# Guest Editors' Introduction: Special Section on Smart Management of Future Softwarized Networks

## I. Introduction

NETWORK softwarization is one of the key enablers of the future Internet evolution, also supporting the road from the fifth generation (5G) to the next-generation communication systems, namely 6G, with their main objective of bringing hyper-connected experience to every corner of society.

Besides network paradigms such as Software Defined Networking (SDN), Network Virtualization (NV), and Network Functions Virtualization (NFV), new paradigms are being considered, such as Edge Computing (EC) and Network Intelligence (NI).

In the new upcoming application scenarios, efficient management of softwarized networks and services, already indispensable for current networks, should follow this trend, now becoming "smart", to cope with the unfolding plethora of challenges provided by softwarization. Flexibility does not only have to be addressed by selecting a configuration among some possible ones, but systems have to adapt continuously to ever-changing network conditions and evolving customer demands, and be able to deal with dynamic demands in an automated and, possibly, zero-touch way. In this perspective, Artificial Intelligence (AI) and Machine Learning (ML) will play a central role in management and orchestration of softwarized networks, but also new networking and computing paradigms need to be defined to handle (in real time) more and more constraining requirements with huge amounts of traffic.

Given the global interest of the networking community (including operators) in network softwarization and cloud computing infrastructures for optimized resource allocation and usage purposes in particular, a series of special issues was established in *IEEE Transactions on Network and Service Management*, which aims at the timely publication of recent innovative research results about the management of softwarized networks.

The first special section in this series was titled "Efficient Management of SDN/NFV-Based Systems". It was published in 2015 in two parts [A1], [A2]. The main reported research contributions were: efficient resource allocation and management of softwarized network functions, design of high-performance platforms to allow network function virtualization on commodity hardware, enabling efficient collaboration between providers in softwarized networks, optimization of flow-based software-defined networks to address scalability and energy optimization requirements, programming abstractions in wireless software-defined networks, and improved network virtualization to efficiently support latency-sensitive applications.

The second special section in this series was published in 2016 with the title "Management of Softwarized Networks" [A3]. The main reported research contributions were: SDN control planes optimization, improvements of OpenFlow traffic balancing and resilience, SDN traffic management optimization, novel virtual network embedding algorithms, including algorithms for reliable embedding and efficient NFV resource management, and advanced platforms for management of softwarized network systems.

The third special section in this series was published in 2017 with the title "Advances in Management of Softwarized Networks" [A4]. The main reported research contributions were: management of softwarized datacenter networks, Virtual Network Function management in NFV-based networks, performance characterization and optimization of NFV-based networks, novel techniques for SDN, advanced softwarized wireless networks, security and verification in softwarized networks, and management of softwarized content distribution networks.

The fourth special section was published in 2018 with the title "Novel Techniques for Managing Softwarized Networks" [A5]. Here, the reported advancements in network softwarization addressed resilience, security, load balancing, configuration and monitoring, VNF management in NFV-based networks for orchestration and resource allocation, advanced softwarized switching and routing including virtual network routing and traffic estimation, management of softwarized wireless and cellular networks, and management of data center networks.

The fifth special section was published in 2019 with the title "Latest Developments for the Management of Softwarized Networks" [A6]. It was focused on many interesting challenges regarding management and control aspects of service function chains, network edge environments, network slices and software-defined network components.

The sixth special section was published in March 2021 with the title "Advanced Management of Softwarized Networks" [A7]. It was focused on virtual network functions, management of control plane and programmable data planes, network slicing, edge computing and security. Many papers emphasized the role of artificial intelligence for advanced network management.

In 2021, other key topics including 5G deployment and 6G research have influenced the management and orchestration of softwarized networks. Their consideration has been the target of this current special section, which aims at reporting

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about smart management of future softwarized networks. To this aim, this special section considers major aspects of softwarized network management, such as smart management and orchestration of 5G and 6G networks, end-to-end network management, programmable control and data plane solutions, network slice management, as well as the application of AI/ML techniques for the management of future softwarized networks.

## II. Special Section Overview

This special section welcomes submissions addressing the important challenges and presenting novel research and experimentation results on Smart Management of Future Softwarized Networks. Survey papers that offer a perspective on related work and identify key challenges for future research have also been considered.

Seventy-one papers were submitted for this special section. After a careful review process, it was finally decided to accept twenty-one papers for this special section. The time between initial submission and online publication of the revised papers in this special issue was less than seven months.

The selected papers in this special section address topics that currently play a very important role for an efficient management of softwarized networks: smart management and orchestration of 5G/B5G/6G softwarized networks, efficient end-to-end management of softwarized network infrastructures, SDN and P4-programmable switch/router architecture and design, edge computing and in-network processing in softwarized networks, design and deployment optimization of Service Function Chains (SFC), network slicing and slice management, network and service monitoring, AI/ML techniques for softwarized networks, and trustworthiness, security and privacy. All these papers particularly focus on the definition of an efficient and flexible allocation and orchestration of network resources, on management techniques of the SDN control plane and the programmable data plane as well as of network edge environments. Also the key aspects of network monitoring and security have been considered.

## III. Accepted Papers

From the selected papers in this special section, eight papers deal with aspects of resource allocation and orchestration (Section III-A), five papers focus on software-defined networks in various environments (including satellite networking) (Section III-B), four papers focus on so-called edge computing designs, dealing with management problems raised by the allocation and the operation of network, storage and computational resources at the edge, as well as specific vertical application environments (Section III-C). Finally, four papers present the most recent advancements regarding monitoring aspects, security and implementation issues raised by the deployment and the operation of softwarized networks (Section III-D).

### A. Resource Allocation and Orchestration

Resource allocation and orchestration play a key role in the design and management of softwarized networks. Eight papers of this special section focus on this main topic, covering slice allocation and orchestration as well as the management operations of virtual network infrastructures. More specifically, the first three papers discuss slice allocation over 5G core networks, radio access networks and network edge. Two papers present the design of some blocks of ETSI's Management and Orchestration (MANO) framework, while the last three papers introduce frameworks for efficient service function chain deployment and traffic steering along the paths selected by the NFVO block of the MANO framework.

Vittal and Franklin [A8] present a novel "High Availability supportive self-Reliant NEtwork Slicing System" (HARNESS) for 5G core networks, powered by the intelligent and autonomous Self Organizing Network (SON) paradigm. The authors include algorithms to intelligently schedule and serve the significant portion of control-plane user service requests for both delay tolerant and delay sensitive slices, to ensure their uninterrupted High Availability (HA) service provision. HARNESS has been developed in a 5G test-bed system using eXpress Data Path (XDP) and extended Berkeley Packet Filter (eBPF) mechanism.

González *et al.* [A9] propose the Dynamic radio Access selection and Slice Allocation (DASA) algorithm, an integral solution that combines SDN and NFV techniques to improve network performance and user satisfaction. DASA is based on a multi-attribute decision making (MADM) and analytical hierarchy process (AHP) to face the complex problem of network selection, and uses a cooperative game theory approach to handle load balancing during overload situations. The DASA algorithm is evaluated through network-level simulations, focusing on flexibility and the effective utilization of network resources during network selection and load balancing mechanisms.

Suzuki *et al.* [A10] propose a dynamic virtual network allocation method based on cooperative multi-agent deep reinforcement learning (Coop-MADRL), with the aim of quickly optimizing network resources even while network demands are drastically changing. This is achieved by learning the relationship between network demand patterns and optimal allocation by using deep reinforcement learning (DRL) in advance. The key idea is to use a multi-agent technique for a dynamic Virtual Network (VN) allocation method based on reinforcement learning (RL) to reduce the number of candidate actions per agent and improve the performance for VN allocation purposes. Presented results demonstrate that the proposed technique has the ability to calculate effective allocation in a very short time, with a consequent reduction of server and link utilizations and also a reduction of the constraint violations when compared with static virtual network allocation methods.

Monteil *et al.* [A11] consider a hybrid advance reservation and spot slice market, and study how the Service Providers should reserve resources to maximize their services' performance while not violating a time-average budget threshold. Moreover, a learning-based framework is developed to allow Service Providers to employ a no-regret reservation policy. The proposed approach can also apply to the scenario where slice composition is dynamically decided in terms of the amount of each different type of resource.

Casetti *et al.* [A12] propose a softwarized 5G network architecture that supports the concept of Machine-Learning-as-a-Service (MLaaS) in a flexible and efficient manner. The designed MLaaS platform can provide the different entities of a MANO architecture with already-trained ML models, ready to be used for decision-making purposes. The proposed platform is then applied to the development of two ML-driven algorithms for network slice subnet sharing and run-time service scaling. The approach is implemented and validated through an experimental testbed in the case of three different services in the automotive domain, while their performance is assessed through simulation in a large-scale, real-world scenario.

Bolla *et al.* [A13] present the Resource Selection Optimizer (RSO), a software-service component in the Operations Support System (OSS) of the MATILDA framework, whose main goal is to select the most appropriate network and computing resources among a set of options provided by the Wide-area Infrastructure Manager (WIM). The RSO's performance is evaluated in terms of the execution times of its submodules while varying their respective input parameters, and additionally, three selection policies are compared. Experimental results highlight the RSO behavior from both an execution time and deployment cost standpoints, as well as the RSO interactions with other OSS submodules and network platform components.

Chen and Zhao [A14] propose a traffic steering management framework named STAR to achieve flexible traffic steering along any path selected by NFVO. Thus, STAR ensures the correct enforcement of path selection decisions from NFVO and significantly reduces forwarding rule consumption and control overhead, as demonstrated with some experiments carried out on a testbed and large-scale simulations. The results show that STAR is scalable in the SDN data and control planes while retaining the flexibility of steering traffic along any SFC routing path to provide full support for path decision enforcement with an acceptable overhead.

Zheng *et al.* [A15] study how to apply network function parallelism (NFP) into the service function chaining and embedding processes, such that the latency, including processing and propagation delays, can be minimized. A novel augmented graph to address the parallel relationship constraint among the required service functions is introduced, and its optimization is achieved by formulating a problem called parallelism-aware service function chaining and embedding (PSFCE). Two solution algorithms are formulated to capture scenarios when computing resources at each physical node are sufficient to host the required SFs, but also when these resources are limited.

### *B. SDN Control Plane and Programmable Data Plane*

SDN and Programmable Data Plane (PDP) have the goal of providing the network with higher flexibility in terms of dynamic network service provisioning in the era of network softwarization. Specifically, SDN enables the programmability of the control plane, which can assist a fine-grained networking traffic control from a global perspective, whereas PDP enables the programmability of the data plane, which can aid the customization of packet processing. The five papers in this category deal with different aspects of this topic, considering techniques to improve performance in both the control and the data planes, and they also consider specific environments like satellite networks.

More specifically, the first three papers introduce techniques to improve performance by optimizing specific modules of SDN switches and leveraging high performance of data plane to improve the control plane, while the last two papers consider SDN satellite networks as specific application scenarios.

Zhang *et al.* [A16] aim at improving the performance of Open vSwitch (OVS). Through a detailed analysis of its architecture, they have found that the MegaFlow Cache (MFC) represents the main source of complexity. After a comparative analysis of different classification algorithms to be used in this part, the authors have shown that Tuple Merge Relaxation (TMR) achieves the best performance, and demonstrate that using this scheme inside OVS can improve the throughput compared to a native OVS implementation. Moreover, the authors have shown that TMR-OVS can also bear the Tuple Space Explosion attack and maintain the performance under such an attack.

Fejes *et al.* [A17] propose DeepQoS, a Hierarchical Quality of Service (HQoS) capable core-stateless packet marker that can be used to mark resource-sharing policies of different layers of HQoS simultaneously and effectively in a single point. Using DeepQoS, an HQoS hierarchy of arbitrary depth can be realized with a very simple scheduler. To demonstrate the simplicity of scheduling, it is applied to implement Virtual Dual Queue Core Stateless Active Queue Management (VDQ-CSAQM) on programmable switches, thereby demonstrating that the constrained Traffic Management engine of the programmable switches can be extended using DeepQoS to realize an HQoS hierarchy of arbitrary depth.

Rottenstreich *et al.* [A18], leveraging device connectivity in the fast data plane where delays are in the order of few milliseconds, propose multiple switches to work together to avoid accessing the control plane where delays are orders of magnitude greater. Moreover, models and algorithms are provided for cooperative rule caching with dependencies, accounting for dependencies among rules implied by existing switch memory types. Caching algorithms for several typical use cases are proposed together with a study to find an optimal cooperative rule placement as a function of the matching pattern, which lay the foundations of cooperative caching with dependencies.

Kumar *et al.* [A19] focus on satellite networks to provide high-speed Internet services and propose a centralized QoS-aware routing algorithm based on SDN, called fybrrLink, in which the global view of SDN controllers about the network is used. Modified Bresenham's and Dijkstra's algorithms are introduced to find the optimal path in a significantly reduced computation time. Moreover, taking advantage of the deterministic satellite constellation, a flow-rule transfer algorithm and a topology-monitoring algorithm are defined. By means of simulation, fybrrLink is evaluated and results confirm that it outperforms other state-of-the-art algorithms.

Hu *et al.* [A20] employ software defined multicast (SDM) techniques in large-scale low earth orbit (LEO) constellations to empower satellite-based Internet video distribution. To be specific, authors present a multi-layer rectilinear Steiner tree (MLRST) construction algorithm for multicast routing, extending the spanning graph and edge substitution to three-dimensional (3D) scenes to efficiently construct MLRSTs with $O(n \log n)$ complexity. Experimental results demonstrate that the proposed approach can improve bandwidth savings compared to existing algorithms.

### C. Management of Network Edge Environments

Edge computing has received significant attention from academia and industries as an emerging paradigm that can facilitate the adoption of the Everything-as-a-Service paradigm in infrastructure segments that are located close to the places where data are generated. This enables combining the advantages of flexible service deployment models with the need to cope with the strict requirements in terms of latency of emerging applications. The first two papers look at resource orchestration aspects to satisfy user requirements, while the other two papers deal with specific issues regarding energy savings and reliability.

Davoli *et al.* [A21] propose an architecture for flexible fog computing service orchestration, with a particular focus on the awareness of service deployment models. Design choices are discussed describing the main components and operations of the proposed orchestration system. An implementation of the architecture is presented, including insights on its ability to handle critical orchestration functions such as service discovery and resource monitoring. An experimental analysis is presented to validate the system and evaluate its performance in real scenarios.

You *et al.* [A22] focus on the topic of Deterministic Networking (DetNet), a forwarding paradigm that aims at guaranteeing deterministic bounded latency and low latency variation for time-sensitive applications (e.g., industrial automation), in particular. With this objective, the authors study the management problem of deterministic Service Function Chain (SFC) lifetime in beyond 5G edge fabric with the final goal of maximizing the overall profits and ensuring the deterministic latency and jitter required for each SFC. The optimization problem is formulated as a mathematical model with the maximal profits for Internet service providers. Extensive simulation results show that the proposed algorithms can achieve better performance in terms of SFC request acceptance rates, overall profits and latency variation compared to already existing algorithms.

Kashyap *et al.* [A23] present a framework named DECENT (i.e., Deep learning Enabled green Computation for Edge centric Next generation 6G neTworks) allowing offload from IoT devices optimizing energy consumption, computation latency and offloading rate in 6G environments. The data-offloading problem is modeled as a Markov decision process. The algorithm learns faster from previous long-term offloading experiences and solves the optimization problem with better convergence speed.

Obiodu *et al.* [A24] focus on specific vertical scenarios regarding Connected Cars (CCs) and vehicle-to-everything (V2X) use cases, which are characterized by stringent reliability requirements for both safety and non-safety use cases. The paper investigates the reality of using Supply Side Managed (SSM) and Demand Side Managed (DSM) cellular connectivity as two possible solutions to the need for multiple redundant connectivity. Capability of QoS assurance is evaluated on the field and, based on the test results that have been presented in the paper, the authors show that DSM can deliver superior performance for CCs than any individual network, and demonstrate that remarkable improvements can be obtained in a practical DSM field implementation.

### D. Network Monitoring, Security and Implementation Issues

Network softwarization can increase flexibility and reliability of networks if supported by efficient tools for monitoring the health of the network infrastructure and guaranteeing security at least comparable with legacy architectures.

The four papers in this category focus on different aspects of this topic, ranging between the definition of monitoring techniques for fault management and security, and the definition of trust frameworks to manage application usage rights. More specifically, the first two papers discuss the monitoring for failure detection and intrusion response purposes, the third paper proposes an implementation of traffic mirroring, while the last paper discusses the management of application usage rights.

Silva *et al.* [A25] introduce a failure detection and localization framework capable of forecasting failures in optical systems based on an unsupervised learning strategy. In this approach, the Long- and Short-term Time-series Network (LSTNet) is exploited for modeling the normal behavior of optical systems. Forecast values and actual measurements from optical equipment are used to derive an outlier detection method to detect and locate failures to improve the decision-making process at the network orchestrator. Lab experiments compare the proposed approach with the Recurrent and Long Short-Term Memory models in terms of failure detection and forecasting performance demonstrate the robustness and the suitability of the proposed framework in real-world environments.

Phan and Bauschert [A26] propose an adaptive intrusion response solution based on deep reinforcement learning, namely DeepAir, a dynamic intrusion response solution to maximize the attack defense performance while minimizing the negative impact on benign traffic forwarding and the policy deployment cost in SDN networks. The intrusion response system is formulated as a Markov Decision Process (MDP), and the intrusion response-control algorithm is based on a Double Deep Q-Network to quickly obtain the optimal intrusion response policy.

Sadrhaghighi *et al.* [A27] present design and evaluation of Open Virtual Tap (OVT), a software-defined solution to replace hardware taps for traffic monitoring in OpenFlow networks by utilizing mirroring capabilities of OpenFlow switches. The key idea behind OVT is the joint configuration

of all switches of the underlying physical network in order to efficiently mirror flows from all virtual (overlay) networks. OVT performance is evaluated using model-driven simulations as well as Mininet experiments with realistic applications for intrusion detection and video telephony analysis purposes.

Raghuramu *et al.* [A28] define a new trust framework to manage application usage rights, and propose Metered Boot to provide trusted, capacity/usage-based rights management for services and applications deployed in virtualized environments. Metered Boot decouples application workload instantiation for service operators, usage rights governance for application vendors, and resource provisioning for infrastructure providers. Moreover, leveraging the presence of cryptoprocessors on commodity servers, Metered Boot generates trusted proofs which are managed by efficient cryptographic construction for usage rights compliance. Integration of Metered Boot with OpenStack demonstrates its high scalability and low overhead for instantiating virtual network functions (VNFs).

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## APPENDIX: RELATED ARTICLES

[A1] F. De Turck, R. Boutaba, P. Chemouil, J. Bi, and C. Westphal, "Guest editors' introduction: Special issue on efficient management of SDN/NFV-based systems—Part I," *IEEE Trans. Netw. Service Manag.*, vol. 12, no. 1, pp. 1–3, Mar. 2015.

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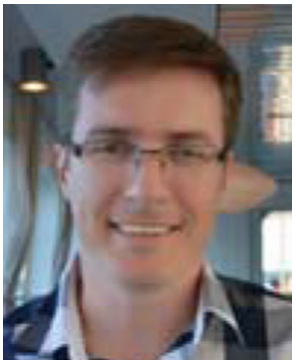

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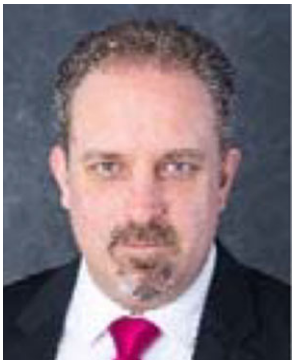

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