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

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## 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 Function Virtualization (NFV), new paradigms are being considered, such as Edge Computing (EC) and Network Intelligence (NI).

In the new upcoming application scenarios, effective and 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 opportunities provided by softwarization. Flexibility does not only have to be addressed by selecting a configuration once, but systems have to be adapted continuously and be able to deal with dynamic demands in an automated and, hopefully, 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 more and more hard requirements with huge amounts of data in real-time.

Given the strong world-wide interest in the softwarization of networks and cloud computing infrastructures, 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 on the management of softwarized networks.

The first special issue in this series was entitled "*Efficient Management of SDN/NFV-based Systems*" and published in 2015 in two parts [1][2]. 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 machines, enabling efficient collaboration between providers in softwarized networks, optimization of flow-based software-defined networks to address the scalability and energy consolidation requirements, programming abstractions in wireless software-defined networks, and improved network virtualization to efficiently support latency sensitive applications.

The second special issue in this series was published in 2016 with the title "*Management of Softwarized Networks*" [3]. The main reported research contributions were: SDN control planes optimization, improvements of OpenFlow network traffic balancing and resilience, SDN traffic management optimization, novel virtual network embedding algorithms, including algorithms for reliable embedding, efficient NFV resource management and advanced platforms for management of softwarized network systems.

The third special issue in this series was published in 2017 with the title "*Advances in Management of Softwarized Networks*" [4]. The main reported research contributions were: management of softwarized datacenter networks, Virtual Network Function (VNF) 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 issue was published in 2018 with the title "*Novel Techniques for Managing Softwarized Networks*" [5]. 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 issue was published in 2019 with the title "Latest Developments for the Management of Softwarized Networks" [6]. It was focused on many interesting challenges regarding management and control aspects of service chains, network edge environments, network slices and software-defined network components.

The sixth special issue was published in March 2021 with the title "Advanced Management of Softwarized Networks" [7]. It was focused on virtual network functions, management of control plane and programmable data plane, network slicing, edge computing and security. Many papers emphasized the role of artificial intelligence for advanced network management.

In the last year, 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 issue, which aims at reporting upon smart management of future softwarized networks. To this purpose, this special issue has considered main aspects 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 for the management of future softwarized networks.

In parallel to the IEEE TNSM series on softwarized networks, the IEEE NetSoft conference was established and dedicated to research on network softwarization. The first seven editions were respectively held in London, UK in 2015, in Seoul, South Korea in 2016, in Bologna, Italy in 2017, in Montreal, Canada in 2018, in Paris, France in 2019, in Ghent, Belgium in 2020 (online), and in Tokyo, Japan in 2021 (online). Each of these editions attracted 180+ participants from academia and industry. IEEE NetSoft 2022 will be organized in Milan, Italy on June 27 - July 1, 2022 with the overall theme "*Network Softwarization Coming on Age: New Challenges and Opportunities*".

## II. Special Issue Overview

This special issue welcomed 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 issue. The submitted papers were thoroughly reviewed and, when needed, some authors were given the time to update their paper and address in detail the concerns raised by the reviewers. It was finally decided to accept twenty-one papers for inclusion in this special issue. 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 issue are addressing the following topics that currently play a very important role for an efficient management of softwarized networks: smart management and orchestration of 5G/5G&B/6G softwarized networks, efficient end-to-end management of softwarized network infrastructures, SDN and P4 switch/router architecture and design, edge computing and in-network processing in softwarized networks, design and deployment optimization of Service Functions Chains (SFC), network slicing and slice management, network and service monitoring, AI/machine learning for softwarized networks, and trustworthiness, security and privacy. Particular attention has been paid to define efficient and flexible allocation and orchestration of network resources, management techniques of the SDN control plane and the programmable data plane as well as of network edge environments, also considering the key aspects of network monitoring and security.

## III. Accepted Papers

From the selected papers in this special issue, eight papers deal with aspects of resource allocation and orchestration (Section III.A), five papers regard software defined networks, considering both the main topics of SDN control plane and programmable data plane also in satellite networks (Section III.B), four papers focus on the edge of the network, dealing with management problems and specific vertical application environments (Section III.C), and finally four papers present advancements regarding monitoring aspects, security and implementation issues (Section III.D).

### *A. Resource allocation and orchestration*

Resource allocation and orchestration play a key role in design and management of softwarized networks. Eight papers of this special issue are focused on this main topic, ranging between slice allocation and orchestration and management operations of virtual network infrastructures. More specifically, the first three papers regard slice allocation of 5G core, radio access network and network edge, other two papers regard the design of some blocks of the Management and Orchestration (MANO) framework, while the last three papers propose frameworks for efficient service chain deployment and traffic steering along the paths selected by the NFVO block of the MANO framework.

In "HARNESS: High Availability supportive Self Reliant Network Slicing in 5G Networks," Vittal and Franklin A [8] 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.

In "Dynamic radio access selection and slice allocation for differentiated traffic management on future mobile networks," González *et al.* [9] propose the Dynamic radio Access selection and Slice Allocation (DASA) algorithm, an integral solution that combines software-defined network (SDN) and network function virtualization (NFV) technologies 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. 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.

In "Cooperative Multi-Agent Deep Reinforcement Learning for Dynamic Virtual Network Allocation," Suzuki *et al.* [10] 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. Presented results demonstrate that the proposed technique is able to calculate effective allocation in a very short time, with a consequent reduction of server and link utilizations and, consequently, of the constraint violations compared with that of the static virtual-network allocation method.

In "Learning-based Reservation of Virtualized Network Resources," Monteil *et al.* [11] 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, and extended to the scenario where Service Providers decide dynamically its slice orchestration.

In "ML-driven Provisioning and Management of Vertical Services in Automated Cellular Networks," Casetti *et al.* [12] propose a softwarized 5G network architecture that realizes 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. 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 proposed approach and solutions are 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.

In "Multi-site Resource Allocation in an Application-Aware 5G Infrastructure," Bolla *et al.* [13] 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 in both execution times and deployment costs, as well as the RSO interactions with other OSS submodules and network platform components.

In "Scalable and Flexible Traffic Steering for Service Function Chains," Chen and Zhao [14] propose a traffic steering management framework named STAR to achieve flexible traffic steering along any path selected by NFVO. In this way, 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 real testbed and large-scale simulations. The results show that STAR is scalable in the SDN data plane and control plane while retaining the flexibility of steering traffic along any SFC routing path to provide full support for path decision enforcement with acceptable overhead.

In "Towards Optimal Parallelism-Aware Service Chaining and Embedding," Zheng *et al.* [15] study how to apply network function parallelism (NFP) into the service function chaining and embedding process 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 enough to host the required SFs, and when these resources are limited.

### *B. SDN control plane and programmable data plane*

Software Defined Networking (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 functionality. 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 specific application scenarios like satellite networks.

More specifically, the first three papers introduce techniques to improve performance 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.

In "Improving Open Virtual Switch performance through Tuple Merge Relaxation in Software Defined Networks," Zhang *et al.* [16] 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.

In "DeepQoS: Core-Stateless Hierarchical QoS in Programmable Switches," Fejes *et al.* [17] 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, demonstrating that the constrained Traffic Management engine of the programmable switches can be extended using DeepQoS to realize an HQoS hierarchy of arbitrary depth.

In "Data Plane Cooperative Caching with Dependencies," Rottenstreich *et al.* [18], 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.

In "fybrrLink: Efficient QoS-aware Routing in SDN enabled Next-Gen Satellite Networks," Kumar *et al.* [19] 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.

In "Software Defined Multicast for Large-scale Multi-layer LEO Satellite Networks," Hu *et al.* [20] employ software defined multicast (SDM) techniques in large-scale low earth orbit (LEO) constellations to empower satellite-based Internet video distribution. More in deep, the 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 achieve improvement in bandwidth saving as compared with 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 saving and reliability.

In "A Fog Computing Orchestrator Architecture with Service Model Awareness," Davoli *et al.* [21] 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.

In "Deterministic Latency/Jitter-aware Service Function Chaining over Beyond 5G Edge Fabric," You *et al.* [22] focus on the recent topic of Deterministic Networking (DetNet), a network paradigm aimed at guaranteeing deterministic bounded latency and low latency variation for time-sensitive applications (e.g., industrial automation). 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 of SFC requests. 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 with already existing algorithms.

In "DECENT: Deep Learning Enabled Green Computation for Edge centric 6G Networks," Kashyap *et al.* [23] 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 environment. 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. Simulation results of the proposed framework show that it maximizes the network utility by overcoming the challenges as compared to the state-of-the-art techniques.

In "DSM-MoC as baseline: reliability assurance via redundant cellular connectivity in Connected Cars," Obiodu *et al.* [24] target the paper 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 uses. The paper investigates the reality of using Supply Side Managed (SSM) and Demand Side Managed (DSM) cellular connectivity as two possible solutions of multiple redundant connectivity. Capability of QoS assurance is evaluated on the field in four different days and across 800 kilometers of major and minor roads in South East England. Based on measuring test results, 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 really increase flexibility and reliability of high-speed networks only if supported by effective 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 in deep, the first two papers regard monitoring for failure detection and intrusion response, the third paper proposes an implementation of traffic mirroring, while the last paper regards management of application usage rights.

In "Learning Long- and Short-Term Temporal Patterns for ML-driven Fault Management in Optical Communication Networks," Silva *et al.* [25] 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. Laboratory experiments comparing the proposed approach with the Recurrent and Long Short-Term Memory models in terms of failure detection and forecasting performance demonstrate robustness and suitability of the proposed framework in real-world environments.

In "DeepAir: Deep Reinforcement Learning for Adaptive Intrusion Response in Software-Defined Networks," Phan and Bauschert [26] 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.

In "Monitoring OpenFlow Virtual Networks via Coordinated Switch-Based Traffic Mirroring," Sadrhaghighi *et al.* [27] present design and evaluation of Open Virtual Tap (OVT), a software-defined solution to replace hardware taps for traffic monitoring in OpenFlow virtual networks by utilizing mirroring capabilities of OpenFlow switches. The key idea behind OVT is the joint configuration of all switches in the substrate physical network in order to efficiently mirror flows from all virtual networks. Performance of OVT is evaluated using model-driven simulations as well as Mininet experiments with realistic applications for intrusion detection and video telephony analysis.

In "Metered Boot: Trusted Framework for Application Usage Rights Management in Virtualized Ecosystems," Raghuramu *et al.* [28] 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).

## ACKNOWLEDGEMENT

The editors would like to thank explicitly all authors who submitted papers to this special issue and all reviewers for their valuable comments, useful suggestions, and timely submission of their reviews. Finally, the editors have appreciated the support of Filip De Turck and Hanan Lutfiyya that worked to the success of this Special Issue with their role of Editor-in-Chief in the first and the second phase of the review process.

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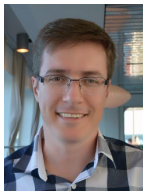

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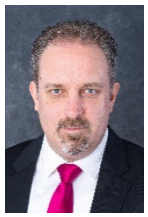

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