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 is a challenge as classic methods do not fit edge cases. Data synchronization is also a common issue for IaaS/PaaS platforms and Mobile Edge Computing environments hosted there. In this paper, we aim at initiating discussions around that challenge. 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 causal consistent systems for edge cases as a common solution for cloud infrastructure owners, DevOps/SRE and MEC applications. Finally, we bring vision of Replication-as-a-Service, unified design approach to benefit applications, like NFV/StatelessNF, and cloud middleware/APIs. Having RaaS implemented as vendors-agnostic commodity software/storage systems that provide interoperability over hybrid clouds and multiple service providers is the ultimate mission for future work.**

***Index Terms*—Open source software, Edge computing, Network function virtualization, 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/management (C/M) planes synchronized eventually and partially, which requires no strong consistency and no global view for the most of the cases and most of the time. That imposes specific availability requirements for distributed data stores, or data replication middleware to keep operating as an autonomous and centralized system at once. Systems must retain its availability while being offline and recover its state fast upon a crash. All that requires smart, WAN-optimized 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 initiating debates on these challenges through numerous communities, foundations and project groups dedicated to building solutions for MEC, Network Function Virtualization (NFV) 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.

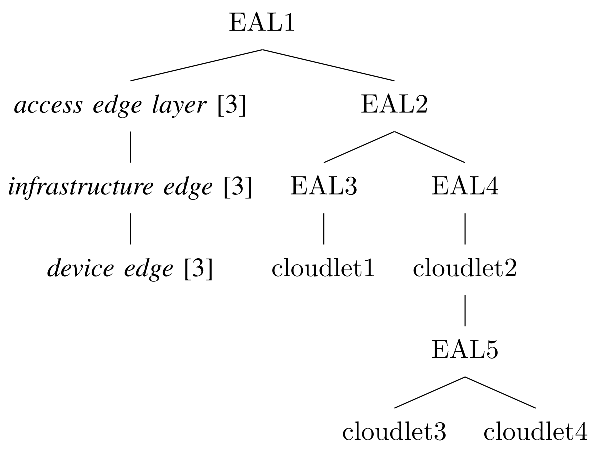
Cloud Data: similarly to deployment data, represents the most recent or the best known internal and publicly visible state of cloudlets, like cloud users or virtual routers. Cloud data also includes logs, performance and usage statistics, state of message queues and the contents of databases. It may 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 VM instance or a Kubernetes pod. 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

Fig. 1. Example Replication Topology



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 C/M-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 C/M 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 C/M 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 or management, we mean exactly any operations executed via the C/M 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.

Causal Consistency [6] ensures ordering of relative operations only, where all causal related writes issued by X can be seen in the same order by all processes connected to all servers (or at least the same server X). Causal dependencies are normally tracked for a version of an object, like a key-value pair. And checked before making that version visible to the clients or another replica. Causal consistency supports non-blocking operations, i.e. allows commiting changes or reading data locally for each server, without waiting for global computation. This overcomes communication latency, which is the primary limit of strong consistency. Cloudlets' autonomy also relies on such non-blocking operations.

Data Replication Conflict: according to [1], two operations on the same target are in conflict if they are not causal related. Such operations require further reconcilation, i.e. resolving the conflict. There is also techniques to avoid such conflicts via immutable Conflict-free Replicated Data Types (CRDTs).

Always Available: the operational mode of the C/M planes or applications that corresponds to the *sticky available causal consistency* [4] model, i.e. *Real-Time Causal*(RTC) [2], or *causal+* [1]. The key constraints and properties are:

- the stickiness property applies so long as clients only talk to the same healty servers, instead of switching to new ones, i.e. maintain sticky sessions.
- 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 constraint for RTC.

III. Analysis and Discussion

A. Autonomy Requirements

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

1) Maintain multiple C/M planes: Autonomous cloudlets may only operate as always available when having multiple C/M 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 C/M 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. its DC-centric quorum requirements still 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 autonomous C/M 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 C/M 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 C/M 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 principle of aliveness of the cloudlets' C/M planes.

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' C/M plane aliveness 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: According to [1], conflicts can be resolved automatically, or by hand and maintained as causal related only after that reconcilation is complete. The conflicts resolving strategies should vary on case-by-case basis. Last-writer-wins (LWW) systems [1] [13] may be best for reconciling operations issued by multiple control planes. While "return them all" [1] [17] strategy better fits the configuration management tasks performed on autonomous cloudlets. Whereby conflicts may have to be reconciled differently when a configuration was either applied locally and is replicated back to the upper aggregation layers, or pushed down after the autonomous cloudlet recovers its uplink connection to the management plane. Or when an NVF application performs a handover for user mobility cases in 5G networks. The source of truth then may be based on distance/placement instead of timestamps.

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,

[1]when we refer to *data* or *state*, we do not differentiate either that is deployment/cloud data, internal state of an NFV application or cloud API operations. That poses the **unified approach principle.**

performance and metering statistics may be collected only from cloudlets to its upper layers.

OpenStack/Kubernetes, have yet support for neither causal consistent storage backends for its cloud/deployment data, nor middleware that could drive replication of casual related state[2]. OpenStack cloud data is stored in a distributed database[3] based on *unavailable* [4] strongly consistent models, e.g. *serializable* [4]. In OpenShift/Kubernetes clusters state is backed with a key-value data store (KVS), which also supports only the strong consistency. These do not scale across datacentres, which poses an open opportunity for designing such causal consistent state replication systems.

From the other side, the *total available* [4] consistency models weaker than causal or eventual, leave the programmers of end systems to deal with *fuzzy reads* [4], *phantoms* [4], discarded write-only transactions or empty state returned for any reads.

D. Data Replication Challenges

All that brings us to challenges that need to be addressed for multiple C/M planes:

- identifying types of C/M operations and replicated data, when grouping those into particular replication topologies. Such groups may be identified by multiple metrics, like communication latency, tolerated duration of network partitions for offline cloudlets, one- or two-way convergence based replication of either low-level data or operations at the higher API-to-API levels.
- the unified replication topology should not bring excessive operational overhead, like maintaining all of the identified types of operations simultaneously for the end system, and require not too much of human care.
- picking the right replication topologies for each of the involved system components, like an identity provider or images streaming services. F.e., an efficient implementation of caching of VMs/containers images may require maintaining a dynamic peer-to-peer mesh topoligy replicated across adjacent cloudlets.
- programming CRDTs for the conflicts-free systems or "smart" conflicts resolvers based on the picked replication topologies.
- keeping the state replication topologies always efficient and adjusting itself dynamically. E.g., when executing a handover for a mobile subscriber in a 5G network, an orchetrator must identify the adjacent endpoints based on the subscriber location and define the numbers of replicas to place there. Or distributing the queued control plane operations targeted for the associated offline cloudlets might require more of the nested edge aggregation layers or peers to be added dynamically or statically, when the load exceeds hardware capabilities of a particular aggregation site.
- programming middleware that abides the unified approach and fits the targeted Replication-as-a-Service (RaaS) cases for IaaS/Paas control and management planes as well as the edge-native, like NFV, workloads. For the most of the cases, one size does not fit all, so future RaaS solutions should be tightly coupled with its suggested replication topologies.
- **Open questions**: what Edge computing cases involving autonomous multiple control planes can be expressed via one-way converged data replication with causality tracked per-key[4]?
- **Open questions**: for the remaining two-way convergent (i.e. bidirectional) data replication, may an API-to-API based synchronization fully address that?

[2]StarlingX:https://storyboard.openstack.org/#!/story/2002842 builds on top of the current strongly consistent database backend

[3]See an evaluation of CockroachDB:https://www.cockroachlabs.com/docs strongly consistent key-value data store:https://github.com/BeyondTheClouds/juice

E. Vision of a Unified State Replication As a Service

The vision of the unified architecture for data replication tooling is solving common problems for C/M planes of IaaS/PaaS, end users and edge-native applications. F.e., generic version control systems are well suited for code and might fit all cases for configuration data replication and conflicts resolving, but would violate the unified design approach for other cloud data/state replication cases. For OpenStack, rearchitecting its relational SQL-based datamodel as RaaS is quite challenging, whenever it's implemented as a global KVS cluster or middleware replicating state across multiple KVS clusters. But in the end that would allow the seamless integration of OpenStack and Kubernetes platfroms into a powerful combo to serve Telco NFV cases and edge computing needs.

Client libraries implementing causal consistent data replication and customizable conflicts resolving rules may provide a unification layer for different underlying databases or KV stores. The replication will be effectively acting as database/KVS-to-database/KVS data synchronization tooling syncing data at low-level across multiple DC/cloudlets. 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 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 C/M planes, including those targeted for offline cloudlets, may be also processed that way.

[4]according to [2], one-way convergence greatly simplifies end-to-end implementation

IV. Related Work

Global/stretched Causal Consistent Databases [6] 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 are mature enough systems that implement Dynamo [17] causal consistency tracked per-key: Riak[5], Cassandra[6] and Voldemort[7].

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 strong fundamentals on creating application-centric programming methodologies that leverage invariant-repair/violation-avoidance techniques and rely on 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 [11] KVS uses a set-like CRDTs. It 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 diverge with different commit orderings. This is also known as sticky available causal consistency model. Walter performs asynchronous replication across multiple sites and supports partial replication for multi-cluster scenarios to address scalability bottlenecks.

SwiftCloud distributed object database [12] brings geo-replication to the client machines instead. It supports interactive transactions that span multiple CRDT types. To its authors' knowledge, asynchronous replication systems ensure fault-tolerant causal consistency only within the boundaries of the DC, while SwiftCloud guarantees convergent causal consistency all the way to resource-poor end clients. SwiftCloud also proposes a novel client-assisted failover mechanism that trades latency by a small increase in staleness of data.

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.

STACK Research 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 interoperability between multiple operators. The latter is an important requirement for hybrid clouds and NFV Edge cases, like Virtual Customer Premises Equipment (vCPE).

[5]https://docs.riak.com/riak/kv/latest/learn/concepts/

[6]https://github.com/wlloyd/eiger

[7]https://github.com/voldemort/voldemort

In Mobile Edge Computing environments, there is also high demand for novel lightweight data replication and applications live migration solutions. Those must perform well over WAN and not being DC-centric. Proactive data replication techniques to cope with user mobility considered in the related work [14]. It poses challenges of efficient scheduling of data replicas over the edge nodes. According to ETSI reference architecture, MEC Orchestrators are responsible for solving these problems via user mobility prediction, while virtualization infrastructure management (VIM) should implement the proposed procedures of proactive migration. It is notable that containerbased VIMs are considered the most promising solutions for MEC environments, mostly due to reduced footprint of containers. Virtualized 5G in Evolved Packet Core (vEPC) Architectures [15] 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). None of these two works mention causal consistency but it reads between the lines as the such, that answers the questions, like which state portions should be replicated, to which cloudlets and under which conditions. E.g. predicted users' trajectories or operations involving particular mobile subscribers may help to establish causal relations and produce ultimate replication decisions at the applications level. StatelessNF [16] rearchitects NFV applications to decouple its internal dynamic state, like connections tracked by firewalls, into a low-latency DRAM storage tier, like one provided by the underneath VIM. StatelessNF relies on RAMCloud[8], where all data is stored in DRAM. That provides 100-1000x lower latency than disk-based systems and 100-1000x greater throughput, which greatly reduces possibility of concurrent updates causing non-mergable data conflicts. While this benefits NFV cases a lot, RAMCloud may not meet well the defined autonomy requirements for C/M planes, where concurrent data updates and cross-datacenter replication is inevitable. In such setups, RAMCloud as a potential RaaS solution has no more its low-latency advantages.

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 emphasizes on challenges of data locality, efficient cloud storage, interoperability peering agreements, autonomous lifecycle tooling and new edge-native cloud APIs as paramount 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

[8]https://ramcloud.stanford.edu

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].

- **Open questions**: as RaaS targeted for OpenStack, Kubernetes and NFV applications, what mature (or in active development) open-source causal consistent data stores support multi-site failures and may fit the edge computing cases, given the defined operational invariants? That can be either of distributed stores, like [11] [12], or middleware, e.g. [1] [2] [7] [10] [13]. E.g., SwiftCloud and Voldemort are open-source projects available under Apache 2.0 license and might be a good start. Combining it with RAMCloud might end up in a powerful NFV option.

V. Conclusion

We defined autonomy requirements for multiple autonomous C/M planes of Fog and MEC environments and imposed operational invariants off it. That brought us to the causal consistency requirement for inter-cloudlets state replication. We introduced concepts for building replication topologies and described challenges associated with that. We propposed design principles, like low-level data replication and API-level queuing with delayed replication, aliveness of the cloudlets' C/M planes and a unified approach for building ultimate RaaS solutions. Such solutions may be based on global per-key causal consistent data stores, like Riak/Cassandra/Voldemort, or shims providing multi-site causal replication on top of traditional strongly consistent and DC-centric data stores, like CockroachDB, or weaker (eventual) consistent systems as well. For novel StatelessNF applications, its data stores must be DRAM based. That is all to synchronize data only and maintain causal consistency low-level. Alternatively, there may be middleware that queues and replicates C/M plane operations at an API-to-API high-level. The latter is well suited for hybrid clouds architecture. For novel StatelessNF applications, its data stores must be DRAM based. That all poses a major problem for composing a unified RaaS what benefits all.

We want to emphasize on the unification principle as the great opportunity for developers to bring the best of IaaS and PaaS worlds for end users whom such data replication tooling might benefit as a service, i.e. DevOps and tenants workloads, like MEC environments and NFV. It is also an opportunity for Telco side to leverage the commodity replication services of infrastructure layers for the hosted virtual network functions (VNFs). The unification principle also applies to any fog-based system and is not limited to OpenStack, Kubernetes or NFV ecosystems. We only focus on those as a good starting point for the future work.

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 C/M 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 C/M planes of Edge clouds.

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References

[1] W. Lloyd, M. J. Freedman, M. Kaminsky, D. G. Andersen, “Dont settle for eventual: Scalable causal consistency for wide-area storage with COPS”, SOSP, 2011.
[2] P. Mahajan, L. Alvisi, M. Dahlin. “Consistency, availability, and convergence,” Technical Report TR-11-22, Univ. Texas at Austin, Dept. Comp. Sci., 2011.
[3] The Linux Foundation, “Open Glossary of Edge Computing,” [Online]. Available: https://github.com/State-of-the-Edge/glossary
[4] K. Kingsbury, “Consistency Models,” [Online]. Available: https://jepsen.io/consistency.
[5] M. Bayer, “Global Galera Database,” [Online]. Available: https://review.openstack.org/600555.
[6] M. M. Elbushra, J. Lindstrom, “Causal Consistent Databases”, Open Journal of Databases (OJDB), Volume 2, Issue 1, 2015.
[7] PRCE (Projet de recherche collaborative Entreprises), “RainbowFS: Modular Consistency and Co-designed Massive File” [Online]. Available: http://rainbowfs.lip6.fr/data/RainbowFS-2016-04-12.pdf.
[8] R. A. Cherrueau, A. Lebre, D. Pertin, F. Wuhib, J. M. Soares, “Edge Computing Resource Management System: a Critical Building Block! Initiating the debate via OpenStack”, USENIX HotEdge18 Workshop, 2018.
[9] A. Lebre, J. Pastor, A. Simonet, F. Desprez, “Revising OpenStack to Operate Fog/Edge Computing Infrastructures”, IC2E, 2017.
[10] V. Balegas, N. Preguia, R. Rodrigues, S. Duarte, C. Ferreira, M. Najafzadeh, M. Shapiro, “Putting Consistency back into Eventual Consistency”, EuroSys, 2015.
[11] Y. Sovran, R. Power, M. Aguilera, J. Li, “Transactional Storage for Geo-replicated Systems”, SOSP, 385-400, 2011.
[12] M. Zawirski, A. Bieniusa, V. Balegas, S. Duarte, C. Baquero, M. Shapiro, and N. Preguica, “SwiftCloud: Fault-Tolerant Geo-Replication Integrated all the Way to the Client Machine”, Research Report RR-8347, INRIA, 2013.
[13] P. Bailis, A. Ghodsi, J. M. Hellerstein, I. Stoica, “Bolt-on Causal Consistency”, SIGMOD, 761772, 2013.
[14] I. Farris, T. Taleb, H. Flinck, A. Iera, “Providing ultrashort latency to usercentric 5G applications at the mobile network edge”, Transactions on Emerging Telecommunications Technologies, Vol. 29, No. 4, e3169, 2018.
[15] E. Cau, M. Corici, P. Bellavista, L. Foschini, G. Carella, A. Edmonds, T. Bohnert, “Efficient Exploitation of Mobile Edge Computing for Virtualized 5G in EPC Architectures”, MobileCloud, 100-109, 2016.
[16] M. Kablan, A. Alsudais, E. Keller, Franck Le,“Stateless Network Functions: Breaking the Tight Coupling of State and Processing”, NSDI, 97-112, 2017.
[17] G. DeCandia, D. Hastorun, M. Jampani, G. Kakulapati, A. Lakshman, A. Pilchin, S. Sivasubramanian, P. Vosshall, W. Vogels, “Dynamo: Amazon's Highly Available Key-Value Store”, SOSP 2007: 205-220, 2007.