J. Richardson, D. S. Schoeman, and M. J. Costello, "Global warming is causing a more pronounced dip in marine species richness around the equator," Proceedings of the National Academy of Sciences, vol. 118, no. 15, Apr. 2021, doi: 10.1073/pnas.2015094118

[24] T. Sutherland and G. Bopp, "The Pacific futures of subsea data centers," New Media & Society, vol. 25, no. 2, pp. 345–360, Feb. 2023, doi: https://doi.org/10.1177/14614448221149944.

[25] "Atlas and Hicloud Join Forces to Lead the Way in Sustainable Digital Innovation with Revolutionary Underwater Data Centers," www.investorsobserver.com. https://www.investorsobserver.com/news/qm-pr/7078877970231180 (accessed May 16, 2023).

[26] P.Judge, 'Building underwater: Projects in the US and China have shown that data centers underwater could be more efficient than those on land. But how do you build them? https://www.datacenterdynamics.com/en/analysis/building-underwater/, March 15 2022, (accessed May 16 2023).

[27] S.Hansen, 'Future of Cloud Computing: Underwater Data Centre Solutions',https://www.datacenterdynamics.com/en/analysis/building-underwater/, January 13, 2022 (accessed May 16 2023).

[28] Ericsson, " Ericsson White Paper BNEW-22:024836 Uen June 2022 – 5G Advanced: Evolution towards 6G," 2022. Accessed: Jan. 02, 2023. [Online].Available:https://www.ericsson.com/49e389/assets/local/reports-papers/white-papers/5g-advanced-evolution-towards-6g.pdf

[29] 3GPP, '3GPP TS 23.548 V17.5.0 (2022-12) – 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; 5G System Enhancements for Edge Computing; Stage 2, (Release 17)'