Multi-Shell Space Data Centers in the Sun-Synchronous Orbit-assisted LEO Mega-Constellation

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Abstract

Space data centers (SDCs), which offer space-based computing solutions, have recently drawn wide attention due to their potential to substitute energy-intensive terrestrial cloud data centers (CDCs). With the rapid development of artificial intelligence (AI) technologies, the increasing number of satellites, and the improved durability of computing devices, the implementation of SDCs has become even more feasible. However, architecture of SDCs has rarely been addressed in previous works. In this position paper, we propose a multi-shell SDC architecture composed of a Low Earth Orbit (LEO) mega-constellation and a single sun-synchronous orbit (SSO) shell. Combined with RIC-assisted control, the proposed architecture can support efficient resource allocation, path selection and computation offloading decision while reducing dependence on traditional terrestrial CDCs. This position paper provides an initial, scalable architecture toward future orbital SDCs.

Ⅰ. Introduction

As communication systems evolve toward sixth-generation (6G) networks, the rapid proliferation of Internet-of-Things (IoT) devices and data-intensive applications has significantly increased the demand for data centers. However, traditional terrestrial cloud data centers (CDCs) have been increasingly questioned due to their high carbon emissions and consumption of massive energy and water [1].

To address these issues, space data centers (SDCs), which perform computation within satellite networks using abundant solar energy, have recently attracted growing attention as a potential alternative future platform to terrestrial CDCs. Although prior studies have included satellites into network architectures for computation, satellites have primarily been treated as auxiliary nodes in terrestrial-centric networks. SDCs are different from those networks in that they are space-centric and most of the tasks are processed within satellite networks. However, in spite of the growing interest in prospective SDCs, the architecture of SDCs was hardly suggested.

Motivated by this observation, we suggest an architecture of SDC and its computation offloading model in this position paper. We propose a multi-shell SDC (MSSDC) architecture composed of a Low Earth Orbit (LEO) mega-constellation and a single sun-synchronous orbit (SSO) shell. SSO, with its fixed Earth-Sun geometry, provides regular solar illumination and therefore predictable on-board computing capabilities. Satellites in traditional LEO mega-constellations have unpredictable battery and computing power that make computation in space unstable and unreliable. However, by complementing a LEO mega constellation with an SSO shell as a supporting computing layer, the proposed architecture is expected to be more stable and reliable for computation. Meanwhile, we also utilize an radio access network (RAN) intelligent controller (RIC) for its computation offloading framework. AI-enabled RIC provides near-real-time (RT) control for path selection, resource allocation, and computation offloading, allowing networks to operate efficiently. This MSSDC framework is expected to provide space-centric computation capability while ensuring reliability, predictability and efficiency.

Ⅱ. Existing Space Computing Architectures

Ⅱ. 1 Description

Satellites have been used for computation in several architectures which are represented by integrated satellite-terrestrial network (ISTN) [2] and space-air-ground integrated network (SAGIN) [3]. In those architectures, satellites are used for computation and relaying nodes. Meanwhile, [4] presents an architecture that models SDCs as cloud-like computing nodes in orbit, organized through a scout–mothership edge hierarchy and interconnected with terrestrial CDCs.

Ⅱ. 2 Problems

In ISTNs and SAGINs, satellites provide limited edge computing and primarily function as relaying nodes via inter-satellite links (ISLs), while computation largely relies on terrestrial CDCs. [4] provides a comprehensive benchmarking framework for SDCs by modeling connectivity, computing, and system-level constraints, however, it does not consider orbit-dependent architectural roles and heterogeneous energy conditions.

Ⅲ. Multi-Shell Space Data Center (MSSDC)

This section introduces the architecture, controller, and computation offloading model of the MSSDC framework, with a focus on its key characteristics and contributions toward an orbit-aware and energy-aware SDC design.

Ⅲ.1 SSO-assisted LEO mega-constellation

Although the increasing number of satellites and advances in on-board computing capabilities have made SDCs feasible, satellite computing resources which are related to battery capacity and power availability remain unstable due to their reliance on solar energy with daily varying illumination conditions. SSO, however, provides stable and predictable solar illumination, enabling reliable power generation and sustained computing capability. We therefore propose a multi-shell architecture consisting of a LEO mega-constellation and an SSO shell, where the SSO acts as a dedicated support computing layer that assists LEO nodes when their computing resources become insufficient or unstable.

Ⅲ.2 RIC

We adopt the RIC framework introduced in [5] to optimize decision-making. In particular, following the LEO satellites-assisted open-RAN architecture in [5], we deploy the near-RT RIC on LEO satellites to perform time-sensitive offloading decisions, path selection, and resource allocation.

Ⅲ.3 Computation offloading model

IoT tasks are offloaded from ground devices to contact LEO satellites and forwarded via ISLs to processing nodes within the network [5]. Unlike conventional architectures that rely on terrestrial CDCs for task computation, the proposed framework replaces them with an SSO layer. A near-RT RIC operates over the LEO satellites as a control plane, jointly coordinating computation offloading, routing, and resource allocation between LEO and SSO shells according to their currently available computing capabilities and bandwidth resources.

Ⅲ.4 Key Characteristics and Contributions

In this subsection we present key characteristics and contributions of the proposed architecture, which are distinguished by an energy-aware orbit framework design and the integration of AI-enabled RIC for network efficiency. These two features, energy and AI-enabled controller, should be jointly and continuously considered in the design of future SDCs to ensure stability and efficiency.

- By relying solely on solar-powered satellites for computation, the architecture reduces carbon emissions, water, and power consumption [1].
- By introducing an SSO shell with predictable daily solar illumination, the proposed architecture establishes stable and reliable computing support, mitigating short-term and irregular variability in battery power and computing resources inherent in LEO-only SDCs and enhancing overall system robustness.
- By taking orbital characteristics and energy constraints into account, the architecture enables energy-aware computing decisions that are not addressed in conventional SDC architectures.
- The RIC enables near-RT path selection, resource allocation, and offloading decisions using AI to effectively utilize computing resources across heterogeneous layers.

Ⅳ. Limitations and Future work

The proposed architecture faces limitations related to ISL feasibility, dynamic topology, and orbit selection. Inter-layer ISLs remain challenging to deploy, introducing communication and latency constraints. Moreover, unlike satellite-terrestrial networks, both layers in a multi-shell architecture exhibit high mobility, requiring topology-aware path selection for near-RT optimization, which can be potentially addressed by using the method in [6]. As SSO characteristics vary with inclination and altitude, careful selection of orbital elements is necessary for practical deployment. Finally, a single SSO shell is insufficient to completely replace terrestrial CDCs primarily due to the limited on-board computing capacity, indicating that the consideration of additional SSO shells is necessary in future designs. Addressing these challenges is essential for realizing a practical and sustainable SDC architecture and is left for future work.

Ⅴ. Conclusion

In this position paper, we proposed an MSSDC architecture for satellite-centric SDCs without reliance on terrestrial CDCs. The proposed architecture has the potential to mitigate global challenges related to energy consumption and carbon emissions and serves as an initial step toward the architectural development of future scalable SDCs for next-generation networks.

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