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Edge Computing Enhancements in an NFV-based Ecosystem for 5G Neutral Hosts

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Abstract—Network Function Virtualization (NFV) framework can increase the flexibility and reduce the cost of network functions deployment and operation, but needs to be tailored when this framework is pushed to the domain of edge computing, which is the typical scenario for a 5G neutral host. In such scenario, edge-heavy NFV systems need to address the pressing requirements that comes into play with regard to infrastructure management and multi-layer orchestration, which are typical in a Multi-access Edge Computing (MEC) framework. The European Telecommunications Standards Institute (ETSI) itself has identified a lot of open issues when trying to merge the orchestration life-cycles of NFV and MEC. In this paper we describe a solution that combines extensions in the orchestration and Virtual Infrastructure Management (VIM) layers, along with concrete solutions to the ETSI-identified open issues for NFV-MEC integration, in order to pave the way towards edge-aware NFV solutions for 5G neutral hosts.

Index Terms—orchestration, edge computing, 5G, NFV, MEC, neutral host

I. INTRODUCTION

The advent of 5G technologies is unlocking the potential of delivering high bandwidth and ubiquitous coverage to a heterogeneous set of emerging services and applications. This requires the development of diverse infrastructures, capable of handling complex operations to support the heterogeneous services and devices. Therefore, 5G networks will be composed of a set of interconnected Virtual Network Functions (VNFs), which can be dynamically instantiated over a distributed cloud and edge infrastructure. The virtualization trend is also leading to the emergence of neutral hosting. Neutral hosting allows infrastructure owners to partition and share network resources among various tenants, as well as expose them to service providers. This model will play a main role in the deployment of 5G networks, especially in urban scenarios where very dense small cell deployments are required to serve businesses or crowded districts and events.

A platform that empowers this kind of 5G neutral hosting needs to be compatible with the standard NFV (Network Function Virtualization) ecosystem; but, it also requires to leverage this ecosystem by supporting a series of edge computing enablers. This is because of two main reasons:

- The neutral hosting business model increases the diversity of 5G slice users, which can now include different kinds

of verticals (e.g., from the media industry) as well as various types of telecom operators. This increases the types of co-managed edge resources, and it introduces the requirement to manage edge services that are not necessarily modelled and handled as VNFs (Virtual Network Functions).

- Neutral hosts tend to own and administer lots of edge computing equipment, such as cabinets (which can host edge servers) or street poles (which can host small cells).

Although there are some approaches for co-managing NFV and edge resources, there is still a series of open issues with regard to their efficient integration (as also identified by ETSI [1]), while there are further gaps with regard to edge application orchestration and edge infrastructure management in NFV ecosystems.

In order to address these gaps, we have taken as baseline the ETSI MEC-NFV integration as proposed in [1], with some modifications in the involved components and interfaces. This has led to the development of a thin layer of orchestration on top of the individual NFV and MEC orchestrators, which essentially allows to glue together the different descriptors used in the two frameworks, as well as enable a smooth communication between the different layers of orchestration. By allowing the MEC orchestrator to focus only on controlling the edge applications and the edge platform management, while letting the NFV orchestrator perform the actual deployment of functions on the NFV Infrastructure (NFVI), we minimize the interdependencies and the complexity of the integration of the two orchestrators. Further, we perform a series of additional edge-related enhancements, e.g., by adding an attestation component to the VIM, which is critical when edge hosts are involved in the NFVI.

To this end, this paper explores the related work and the gaps towards integrating edge computing orchestration and management in NFV-based ecosystems in section II. Then, it describes our NFV-oriented edge computing enhancements in sections III-A and III-B, and provides a summary and conclusion in section IV.

II. BACKGROUND AND RELATED WORK

Recent studies, standardization agencies (i.e., ETSI) [2], [3] and projects like 5GCity [4] have been focusing in the extension of the NFV ecosystem to support flexible edge computing deployments and MEC architecture. In this section we introduce the background and related works of NFV orchestration at the edge followed by NFV in MEC.

A. Bridging NFV orchestration and edge computing

ETSI NFV [3] and ETSI MEC [2] are a set of standards which describe two frameworks where virtual services are built over a pool of shared, non-homogeneous physical resources.

While the first has been around for some years and has seen its typical adoption in a data-center centric environment by Service Providers, the second is quite new, its architecture is still under specification and consequently its adoption in a real production environment is yet to happen.

ETSI MEC architecture inherits the NFV approach (it defines its own orchestrator, its own VNF manager its own VIM, NFVI infrastructure and related interfaces) with the caveat that pushing an NFV-like framework from the core network to the access domain inevitably imposes several constraints depending on access technology requirements. More concretely, whenever a MEC application is spawned on a MEC host resource, the application itself is bound to a set of services (e.g., DNS, RNIS, location, bandwidth management), which exposes a set of functionalities that complements the MEC application. This rationale brings up the following main key points: (i) Different MEC applications need their own combination of MEC host services (ii) the life cycle of the MEC application is strictly bound to the services exposed by the local MEC host. This dependency between MEC applications and local services has a huge impact on MEC application descriptors and deployment templates, which are the formal items which enable the application life cycle management. The gaps between ETSI NFV and ETSI MEC architectures, described in [1], raise a set of issues that a researcher would face when trying to unify the two frameworks. These issues are mainly related to three areas: (i) the different life-cycle management of MEC applications and VNFs, as handled by the orchestrators and as reflected in AppD and VNFs, (ii) the interaction and interfaces between NFV MANO and MEC architecture components for operational actions (e.g. service instantiation and termination), and (iii) the management of additional, MEC-specific orchestration actions, like traffic steering and dynamic MEC app relocation. While this gap analysis and the potential solution to those keys issues are yet to be solved, we are proposing ways to address them, by describing a unified MEC and NFV framework that is designed to support 5G neutral hosting use cases.

B. Related works for NFV-MEC integration

The MEC architecture, related use cases and open research issues were surveyed in [5], [6], [7] by highlighting the necessity to extend the NFV ecosystem at the edge and far-edge scenarios to deal with IoT and 5G networks deployments.

TABLE I
NFV-MEC EFFORTS OF KEY PROJECTS (UP TO AUGUST 2018)

Project	SL	RO	SE	CO	IoT	EE	NH
SESAME [11]	Y	Y	-	Y	-	Y	-
ANASTACIA [12]	-	-	Y	-	Y	Y	-
5G-Pagoda [13]	Y	-	-	-	Y	Y	-
5G-MoNArch [14]	Y	-	Y	-	Y	Y	-
5G-ESSENCE [15]	Y	Y	-	-	Y	Y	-
MATILDA [16]	Y	Y	-	-	Y	Y	-
5G-CORAL [17]	-	-	Y	Y	-	Y	-
5GCity [4]	Y	Y	Y	-	Y	Y	Y

As mentioned before, management and resource orchestration are essential for the NFV-MEC deployments. One of the first attempts to define a double-tier NFV-MEC architecture aligned to ETSI NFV MANO specifications was suggested in [8], by improving the resource orchestration for Mobile Edge (ME) functions and IoT deployments (e.g., Cloud RAN).

A comparison between the traditional cloud approach and MEC-based solutions in [9] demonstrates the benefits from efficient orchestration. This article also introduces a NFV-MEC orchestrator called OpenVulcano for multiple MEC nodes. However, slice-ability is not properly addressed and is essential for the platform operator to enable efficient assignment, management, and isolation of the shared resources which is key for 5G networks. So, a study in [10] introduces an effort that is similar to the 5GCity and Neutral host approach in terms of exploring NFV-MEC slicing functionalities.

In terms of broader works that focus on improving the NFV ecosystems, some EU projects are focusing on identified potential 5G functionalities to be enabled on NFV-MEC environments; sliceability (SL), resource orchestration (RO), security (SE), computing offloading (CO), IoT enable functionalities (IoT), edge to extreme edge (EE) (e.g., Fog), and neutral host. Table I summarizes and compares recent (but not conclusive) efforts on NFV-MEC between main EU projects focusing in one or more of these seven functionalities. Observing the given table we can determine the efforts of 5GCity compared with other projects to improve the NFV-MEC ecosystem and the lack of effort on neutral host functionalities, multi-layer orchestration, edge VIM security requirements (SE), and ETSI-identified integration issues. Hence in this work we introduce the progress of 5GCity project in terms of multi-tier orchestration platform tailored to enable 5G neutral host and other functionalities essential for 5G networks.

III. EDGE COMPUTING ENHANCEMENTS IN AN NFV-BASED ECOSYSTEM

This section firstly presents the main architectural extensions that we did in the NFV ecosystem in order to make it edge-ready. Then, it describes the solution that we designed for achieving an efficient NFV-MEC integration, including our answers to the respective ETSI-identified open issues.

A. Multi-tier orchestration and edge infrastructure management extensions

The 5GCity architecture (described in detail in [4]) has been designed as an NFV-compatible architecture with all

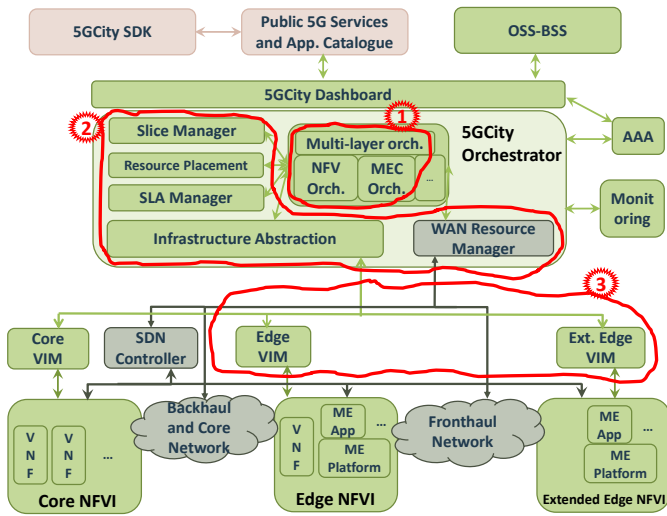


Fig. 1. Edge-related enhancements of the 5GCity orchestration system

the tweaks and extensions that are necessary to support 5G neutral hosts. In Figure 1 we illustrate upon the 5GCity architecture the following three main differentiators that we have introduced in order to support edge computing:

- 1) **Multi-layer orchestration:** The core orchestration functionalities, namely onboarding and instantiation of 5G services and their components, are typically handled by an NFVO (NFV Orchestrator) such as OSM (Open-SourceMano [18]). In order to allow for smooth integration of orchestrators that handle similar parts of the 5G service lifecycle, but using different descriptors and technologies, we have introduced a layer on top of these orchestrators, which parses orchestration requests and service descriptors, performs the appropriate system preparation actions (e.g., configuration of resources related to an onboarded service), and dispatches the job to the appropriate underlying orchestrator. The underlying NFVO can be an ETSI-compatible implementation like OSM, while the underlying MEC orchestrator is integrated based on the principles described in detail in section III-B. The multi-tier orchestration layer exposes then a simplified and uniform API to other components.
- 2) **Re-architecting the rest of the orchestration functionalities:** Orchestration-related components that perform functionalities independent to the nature of the onboarded service (i.e., equally for VNFs and ME applications) have been extracted and decoupled from the core service orchestration logic and re-architected in order to interoperate with both the NFVO and the MEC orchestrator. Such components are the Slice Manager, which manages groups of infrastructure resources belonging users and their linking to Network Services (NS) that run on top of them, the WAN Resource Manager, which "stitches up" VNFs and/or ME applications on the network level by managing the (virtual) links between them, and more.

3) Edge virtualization security and trust developments:

Security and trust are particularly important in smart cities environments because of the distributed architecture and the potential privacy issues in the data they use. In fact, citizens data (coming from cameras, mobility services, health, etc.) need to be well protected to avoid data leakages that can be sold or used for retaliations by attackers. The 5GCity Edge VIM and Edge NFVI provide a virtualization-based security and trust infrastructure for Arm-based edge devices that enable enhanced security, authenticated devices, and secret storage. This infrastructure includes VNF-, NFVI- and VIM-extensions, setting the ground of security and trust features at the lower level of the software architecture. At the base of the 5GCity Edge VIM and Edge NFVI extensions there is VOSYSmonitor [19], a system partitioner for Arm devices that leverages Arm TrustZone to enable a Trusted Execution Environment (TEE) [20], i.e., a secure area of the main processor that provides an isolated and trusted environment. This TEE is used for the implementation of a virtualized Trusted Platform Module (TPM) [21], a set of security features standardized by the Trusted Computing Group. The virtualized TPM functions are made available to the VNFs as well as to the hypervisor. As for the VNFs, vTPMs are used to enhance the security of the network functions with secret storage and cryptographic functions. Standardized and open APIs are used to call secure services, in a way that provides portability and legacy application support. With regard to the hypervisor, the TPM function is used to expose trusted computing features to the Edge VIM. The 5GCity Edge VIM is based on OpenStack and leverages the Edge NFVI to support trusted computing functions. Asset tagging and geo-tagging are supported thanks to a specific OpenStack scheduler that we developed in order to use an attestation service, coupled with an attestation agent that runs on each trusted compute node. Figure 2 shows how the attestation service is linked to the agents to certify the trustworthiness of a specific compute node for a given request. In fact, in order to enforce security and enable multi-tenancy, the attestation procedure is repeated for each request.

B. Integrated NFV-MEC orchestration solution

As ETSI NFV and ETSI MEC share the same principles, they can be combined in a single infrastructure. Therefore, in the 5GCity architecture we have opted for extensions that support both NFV components (e.g., the NFVO) and MEC ones (e.g., the MEAO and the ME-Platform; see Figure 3), as well as integrate the descriptors used in MEC. This requires our full MANO stack to be accompanied by a partial implementation of the following MEC-specific components:

- The Multi-access Edge Application Orchestrator (MEAO)
- The Multi-access Edge Platform Manager - NFV (MEPM-V)
- The Multi-access Edge Platform (ME Platform)

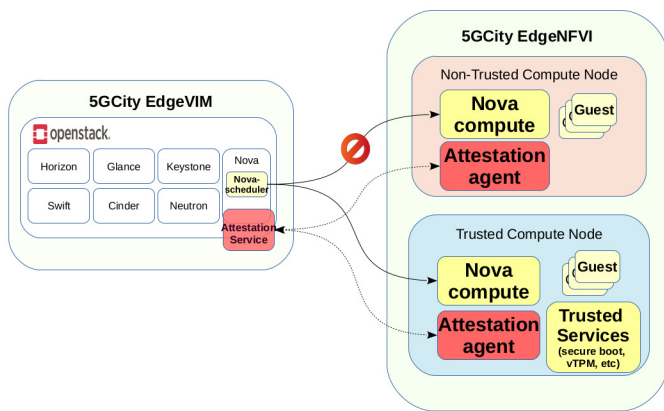


Fig. 2. 5GCity Edge VIM and EdgeNFVI solution for trusted computing

Figure 3 depicts the updated architecture for MEC over NFV that is used as a basis for the integration of MEC and NFV in 5GCity. Some reference points have been removed (e.g., the ones highlighted using dashed lines, as well as the federation reference points), while MEAO and MEPM-V are implemented by using Eclipse fog05 [22]. fog05 is an OpenSource project that aims to provide an IaaS Software for MEC. Due to its fully distributed and pluggable architecture, it allows extensions on functionalities and on the information model, allowing to achieve all the requirements coming from ETSI MEC. The MEAO and the MEPM-V are developed as plug-ins on top of fog05 and leverage the fully distributed Pub/Sub communication fabric provided by fog05 to communicate between each other, while the ME Platform is developed in a way that allows communication between different ME apps that expose services.

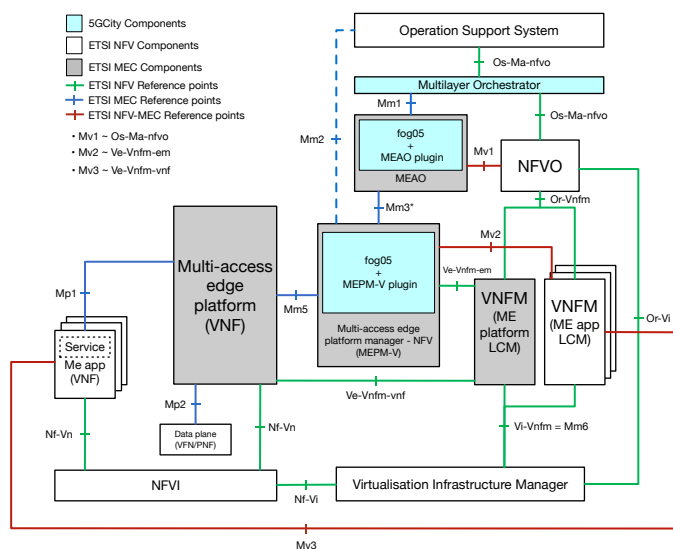


Fig. 3. 5GCity MEC Mapping

Figure 4 describe the deployment of an Network Service over the 5GCity NFV enabled architecture and the interaction

between the different components envisioned in this paper. More in detail the request of NS deployment will be send to the MultiLayer Orchestrator, that will operate a formal check on the NS descriptor. If MEC Application descriptor is present within the NS descriptor, the MultiLayer Orchestrator will originate two parallel work flows: (i) the first flow will consist in a ETSI NFV standard Network service deployment, where AppD are treated as standard VNFd (ii) the second flow consists in the interaction between MEAO, MEPM-V and ME Platform to enable MEC services consumed by an AppD. Example of MEC services [2] are Radio Network Information Services (RNIS), location service, Bandwidth manager service.

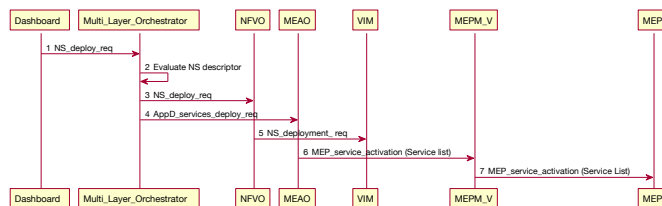


Fig. 4. 5GCity MEC Service Deployment

Moreover, in the 5GCity architecture, the role of the master orchestrator is taken by a thin layer on top of both MEAO and NFVO. This layer is called Multi-layer Orchestrator, while the final decision regarding the placement will be always taken by the 5G service placement algorithms, and the actual deployment of the VNFs will be done by the NFVO, as the MEAO will have no direct connection to the VIM/NFVI. This means that the MEAO and the NFVO should collaborate when it is time to instantiate or migrate an ME application that is composed by VNFs. Another key component of the MEC architecture is the MEPM-V, which is responsible of the Life Cycle Management (LCM) and the Performance Monitoring (PM) for the ME Platform. This component acts like an Element Manager from an NFV point of view, and interacts with the NFVO using the Mm3* reference point. The information exchanged through this reference point are a subset of what is defined by ETSI MEC Mm3, because LCM interact directly with the VNFM. The reference point Mm5, which is not yet specified in ETSI MEC, is used for sending configuration to the ME Platform, as well as for receiving related notifications. Further, the ME Platform allows ME apps to register and access the different services exposed by the platform or by other ME apps. It also provides DNS (Domain Name Service) rules and useful information such as RNIS (Radio Network Information Services). Regarding cardinalities, one MEAO manages different MEPM-V, but one MEPM-V is managed by only one MEAO, while the mapping between ME Platform and MEPM-V is one to one. Traffic redirection is triggered by the MEAO under requests coming from the MEPM-V, and are put in place by the NFVO.

Table II depicts for each of the open issues identified in [1] the approach adopted in 5GCity.

TABLE II
5GCITY SOLUTIONS TO ETSI-IDENTIFIED OPEN ISSUES

ETSI-identified Open Issue	5GCity Solution
1. Mapping between ME app VNFs and NS	In 5GCity, the MEAO maintains a register of ME app VNFs that are used as ingredients of NSs. This register is updated whenever the MEAO gets the NS descriptors of the NFVO
2. Usage of NFV Network Service.	In 5GCity, the MEAO maintains an extended NSD (NS Descriptor) with MEC-relevant fields that include dependencies of NSs to MEC services.
3. Communication between MEAO and NFVO.	In 5GCity, this communication goes through the Mv1 interface, which is developed as a subset of Os-Ma-nfvo
4. Communication between MEPM-V and VNFM via Mv2.	In 5GCity, this communication goes through Mv2, which is developed as a subset of Ve-Vnfm-em. MEPM-V acts as an Element Manager for the ME Platform and it keeps track of LCM operations initiated by the NFVO. It also accesses PM counters for the virtualized resources that host ME app VNFs related to the ME platform.
5. Communication between VNFM and ME App VNFs.	Since ETSI MEC doesn't cover this part in detail, 5GCity will use the NFV approach, i.e. Mv3 will be developed as Ve-vnfm-vnf without any changes, and it will be used for this communication.
6. MEC AppD vs NFV VFND for ME app VNFs.	5GCity uses both descriptors, with MEAO handling AppDs and NFVO handling VNFDS.
7. VNF Package vs. MEC application package.	Similarly to the descriptors (see previous issue), 5GCity packages contain files (descriptors, VM images, executables etc.) related to both NFV and MEC.
8. NS/ME app onboarding.	The Multi-layer Orchestrator acts as the master for onboarding, dispatching requests to MEAO and NFVO. This means that the onboarding starts from the Multilayer Orchestrator, which will then validate eventual MEC information, and send MEC descriptors to MEAO and NFV descriptors to the NFVO.
9. Management of traffic redirection.	In 5GCity, the ME platform requests traffic redirection through Mm5. This information goes then to MEAO through Mm3*, and the MEAO creates a forwarding path based on the new traffic rules and uses Mv1 to ask the NFVO to instantiate them. The MEAO is the trigger for traffic redirection, then the actual configuration is done by NFVO for the NFV part and by the ME platform for the MEC-related part.
10. Comparison between AppD and VNFND data structures	Since 5GCity handles both descriptors in separate sub-orchestrators, the solution can be developed without requiring a deep comparison of the two data structures.
11. NFV construct that corresponds to ME Host.	In 5GCity an ME Host is mapped with the NFVI present in a cabinet, meaning that an NFVI-PoP correspond to a ME Host. MEC should be able to reuse such as NFVI-PoP (basically, a data centre) and Zone (a set of co-located and well-connected physical resources which is a subset of an NFVI-PoP).
12. ME App VNF Instance Relocation.	The MEAO and the NFVO collaborate when it is time to relocate an ME App instance. This communication goes through a reference point separate from Mv1, because it is unrelated to Os-Ma-nfvo. Relocation is triggered by MEAO based on information coming from MEPM-V.
13. Application instantiation.	Similarly to issue 12, ME app instantiation is triggered by the MEAO.
14. Application instance termination.	Similarly to issue 12, ME app termination is triggered by the MEAO based on information coming from MEPM-V.

IV. CONCLUSION

ETSI NFV and ETSI MEC architectures have proven to be pivotal enablers for 5G landscape, being able to bring innovative solutions and accelerate the adoption of the neutral host paradigm.

In this paper we have analysed the issues identified by ETSI [1] related to the integration between NFV and MEC paradigms and we have proposed a solution which (i) takes into account constraints and requirements and (ii) is able to inherit and boost benefits offered by both architectures.

With regard to future work, while detailed specifications

exist for the case of NFV, MEC is somewhat less mature, meaning that our solutions might have to be updated as soon as detailed specifications of MEC protocols that address some of the open issues are published. Further, some of the benefits and limitations of our architecture and our NFV-MEC integration approach will be evaluated and further refined through our respective deployments and tests in three European cities, as explained also in [4].

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REFERENCES

- [1] ETSI. Mobile Edge Computing (MEC) - Deployment of Mobile Edge Computing in an NFV Environment, ETSI GR MEC 017 V1.1.1. 2018.
- [2] Y.C. Hu, M. Patel, D. Sabella, N. Sprecher, and V. Young. Mobile Edge Computing - A Key Technology Towards 5G. 2015.
- [3] ETSI. Network Functions Virtualisation (NFV) - Terminology for Main Concepts in NFV, GS ETSI NFV 003 v1.4.1. 2018.
- [4] 5GCity Project. Deliverable 2.2, 5GCity Architecture and Interfaces Definition. Technical report, 2018.
- [5] Y. Yu. Mobile Edge Computing towards 5G: Vision, recent progress, and open challenges. *China Communications*, vol. 13, no. Supplement2, pp. 89-99, 2016.
- [6] P. Kuure U. Rauschenbach F. Giust D. Sabella, A. Vaillant. Mobile-edge computing architecture: The role of mec in the internet of things. *IEEE Consumer Electronics Magazine*, vol. 5, no. 4, pp. 84-91, 2016.
- [7] P. Mach and Z. Becvar. Mobile edge computing: A survey on architecture and computation offloading. *IEEE Communications Surveys Tutorials*, 19(3):1628–1656, thirdquarter 2017.
- [8] V. Sciancalepore, F. Giust, K. Samdanis, and Z. Yousaf. A double-tier mec-nfv architecture: Design and optimisation. In *2016 IEEE Conference on Standards for Communications and Networking (CSCN)*, pages 1–6, Oct 2016.
- [9] C. Quadri, S. Gaito, R. Bruschi, F. Davoli, and G. P. Rossi. A mec approach to improve qoe of video delivery service in urban spaces. In *2018 IEEE International Conference on Smart Computing (SMARTCOMP)*, pages 25–32, June 2018.
- [10] S. Song and J. Chung. Sliced nfv service chaining in mobile edge clouds. In *2017 19th Asia-Pacific Network Operations and Management Symposium (APNOMS)*, pages 292–294, Sept 2017.
- [11] SESAME Project, H2020 EU project, 2018. <http://www.sesame-h2020-5g-ppp.eu/Home.aspx>.
- [12] ANASTACIA Project, H2020 EU project, 2018. <http://www.anastacia-h2020.eu/>.
- [13] 5G PAGODA Project, H2020 EU project, 2018. <https://5g-pagoda.aalto.fi/>.
- [14] MONARCH Project, H2020 EU project, 2018. <https://5g-monarch.eu/>.
- [15] ESSENCE Project, H2020 EU project, 2018. <https://5g-ppp.eu/5g-essence/>.
- [16] MATILDA Project, H2020 EU project, 2018. <http://www.matilda-5g.eu/>.
- [17] 5GCORAL Project, H2020 EU project, 2018. <http://www.sesame-h2020-5g-ppp.eu/Home.aspx>.
- [18] ETSI. Open Source MANO (OSM), 2018. <https://osm.etsi.org/>.
- [19] P. Lucas, K. Chappuis, M. Paolino, N. Dagieue, and D. Raho. VOSYS-monitor, a Low Latency Monitor Layer for Mixed-criticality Systems on ARMv8-A. In *LIPICs-Leibniz International Proceedings in Informatics*, volume 76. Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik, 2017.
- [20] GlobalPlatform. TEE System Architecture v1.1, GPD_SPE_009. Technical report, Tech. rep., GlobalPlatform Inc, 2017.
- [21] N. Sumrall and M. Novoa. Trusted computing group (TCG) and the TPM 1.2 specification. In *Intel Developer Forum*, volume 32, 2003.
- [22] A. Corsaro and G. Baldoni. fog05: Unifying the Computing, Networking and Storage Fabrics End-to-End. In *2018 3rd Cloudification of the Internet of Things (CIoT) (CIoT'18)*, July 2018.