DRAFT Position Paper: Edge Clouds Multiple Control Planes Data Replication Challenges

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***Abstract*—Fog computing is an emerging paradigm aiming at bringing cloud functions closer to the end users and data sources. Traditional DC-centric DevOps paradigms established for cloud computing should also span to Edge clouds, which expects them being always manageable and available for monitoring/alerting, scaling, upgrading and applying security fixes. That poses a challenge for edge as classic methods do not apply here. Moreover, data synchronization became a common challenge for OpenStack/Kubernetes platforms hosting Mobile Edge Computing environments. In this paper, we aim at initiating discussions around that. We define operational invariants for Edge clouds based on the Always Available autonomy requirement and related state-of-art work. We evaluate global/replicated causal consistent data stores and middleware as possible match for meeting those invariants. We point out a great opportunity for designing such systems for edge cases as a unified solution applicable for infrastructure owners, DevOps/SRE people and MEC applications hosted on IaaS/Paas platforms, like OpenStack and Kubernetes. Finally, we bring vision of such edge-native applications and cloud APIs to be designed as vendors agnostic and provide inter-operability over multi-vendored hybrid Edge clouds.**

***Index Terms*—Open source software, Edge computing, Distributed computing, System availability, Design**

I. Introduction

Hybrid and multi-cloud environments is inevitable future of cloud computing. Interconnected private and public clouds, optionally hosting Platform-as-a-Service (PaaS) solutions on top, like OpenShift/Kubernetes, with its workloads pushed closer to end users, unlock great potential for Mobile Edge Computing (MEC) and massively distributed scenarios. In fog environments, expectations for management, control and operational capabilities are pretty same as to the traditional cloud environments, while DC-centric approaches do not work over wide area networks (WANs) and multiple autonomous control planes. Whereby we can have state of applications or control planes synchronized eventually and partially, which requires no strong consistency and no global view for the most of the cases. Think of autonomous unmanned drones controlled via compact mobile datacenters that cannot always maintain its upstream links up. Or 5G cellular networks, where realtime speech/video recognition or streaming/gaming applications go far beyond the computing powers of tiny devices running it, exceed communication latency of the centralized data processing in a traditional cloud and require smooth handovers for user mobility cases. Such autonomy and data locality requirements impose multiple control and configuration management planes to maintain constant availability for operations and local manageability of systems/applications. Those must be available, while being offline, or keep operating over low-latency channels, while executing a handover between base radio network stations, which require state transfers and resolving of possible conflicts caused by concurrent updates or applying locally cached operations after a network drop out ends. We aim at initating debates on these challenges through numerous communities, foundations and project groups dedicated to building solutions for MEC and other edge computing cases that involve multiple control planes and multi-site or multi-cloud operations.

II. Background Concepts

Aside of the established terms [3], we define a few more for the data processing and operational aspects:

Deployment Data: data that represents the configuration of *cloudlets* [3], like API endpoints URI, or numbers of deployed *edge nodes* [3] in *edge clouds* [3]. That data may represent either the most recent state of a deployment, or arbitrary data chunks/operations required to alter that state. When there is unresolved data merging conflicts or queued operations pending for future execution, the most recent state becomes the *best known* one.

Fig. 1. Example Replication Topology

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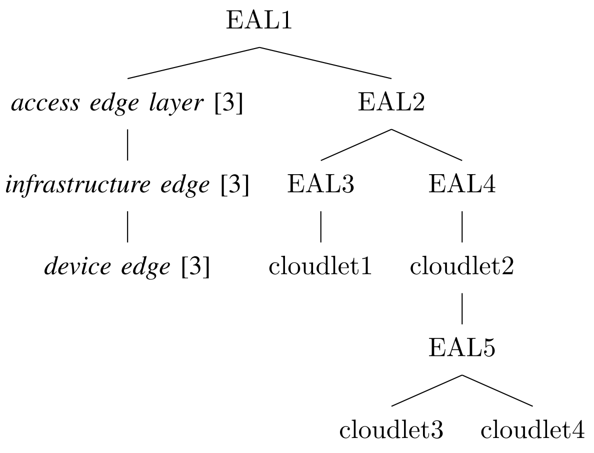

Cloud Data: similarly to deployment data, represents the most recent or the best known internal and publicly visible state of cloudlets, like cloud users or virtual routers. Cloud data also includes logs, performance and usage statistics, state of message queues and the contents of databases. It may as well represent either data chunks or operations targeted for some state S transitioning into a new state S'.

Control Plane: corresponds to any operations performed via cloudlets API endpoints or command line tooling. E.g. starting a virtual machine instance or a Kubernetes pod, or creating an OpenStack Keystone user. Such operations are typically initiated by cloud applications, tenants or operators.

Replication Topology: represents a graph for allowed state replication flows and targets for operations on interconnected cloudlets, including *edge aggregation layers* [3]. For hierarchical topologies, there would be a limitation for horizontally interconnected cloudlets cannot be replicating its state nor targeting operations to each other. This corresponds to the acyclic graph (tree) topology. There may be also P2P topologies [9] or mixed cases.

For the example tree (Fig. 1), the infrastructure edge can replicate data, like contributing its local stats into the global view of hardware and performance metrics, to the the edge aggregation layer EAL1 omitting the access edge layer. Meanwhile the latter can be pushing something, like deployment data changes, to the device edge and infrastructure edge. On the right side of the graph, cloudlet3 and cloudlet4 cannot replicate to each other, but can do to the edge aggregation layer EAL1 either directly or consequently via EAL5, cloudlet2, EAL4 and EAL2, which is totally the replication implementation specific. We also say that EAL2 and EAL1 are hierarchically upper associated with EAL4 and EAL5, or just EAL1 is an *upper layer* for EAL2, when we mean that the latter is a potential subordinate of the former. Finally, we can say that EAL4 controls/manages cloudlet2 and anything sitting down of it.

That is, a control/manage-subordinate hierarchical association only defines influence domains and does not imply state replication as a mandatory thing nor imposes bidirectional data synchronization, but rather provides an opportunity of one-way or bidirectional state replications and regulates a possibility of issuing control/management operations. State replication may be performed from subordinates to its upper associates, think of sending reports. Or vice versa, think of sending directives to subordinates. While control/management operations may only flow up-down, think of planning future work for subordinates.

Management Plane: corresponds to administrative actions performed via configuration and lifecycle management systems. Such operations are typically targeted for cloudlets, like edge nodes, *edge datacenters* [3], or edge clouds. E.g. upgrading or reconfiguring cloudlets in a *virtual datacenter* [3], or scaling up edge nodes. And typically initiated by cloud infrastructure owners. For some cases, like Baremetal-as-a-Service, tenants may as well initiate actions executed via the management plane. Collecting logs, performance and usage statistics for monitoring and alerting systems also represents the management plane operations, although it operates with the cloud data.

When we refer to an edge aggregation layer and cloudlets under its control/management, we mean exactly any operations executed via the control/management planes of that edge aggregation layer and targeted for cloudlets sitting down the nested connections graph. And a replication topology regulates allowed targets for operations and state replication.

Data Replication Conflict: according to [1], two operations on the same target are in conflict if they are not related by causality.

Always Available: the operational mode of the control and management planes that corresponds to *sticky available causal consistency* [4] data replication models, i.e. RTC (*Real-Time Causal* [2]), or *causal*+ [1]. Depending on the consistency model choices, there may be additional constraints:

- the stickiness property is a mandatory constraint for sticky available causal consistent systems. That is: "on every non-faulty node, so long as clients only talk to the same servers, instead of switching to new ones" [4].
- the real-time constraint is keeping the system time synchronized for all cloudlets. That is a mandatory constraint for RTC.
- *one-way convergence* [2] is a mandatory for RTC.

Causal+ and RTC consistency ensure ordering of relative operations, i.e. all causal related writes can be seen in the same order by all processes (connected to the same server). It is also known that "the causal consistency supports non-blocking operations; i.e. processes may complete read or write operations without waiting for global computation. Therefore, the causal consistency overcomes the primary limit of stronger criteria: communication latency" [6]. All that provides the best causal consistency guarantees we can get for today for always available systems.

III. Analysis and Discussion

A. Autonomy Requirements

We define always available autonomy for cloudlets as the following strict requirements:

1) Maintain multiple control/management planes: Autonomous cloudlets may only operate as always available when having multiple control/management planes. For example, when an offline cloudlet cannot start virtual machines or containers, that violates the autonomy requirements.

2) Provide no read-only or blocking access for inter-cloudlet operations: Any operations performed on cloudlets state, despite its aliveness/failure conditions as it's shown in the global view of upper edge aggregation layers, fit consistency models that allow the involved control/management planes operating as always available, and there is no limitations, like read-only or blocking access. Operations may be queued for future processing in order to meet this autonomy requirement though. Internal state of cloudlets is allowed to keep its failure modes unchanged. E.g. for a local or distributed Galera/MariaDB database or a Etcd cluster, its standard quorum requirements apply for internal data transactions. That is a transitioning requirement until the internal cloudlets state can be migrated to causal consistent data storages as well.

3) Provide a local control/management plane, whenever possible: Operations on cloudlets can be scheduled at any given moment of time. For offline/partitioned autonomous cloudlets, that can be done via local control/management plane, if it exists and not failed. The same transitioning considerations for internal cloudlets state apply.

4) Support fully autonomous (offline) cloudlets: Aggregation edge layer cloudlets should allow for arbitrary or all of its managed/controlled cloudlets running fully autonomous long-time or indefinitely long, queuing any operations targeted for such cloudlets. That is, to have failure domains size of a 1. For a permanently disconnected cloudlet it may make more sense though to detach it from its adjacent aggregation layer and/or reorganize its place taken in the replication topology.

5) Queue operations to keep it always available at the best effort: Queued operations have to be eventually replayed if/after the control/management plane capabilities restored, or dropped (e.g. expired) otherwise. That poses a delayed replication principle. If there is intermediate aggregation edge layers down the way to the target of the queued operations, the queue may be shared across each of the involved aggregation edge layers or optionally, queued operations may be distributed across not shared queues. That should reduce the associated memory and disc pressure for aggregation layers. Note that we induced no ordering constraints for the operations replayed from queues, that should be defined on case-by-case basis and ideally maintain ordering of causal related operations only, like create a VM and snapshot that VM. Global unique IDs may be a good fit for maintaining such a causal ordering.

6) Provide a global view for cloudlets aliveness state: Global view of cloudlets needs to be periodically presented for at least one of upper aggregation edge layers. For example, with the state marks, like "unknown", or "autonomous"; "synchronizing", "connected"; "failed", or "disconnected", or "fenced", if and only if it is confirmed as failed, or manually disconnected, or fenced automatically. That poses the aliveness of the control/management planes principle.

B. Operational Invariants

To be always available as we defined it, control and management planes of cloudlets should provide the following operational capabilities (*invariants* hereafter):

1) Keep control planes always available at best effort: CRUD (Create, Read, Update and Delete) operations on cloud data can always be requested via API/CLI of local cloudlets or upper layers. The same queuing requirements apply as it is defined for the autonomy requirements.

2) Do not wait for edge aggregation layers control planes for local operations: Local CRUD operations for offline cloudlets, if its control plane exists and not failed, can be processed without waiting for the upper aggregation layers to recover its control over the cloudlets. When a cloudlet is running only compute/storage resources, it cannot meet this requirement.

3) Allow local scaling of infrastructure edge nodes without waiting for management planes of upper aggregation layers: Similarly the to control plane operations, deployed infrastructure edge nodes can always be scheduled for scaling up/down by the cloudlets local management planes, if it is possible (a cloudlet may be relying on the remote configuration management only), or via its upper layers. Same queuing requirements apply for operations.

4) Allow hotfixes and kernel/software updates applied locally for cloudlets: Security patches and minor system updates, including kernel upgrades, can always be scheduled for installation by the same meanings (via operations issued locally or by the associated aggregation layers, including the same queuing requirements).

5) Allow major software versions upgrades applied locally for cloudlets: Similarly, major versions of system components, like OpenStack or OpenShift/Kubernetes platforms, can be always scheduled for upgrades, using the same meanings as above.

6) Provide an extended global view for cloudlets: Additionally to the aforementioned global view for cloudlets control/management plane aliveness state marks, there needs to be a periodically updated global view for each of the edge aggregation layers into its controlled/managed cloudlets, at least the adjacent ones, for the key system administration aspects, like hardware status, power management, systems state logging, monitoring and alerting events, performance and metering statistics.

C. State Replication Consistency Requirements

As it follows from the defined always available autonomy requirements and operational invariants, we define the following data replication requirements[1]:

1) Incorporate convergent conflict handling [1]: Data replication conflicts can be resolved automatically, or by hand and maintained as causal related. The conflicts resolving strategies and rules should be customizable, like "last writer wins" or "return them all". After the conflicts resolved, the data may be considered causal related, that is by definition [1] of the data conflicts in eventually consistent systems.

2) Prefer one-way convergence in replication topologies: As far as the replication topology and queuing capabilities allow that, causal related data can be replicated across cloudlets. Prefer one-way convergence and avoid bidirectional replication whenever possible.

3) Bidirectional replication is only a nice to have requirement: Bidirectional (two-way convergence) data replication is not a strict requirement but is nice to have. Indeed, some state needs to be replicated one-way from aggregation edge layer to cloudlets under its control/management, like virtual machine or hardware provisioning images data. While logs, performance and metering statistics may be collected only from cloudlets to its upper layers.

[1]when we refer to just *data* or *state*, we intentionally do not differentiate either that is deployment or cloud data, or queued API/CLI operations, to be replicated/replayed for management or control planes. That poses the **unified approach principle**

OpenStack/Kubernetes, have yet support for neither causal consistent storage backends for its cloud/deployment data, nor client libraries that could drive replication of casual related state. That poses an open opportunity for developers and system architects to design and implement such state replication tooling for multiple control/management planes.

OpenStack cloud data is normally stored in databases via transactions based on stronger than causal *unavailable* [4] data consistency models, e.g. *serializable* [4], or *repeatable read* [4]. OpenShift/Kubernetes clusters state, some of SDN (Software Defined Network) solutions are backed with Etcd, which also only supports the stronger than causal consistency models. Those cannot tolerate high network latency, serve two-way convergence only, therefore do not scale for potentially dozens of data replicas.

From the other side, the weaker consistency models, which is *total available* [4], provide a poor alternative that brings greatly increased implementation complexity. E.g. *monotonic atomic view* [4] would require handling of *fuzzy reads* [4], *phantoms* [4], discarded write-only transactions, empty state returned for any reads.

D. Data Replication Challenges

All that brings us to challenges that need to be addressed for multiple control/management planes:

- categorizing control/management operations and data flows associated with it, then grouping those into particular replication topologies. Such groups may be identified by multiple metrics, like communication latency, network partition duration tolerance for offline cloudlets, one- or two-way convergence based, a shared causal data storage or client libraries implementation specific. For the latter case, either it should allow replicating data low-level, or replaying queued operations at API level. Finally, that grouping should also be done for built-in state replication capabilities of components. Depending on the constraints for latency or maximum nubmers of replicas, a distributed control/management plane may be a fit for some types of virtual data centers [3].
- in the end, the final design should not bring excessive operational overhead, like if maintaining all of the identified replication topologies simultaneously for a deployment, and require not too much of human care, but still meet the unified approach principle as we defined it earlier.
- picking/combining identified replication topologies to use with each of the involved system components, like identity provider or images serving services. Ideally, (almost) stateless components will not require data replication aside of built-in capabilities of a single distributed control plane.
- designing strategies and rules for conflicts resolving based on picked replication topologies identified the previous steps. A "last writer wins" may be a good fit for database/KVS conflicting data synchronization, while "return them all" seems the best choice for manual or artificial intelligence driven/assisted "smart" conflict resolvers.
- keeping state replication topologies efficient, e.g. distributing locally queued operations targeted for offline cloudlets by nesting more of the edge aggregation layers underneath. Also, stateless or almost stateless components may be happy with only built-in capabilities of a single distributed control plane.
- abiding the unified approach/architecture principles for Edge clouds IaaS, optional Paas, and edge-native workloads as well.

E. Vision of a Unified Deployment/Cloud State Replication Design

The definition we made for always available distributed systems self-explains why the causal consistent state replication is the best match for the massively distributed cloudlets autonomy requirements and operational invariants as we defined those.

The vision of the unified architecture for future state replication tooling imposes it should be solving the multiple control/management planes data synchronization problems for IaaS, PaaS and end users consuming it as Replication-as-a-Service. Although generic version control systems, like Git, might fit all cases for deployment data replicating and conflicts resolving, that would break the unified design approach for cloud data/state replication.

Client libraries implementing causal consistent data replication and customizable conflicts resolving rules may provide a unification layer for different underlying databases/KVS (Key Value Storage). The replication will be effectively acting as database/KVS-to-database/KVS data synchronization tooling syncing data at a database level. The main benefit for such an approach is no a shared data storage needed. Instead, the underlying local to cloudlets data storages may keep operating as is, share nothing and provide unavailable consistency models stronger than causal consistency. And cloudlets may keep using different solutions for its local data storages as far as the state replication tooling may support such backends.

Additionally, client libraries may replicate not only data but operations at an API level[2] as well, i.e. resolve conflicting operations on-fly, then apply the resulting causal related operations for its original targets, effectively replicating changes at an API level. Operations queued by the control/management planes, including those targeted for offline cloudlets, may be also processed that way.

IV. Related Work

COPS [1] provides theoretical fundamentals for causal+ consistency and focuses on highly scalable middleware libraries implementing causal consistent data operations. The similar approach is taken for Indigo middleware [10] that gives

[2]For OpenStack Nova, there had been an example for such an API level replication, that is a Cells V1 protocol. But it had been deprecated as real cells v1 deployments required constant human care and feeding operationally

strong fundamentals on creating application-centric programming methodologies that leverage invariant-repair/violation-avoidance techniques and rely on immutable data structures (CRDTs). Ultimately, that should help programmers to enforce Explicit Consistency by extending existing applications logic and building middleware libraries that operate on top of the underlying causal consistent storage backends. That is, like Walter [11] or SwiftCloud [12].

Walter distributed key-value store system [11] provides a strong consistency guarantee within a site and causal ordering across sites. It introduces Parallel Snapshot Isolation (PSI) property that extends snapshot isolation by allowing different sites to have different commit orderings. PSI allows sites to diverge, which is known as sticky available causal consistency model. So that applications should be designed with that notion of sticky sessions. PSI also precludes write-write conflicts, supports update-anywhere for certain objects and performs asynchronous replication within a cluster that spans across multiple sites. The partial replication is also available for multi-cluster scenarios to address scalability bottlenecks. A single site normally operates a single instance of Walter KVS, but there is also an unexplored option of multiple servers per site. Such setups require switching the cluster(s) to distributed commits instead of the default fast commit protocol.

SwiftCloud distributed object database [12] instead of being traditionally DC-centric, pushes causal consistentcy to client-side by bringing geo-replication all the way to the client machines. This approach looks novel and fitting well into Edge computing cases, if we think of the clients as edge-native applications running close to real clients (users).

There is more of distributed/stretched Global Causal Consistent Databases [6]. That work presents potential applications and databases that could use the causal consistency and shows possible methods to implement that model. It also compares serializability, eventual and causal consistency using a running example. There is an important conclusion that to the authors knowledge there is no commercial or mature systems using the causal consistency.

Bolt-on [13] shim takes another approach and allows to leverage existing production-ready eventually consistent data stores virtually upgrading it to provide convergent causal consistency.

- **Open questions**: what generic data replication cases can we break down to be always performed one-way? That simplifies implementation a lot: "Although most implementations use bidirectional communication, the communication from the update-receiver to the update-sender is just a (significant) performance optimization used to avoid redundant transfers of updates already known to the receiver. One-way convergence is also important in protocols that transmit updates via delay tolerant networks" [2]. And for the remaining cases, may an API-to-API based synchronization mechanisms fully address the needs for bidirectional data replication? Like predictable cloud users/projects' IDs that require no shared replicating databases.
- **Open questions**: are there opensource projects to benefit OpenStack/Kubernetes cloud platforms for edge cases that rely on multiple autonomous control planes? Either mature or in active development, implementing a causal consistent database/KVS, like Walter/SwiftCloud, or midleware/shims operating on top of such weakly consistent systems, like RTC/COPS/Indigo/Bolt-on? For example, SwiftCloud is an opensource project available under Apache 2.0 license and might be a good start for future work of adopting it for OpenStack/Kubernetes and edge-native applications as Replication-as-a-Service.
- **Open questions**: what of the stretched/global clusters can support multi-site failure events, assuming at the edge there may be a lot of small failure domains? And which of those can provide two-way convergent causal consistent data replication across edge sites?

STACK Reseach Group [8] provides a list of the features required to operate and use edge computing resources. The listed requirements are complementary to this work and represent the operational invariants approached from OpenStack developers and operators (DevOps) angle, the view point that also covers inter-operability between multiple operators. The latter is an important requirement for hybrid clouds and Network Functions Virtualization (NFV) Edge cases, like Virtual Customer Premises Equipment (vCPE).

Speaking more of Telcos and dynamic Mobile Edge Computing environments, there is also high demand for modern lightweight latency-tolerant data replication and live migration solutions performing well over WANs and not being DC-centric. The related work [15] focuses on stateful migration, which involves moving running states of MEC applications in containers based environment without storage area networks (SANs) and shared storage constraints. The designed method works over WAN, which is envisioned to be the way that MECs are interconnected, and is a generic mechanism that applies for different types of containers and VMs. Fast and lightweight data replication techniques to cope with user mobility considered in another related work [16] what covers statless cases and may be also extended to stateful MEC applications (which is dependent on the underlying containers orchestration engine (COE) capabilities). It is notable that in these two works containerbased virtualization is considered one of the most promising solutions for MEC environments. Virtualized 5G in Evolved Packet Core (vEPC) Architectures [14] serves another good example of high demand emerging from the world of Telcos. The work describes a state sharing mechanism across different datacenters that leverages Edge Synchronization Protocol(ESP) and Abstract Syntax Notation.1 (ASN.1). There is no mentions of causal consistency models at all but it really reads between the lines as a such. That is exactly causal consistency provides the best choices for picking which state portions should be shared/replicated, to which cloudlets and under which conditions. With causal ordering may be bound here onto operations applied over distict subscribers/sessions and any state associated with it.

The unified approach plays the best here and might bridge those seemingly orthogonal Telco and IaaS/PaaS worlds into the plain of common middleware.

A. Lebre et al. [9] bring vision of a Peer-to-Peer (P2P) OpenStack IaaS Manager, which is opposed to hierarchical distributed topologies. It is stated that P2P saves maintenance costs associated with hierarchies, while the latter also require complex operations in case of failures. The unified IaaS Manager is positioned as an alternative to stretched control plane and federated clouds. It emphasises on challenges of data locality, efficient cloud storage, inter-operability peering agreements, autonomous lifecycle tooling and new edge-native cloud APIs as paramaunt requirements. Such a view-point naturally complements the vision of unified management plane as we introduced it for this paper.

The edge-cloud native APIs may be also designed with the approaches that Indigo [10] or RainbowFS [7] takes. The latter work focuses on Just-Right (modular) Consistency and flexible service level agreements, like latency requirements, enforced data locality and smart storage placement strategies unique to Fog/Edge platforms and dictated by applications designed for it on case-by-case basis. "Whereby an application pays only the consistency price that it strictly requires" [7].

V. Conclusion

We defined autonomy requirements for multiple control/management planes of massively distributed Fog environments and imposed operational invariants off it. That brought us to consistency requirements for cloudlets state replication and associated challenges. We introduced a replication topology building concepts. We posed vision of key design principles, like queuing and delayed replication, aliveness of the control and management planes and a unified approach for the middleware tooling. Possible subject solutions may be based on either of global/stretched causal consistent data stores, or DC-centric shims that operate on top of eventually or causal consistent replicated autonomous data stores. Or client-side middleware placed at the edge. That is all to synchronize data low-level. Alternatively, that may be middleware that replicates operations at an API-to-API high-level.

We want to position the unification principle as the most important thing and the greatest opportunity for developers to do it "the right way", which is to bring the best of two IaaS and PaaS worlds for end users whom such data replication tooling might benefit as a service, i.e. infrastructure owners, DevOps, and tenants workloads, like those next-gen highly dynamic Telco MEC environments we have had a quick glimpse onto. That unification principle also applies to any fog-based system and is not limited to OpenStack or Kubernetes ecosystems.

To draw the line for where/when future work starts, we should remember that "retain workloads operational as the best effort" principle provides a good start for minimum viable products (MVP), like Distributed Compute Node (DCN) scenario. It is also known to be highly wanted by Telco segment for its next-generation Virtual Radio Access cellular Networks (vRAN).

A centralized control/management plane enables early implementations for DCN as it has no autonomy requirements. While post-MVP phases should be evaluated for the most advanced cases, like MEC vEPC, IoT, AI, autonomous aerial drones, big data processing at the edge networks etc. That is where the data replication challenges to fully arise for expensive handover procedures, mobile networks' subscribers state transfers and just generic Day-2 operations of multiple control/management planes of Edge clouds.

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