Guest Editors Introduction: Special Issue on Advanced Management of Softwarized Networks

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I. Introduction

THE SOFTWARIZATION of networks is enabled by the SDN (Software-Defined Networking), NV (Network Virtualization), and NFV (Network Function Virtualization) paradigms, and offers many advantages for network operators, service providers and data-center providers. Given the strong interest in both industry and academia in the softwarization of telecommunication 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 titled "Efficient Management of SDN/NFV-Based Systems" and published in 2015 in two parts [item 1) in the Appendix], [item 2) in the Appendix]. 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" [item 3) in the Appendix]. 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" [item 4) in the Appendix]. The main reported research contributions were: management of softwarized data-center 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" [item 5) in the Appendix]. 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.

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The fifth special issue was published in 2019 with the title "Latest Developments for the Management of Softwarized Networks" [item 6) in the Appendix]. 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.

In the last year, after the publication of the above mentioned special issue, other key elements have gained a crucial importance for management and orchestration of softwarized networks. Considering all of them has been the target of this current special issue, which aims at reporting upon advanced management and optimization of softwarized networks, encompassing the main enabling technologies and paradigms in the process of network softwarization. To this purpose, this special issue has considered main aspects as resource allocation and orchestration, virtual network function placement and chaining, management of control plane and programmable data plane, network slicing in both radio access and edge networks, design and implementation of edge computing platforms, network monitoring and security. Many papers included in this special issue have demonstrated the significant role of artificial intelligence in providing new solution opportunities for advanced network management.

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 five editions were respectively held in London, U.K., in 2015, in Seoul, South Korea, in 2016, in Bologna, Italy, in 2017, in Montreal, Canada, in 2018, in Paris, France, in 2019 and in Ghent, Belgium, as an online event in 2020. Each of these editions attracted 180+ participants from academia and industry. IEEE NetSoft 2021 will be organized in Tokyo, Japan on June 28 - July 3, 2021 with the overall theme "Accelerating Network Softwarization in the Cognitive Age" as a hybrid on-line conference.

II. Special Issue Overview

This special issue welcomed submissions addressing the important challenges and presenting novel research and experimentation results on management of softwarized networks. Survey papers that offer a perspective on related work and identify key challenges for future research have also been considered.

One hundred and twenty-eight 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 fifty-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 six 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: management and orchestration of NFV platforms, resource allocation, management of user and device mobility, application of machine learning and federated learning for resource provisioning and allocation in network slicing, VNF placement and service function chain (SFC) composition and network service embedding. Particular attention has been paid to define an efficient and flexible management 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, five papers deal with aspects of resource allocation and orchestration (Section III-A), thirteen papers deal with the placement of VNFs and service chaining (Section III-B), ten papers regard software defined networks, considering both the main topics of SDN control plane and programmable data plane (Section III-C), five papers focus on Radio Access Network (RAN) and mobility management (Section III-D), six papers focus on the edge of the network, dealing with management problems and specific application environments (Section III-E), seven papers present advancements regarding monitoring aspects and implementation issues (Section III-F), and finally five papers focus on security, formal verification and protocol misuse in softwarized networks (Section III-G).

A. Resource Allocation and Orchestration

Resource allocation and orchestration are two primary targets in the complex process of network softwarization. The papers in this category focus on different aspects of this topic, ranging between design choices to resource provisioning. The first two papers provide an overview of the state of the art of NFV platform design and optimization with a particular focus on 5G network slicing. The third paper explores the problem of optimizing network resources in multi-domain 5G networks and beyond. Finally, the last two papers propose forecasting models for resource provisioning and slice allocation in softwarized networks.

In "NFV Platforms: Taxonomy, Design Choices, and Future Challenges," Zhang *et al.* [item 7) in the Appendix] present a comprehensive survey on NFV platforms and their taxonomy based on features of network function life cycles. The paper further discusses NFV platform design in the 5G era and provides detailed guidelines for network operators or service providers to choose the most appropriate NFV platform based on specific requirements.

In "A Comprehensive Survey on the E2E 5G Network Slicing Model," Chahbar *et al.* [item 8) in the Appendix] aim at providing the up-to-date end-to-end (e2e) 5G network slicing model based on a deep analysis of the major existing works. Also, an in-depth technology-independent definition of network slices as well as the network slicing process from the network slice provider/operator perspective is bestowed to the research community. Overall, this survey provides a comprehensive reference to network slicing information models and frameworks involved in network slice life-cycle from requirement and preparation to decommissioning phases.

In "Centralized and Federated Learning for Predictive VNF Autoscaling in Multi-Domain 5G Networks and Beyond," Subramanya and Riggio [item 9) in the Appendix] explore the problem of satisfying QoS requirements and optimizing network resources for dynamically changing network service

demands in multi-domain scenarios. The paper focuses on NFV autoscaling and proposes to use deep learning models, both, centralized and federated approaches, to perform horizontal and vertical autoscaling in multi-domain networks. To investigate the potential of the proposed approach and to demonstrate its applicability, the paper relies on an evaluation of the traffic prediction accuracy of various deep learning models and their impact on QoS parameters using a Kubernetes-based orchestration prototype within a Multi-access Edge Computing platform.

In "Uncertainty-Aware Resource Provisioning for Network Slicing," Luu *et al.* [item 10) in the Appendix] propose a resource provisioning approach for virtual networks (slices) aiming to maximize the earnings of infrastructure providers taking into consideration several constraints pertaining to slice requirements, priority and usage. They first formulate the problem as an Integer Linear Program (ILP) and then put forward a suboptimal approach to solve it.

In "An Adaptive Forecasting Model for Slices Allocation in Softwarized Networks," Oliveira *et al.* [item 11) in the Appendix] focus on quality of Internet Access Service (IAS) in presence of elastic demand for network resources. In this context, this paper considers network slices as a possible solution, and presents a joint approach of an Adaptive Demand Forecasting model (ADF) and a slice allocation algorithm. The gain achieved with the proposed approach is demonstrated with a set of experiments based on a real resource demand dataset.

B. VNF Placement and Chaining

NFV is changing the way networking services are created and provided, mainly due to its peculiarity of realizing services as chains of VNFs. VNF placement and chaining is a complex problem that requires efficient solutions to determine where to place VNFs given a set of Network Points of Presence (N-PoPs), and how to steer network flows between them, as specified in Service Function Chains (SFCs).

The papers in this category focus on different aspects of VNF placement and chaining. The first two papers focus on optimizing service chains and VNF placement, the first applying an ILP approach, the second a deep Q-Learning approach. The third paper proposes a different technique for building and running NFs, enabling the creation of networking components that reside inside the kernel of the host machine. The fourth and the fifth papers aim at defining a reliable architecture for distributed chaining that is able to guarantee required performance. The sixth and the seventh papers consider the performance gain obtained by parallelizing portions of service function chains and propose optimization policies for their placement. The next three papers design service chain composition and network service embedding also introducing backup solutions in presence of failures. Finally, the last three papers propose algorithms for performance assessment in specific application environments, like multimedia and delay-sensitive service provisioning and information centric networks.

In "Capacitated Shortest Path Tour Problem Based Integer Linear Programming for Service Chaining and Function Placement in NFV Networks," Sasabe and Hara [item 12) in the Appendix] develop a network model called augmented network, and formulate the shortest path tour problem (SPTP)-based ILP problem for the service chaining with focus on the similarity between the service chaining problem and the SPTP.

In "DDQP: A Double Deep Q-Learning Approach to Online Fault-Tolerant SFC Placement," Wang *et al.* [item 13) in the Appendix] study online Fault-tolerant SFC Placement in NFV, presenting a Double Deep Q-Learning Approach.

In "A Framework for eBPF-Based Network Functions in an Era of Microservices," Miano *et al.* [item 14) in the Appendix] present Polycube, a framework for developing, deploying and managing in-kernel virtual network functions. For that, they exploit the eBPF subsystem available in the Linux kernel to dynamically inject custom user-defined applications into the Linux networking stack. Improvements in terms of simplifications and performance over existing applications are discussed and the applicability of the Polycube programming model for various complex use-cases is shown.

In "Necklace: An Architecture for Distributed and Robust Service Function Chains With Guarantees," Esposito *et al.* [item 15) in the Appendix] address the problem of providing wide-area (federated) virtual network services. To this end, they propose a prototype of an architecture for robust service function chain instantiation with convergence and performance guarantees, and demonstrate that a better optimal chain approximation cannot exist. Moreover, to establish the practicality of the proposed approach, they evaluate system performance, policy tradeoffs, and overhead.

In "Petri Net-Based Reliability Assessment and Migration Optimization Strategy of SFC," Rui *et al.* [item 16) in the Appendix] focus on leveraging Petri net models to propose a reliability evaluation method and a reliability optimization algorithm that improve cost and resource pre-emption of VNF migration.

In "Availability- and Traffic-Aware Placement of Parallelized SFC in Data Center Networks," Wang *et al.* [item 17) in the Appendix] propose the multi-flow backup model for parallelized service function chain placement in data center networks. The main constraints considered in the paper are availability guarantee and resource optimization. Three placement strategies and a hybrid placement algorithm are proposed.

In "FlexChain: Bridging Parallelism and Placement for Service Function Chains," Xie *et al.* [item 18) in the Appendix] design a flexible parallel system for Service Function Chain (SFC) called FlexChain, enabling the parallelism among VNFs to reduce the processing latency. To leverage the benefits of parallelism, they consider the problem of joint optimization over SFC parallelism and placement with the objective of maximizing the request acceptance rate. Moreover, they propose a parallelism-aware approximation placement algorithm with performance guarantees, and an efficient heuristic algorithm for large-scale data center networks.

In "Network Service Embedding Across Multiple Resource Dimensions," Pentelas *et al.* [item 19) in the Appendix]

explore the methods for Network Service Embedding (NSE) optimization across multiple resource dimensions. The authors first study and compare the efficiency of various multi-dimensional mapping metrics, which were introduced in the context of multi-dimensional virtual machine assignment. Utilizing the most suitable and efficient metrics, they propose and evaluate two heuristics and a mixed integer linear program (MILP) for optimized multi-dimensional NSE.

In "Service Chain Composition With Failures in NFV Systems: A Game-Theoretic Perspective," Bian *et al.* [item 20) in the Appendix] address the problem of service chain composition with resource failures like breakdown of virtual machines and loss of connections of users. They hence formulate the problem as non-cooperative game and also devise three schemes to adapt service chains to resource failures in a timely manner. They also show how such schemes reduce latency and mitigate congestion when failures occur.

In "Reliability-Oriented and Resource-Efficient Service Function Chain Construction and Backup," Wang *et al.* [item 21) in the Appendix] focus on a service function chain provisioning problem with the aim of ensuring reliability through efficient backup deployment. They first propose a construction algorithm to aggregate multiple SFCs into a service function graph, and then complement this graph with backup nodes thanks to a backup selection and instance deployment algorithm aiming at satisfying the requested reliability of the SFCs.

In "Comparative Performability Assessment of SFCs: The Case of Containerized IP Multimedia Subsystem," Mauro *et al.* [item 22) in the Appendix] propose a joint analysis of the availability and the performance of an IP Multimedia Subsystems (IMS) implemented using container technology. They model the probabilistic behavior of such an IMS in terms of reliability taking into account failure and repair events and then evaluate its robustness considering different configurations.

In "Provisioning Optimization for Determining and Embedding 5G End-to-End Information Centric Network Slice," Liu *et al.* [item 23) in the Appendix] determine and embed 5G e2e network slices for ICN networks. They formulate the ICN network slices determination and embedding (ICN-NS-DE) problem through an ILP formulation, such that the ICN-NS determination and embedding problems are jointly solved for a hierarchical ICN system without requiring a-priori knowledge on the VN's topology and resource provisioning information.

In "Delay-Sensitive Multi-Source Multicast Resource Optimization in NFV-Enabled Networks: A Column Generation Approach," Muhammad *et al.* [item 24) in the Appendix] focus on resource allocation for multicast service chains in networks empowered with NFV technology. They consider multicast service chains with multiple sources of data and stringent end-to-end delay and bandwidth requirements. The authors mathematically define and formulate the problem using MILP, then develop two heuristics to address the large-scale instances of the problem.

C. SDN Control Plane and Programmable Data Plane

Efficient management of the control plane and its next step that consists in data plane programming are at the heart of softwarized networks. The papers in this category, on one side, focus on various aspects of software-defined network control, considering minimization of traffic between switches and controllers, control of SD-WANs, SDN controller placement, definition of content-centric network architectures, and on the other side, on crucial aspects of programming data plane, including link failure recovery, programming orchestration, in-network event detection and in-network computing.

The first two papers focus on controller placement and control devolution in SDN systems. The third and the fourth paper regard application of SDN in multi-domain and wide area networks (WAN). The next two papers focus on SDN applied to content-centric architectures. Finally, the last four papers deal with important aspects of programmable data plane.

In "SDN Controller Placement With Availability Upgrade Under Delay and Geodiversity Constraints," Santos *et al.* [item 25) in the Appendix] propose a novel controller placement algorithm for SDN aiming at satisfying QoS requirements and offering robustness against disaster-based failures. For that, the authors address the joint controller placement and availability link upgrade optimization problem for SDN networks, aiming to minimize the upgrade cost, while delay, geodiversity and availability requirements are guaranteed. Based on real-world topologies the trade-off between path redundancy, controller redundancy and upgrade costs are discussed.

In "Joint Switch-Controller Association and Control Devolution for SDN Systems: An Integration of Online Control and Online Learning," Huang *et al.* [item 26) in the Appendix] present a solution to address switch-to-controller association in SDN networks with the goal of minimizing the costs of communication among controllers and to ensure better stability of the controllers' queues of requests. They hence formulate the problem as a combinatorial multi-armed bandit problem, propose a learning-aided switch-to-controller association scheme and then study the impact of the solution's parameters on different performance metrics.

In "DOLPHIN: Dynamically Optimized and Load-Balanced PatH for INter-Domain SDN Communication," Latif *et al.* [item 27) in the Appendix] propose an inter-domain routing scheme that ensures load balancing in SDN. They propose a Dynamically Optimized and Load-balanced Path for Inter-domain (DOLPHIN) communication system, a customized solution for different SDN controllers. They also show through extensive simulations how DOLPHIN distributes the traffic load evenly through multiple domains.

In "Improving SD-WAN Resilience: From Vertical Handoff to WAN-Aware MPTCP," Zhang *et al.* [item 28) in the Appendix] propose WAN-aware MPTCP (WaMPTCP) that keeps the benefits of MPTCP with a single physical NIC situation with consideration of WAN side network. The proposed method also provides fast recovery and congestion control by handing off the problematic TCP connection. In their

evaluation, they demonstrate the good performance gain of the WaMPTCP on both, emulated testbeds and real-world deployment.

In "OFaaS: OpenFlow Switch as a Service for Multi Tenant Slicing in SD-CDN," Erel-Özçevik and Canberk [item 29) in the Appendix] propose an OpenFlow as a service (OFaaS) design where each tenant has flow management and switch configuration permissions on own virtual slices. The paper presents a new service oriented architecture (SOA) that dynamically configures OFaaS with a new content management algorithm.

In "NDN Fabric: Where the Software-Defined Networking Meets the Content-Centric Model," Madureira *et al.* [item 30) in the Appendix] propose NDN Fabric, a new network architecture combining SDN and Named-Data Networking (NDN) to improve the scalability of NDN. The proposed architecture is a hybrid network architecture for NDN that uses a content-based model in the access network and a path-based model in the core network.

In "P4Neighbor: Efficient Link Failure Recovery With Programmable Switches," Xu *et al.* [item 31) in the Appendix] tackle the issue that a traditional proactive failure recovery mechanism introduces huge switch storage overhead and discuss the flexibility and limitations of the programmable data plane. P4Neighbor proposed in the paper provides a proactive link failure recovery framework based on the programmable data plane by encapsulating backup paths into the header of packets. They are used to recover link failures.

In "P-SCOR: Integration of Constraint Programming Orchestration and Programmable Data Plan," Melis *et al.* [item 32) in the Appendix] present and evaluate their realization of AI-enriched network management functions that exploit network data via P4 programmable data plane.

In "Towards In-Network Event Detection and Filtering for Publish/Subscribe Communication Using Programmable Data Planes," Vestin *et al.* [item 33) in the Appendix] propose FastReact, an event based publish/subscribe Industrial IoT (I-IoT) processing framework in P4 language, which can be flexibly customized from the control plane. The proposed FastReact system can forward a sensing data flexibly for the I-IoT area.

In "Hybrid Flow Table Installation: Leveraging External Memory to Enhance Programmable Data Plane Switches for In-Network Computing," Xue and Zhu [item 34) in the Appendix] address the problem of limited memory resources in programmable data plane switches through a MILP model formulation and approximation algorithm to optimize placement of flow tables on multiple servers using RDMA.

D. RAN and Mobility Management

Management of Radio Access Networks (RAN) and mobility plays a crucial role on the performance of a whole 5G network. The papers in this category focus on different aspects of technologies for improving performance of wireless channels and wireless network slices, and for mobility management in seamless handover.

The first paper looks at the wireless link layer, proposing a design methodology of optimal downstream OFDM profiles in clusters of modems for softwarized network architectures. The next three papers focus on virtualization of wireless resources and wireless network slice deployment. Finally, the last paper deals with handover management in software-defined heterogeneous networks.

In "Towards Programmable DOCSIS 4.0 Networks: Adaptive Modulation in Full Duplex Channels," Schnitzer *et al.* [item 35) in the Appendix] study resources optimization in DOCSIS, proposing a softwarized adaptive subcarrier modulation management framework.

In "Understanding the Performance of Flexible Functional Split in 5G vRAN Controllers: A Markov Chain-Based Model," Diez *et al.* [item 36) in the Appendix] propose a Markov Chain-based approach for the probabilistic modeling of delay and loss performance of flexible functional split functionality of infinite and finite-buffer vRAN controllers in 5G networks.

In "RAN Engine: Service-Oriented RAN Through Containerized Micro-Services," Schmidt and Nikaein [item 37) in the Appendix] address the problem of service customization and functionality extension in a RAN of a 5G infrastructure supporting network slices. In this context, they present a RAN service engine that allows services to customize and extend RAN functionalities using containerized micro-services. This is achieved through micro-SDKs that abstract key RAN control end-points.

In "Service Orchestration Over Wireless Network Slices: Testbed Setup and Integration," Makris *et al.* [item 38) in the Appendix] present an open experimentation testbed, with focus on wireless networking, and adopt the Open Source MANO framework for provisioning virtual services on top of the experimentation equipment. The developed approach is a fully-fledged solution for application prototyping and experimentations over testbeds, allowing with minimal overhead for the experimenters to deploy them over a distributed datacenter with wireless technologies.

In "Mobility-Aware Seamless Handover With MPTCP in Software Defined HetNets," Tong *et al.* [item 39) in the Appendix] study vertical handover in SDN-based heterogeneous networks (HetNets), proposing a mobility-aware seamless handover method based on multipath transmission control protocol (MPTCP).

E. Management of Network Edge Environments

One of the main novelties of the softwarized networks is to allow in-network programming at the edge of the network, so enabling services that are not possible with computing placement too far from the user devices. The papers belonging to this category focus on different aspects of management of network edge environments. The first paper regards resource allocation at the edge to support time-critical applications. The second and the third paper propose techniques for traffic management and service chaining for advanced IoT applications. The fourth paper considers network management for a real-time video streaming environment, while the last two papers focus on Internet of Vehicles scenarios.

In "Managing Chains of Application Functions Over Multi-Technology Edge Networks," Akhtar *et al.* [item 40) in the Appendix] study the problem of allocating resources at the edge in support of envisioned next-generation applications, e.g., virtual and augmented reality, on top edge networks with multiple link technologies, namely, Wire and mmWave. The workload model considers service chains with varying capacity requirements. They formulated a binary integer optimization problem whose objective is to minimize the deployment costs over the edge network, while satisfying their high throughput and ultra-low latency requirements.

In "Deploying SDN Control in Internet of UAVs: Q-Learning-Based Edge Scheduling," Zhang *et al.* [item 41) in the Appendix] address the problem of smart control of distributed data collection systems for applications like agricultural production, environmental protection and disaster monitoring. To this end, they propose a UAV-based solution that uses a deep Q-learning (DQL) network to infer the future changes according to the current network state, so optimizing network performance.

In "Optimized IoT Services Chain Implementation in Edge Cloud Platform: A Deep Learning Framework," Pham *et al.* [item 42) in the Appendix] propose a new algorithm for determining where to deploy the virtual network functions (VNFs) consisting of the IoT service chain in the edge-cloud network. The proposed algorithm utilizes a learning method in order to decide the near-optimal solution in a short time.

In "OSCAR: On Optimizing Resource Utilization in Real-Time Video Streaming," Erfanian *et al.* [item 43) in the Appendix] leverage the SDN concept to optimize resource utilization for DASH-based real-time video streaming. The proposed system combines IP multicasting with virtualized network functions, particularly virtualized reverse proxies forwarding requests from video clients to the SDN controller and virtualized video transcoders adjusting video qualities for multicast groups in the network. Multicast trees are determined with respect to resource efficiency and video service latency requirements using a MILP formalization and a heuristic algorithm. The benefits of the proposed system are studied in a comparative analysis with related approaches using the Mininet network emulator.

In "Mobility Aware and Dynamic Migration of MEC Services for the Internet of Vehicles," Labriji *et al.* [item 44) in the Appendix] study mobility aware and dynamic migration of MEC services for the Internet of Vehicles, proposing a Lyapunov-based closed form approach with low-complexity.

In "Dynamic Controller Assignment in Software Defined Internet of Vehicles Through Multi-Agent Deep Reinforcement Learning," Yuan *et al.* [item 45) in the Appendix] study dynamic controller assignment in software defined Internet of Vehicles, presenting a multi-agent deep Reinforcement Learning approach.

F. Network Monitoring and Implementation Issues

Novel paradigms for softwarized networks, such as SDN and NFV, can increase flexibility and reliability of high-speed networks only if supported by effective tools for monitoring the health of the infrastructure and the behavior of network components, and if specific implementations are available to realize softwarized nodes that are comparable with the hardware middleboxes in terms of performance.

The papers in this category focus, on one hand, on different aspects of network monitoring and profiling, and on the other hand on implementation aspects of virtualized and containerized network elements. The first three papers focus on monitoring of different kinds of network architectures. The next two papers propose profiling methods for network orchestration and performance evaluation. Finally, the last two papers are devoted to optimize implementation of network nodes.

In "Software Packet-Level Network Analytics at Cloud Scale," Michel *et al.* [item 46) in the Appendix] propose a system, Jetstream, enabling sophisticated, network-wide packet analytics without compromising generality or performance of analytics applications. The core idea of the paper is to offload only critical pre-processing tasks that are shared among applications, e.g., network feature extraction or load balancing, to a line-rate hardware frontend while optimizing the core analytics software to exploit properties of network analytics workloads. Based on a prototypical implementation of Jetstream the performance and efficacy of the proposed system are demonstrated.

In "SRv6-PM: Performance Monitoring of SRv6 Networks With a Cloud-Native Architecture," Loreti *et al.* [item 47) in the Appendix] propose an architecture, segment routing v6-performance monitoring (SRv6-PM), for performance evaluation and monitoring of SRv6 networks. SRv6-PM supports ingestion, processing, storage and visualization of performance monitoring data and provides SDN-based control of network routers to drive the performance monitoring operations. SRv6-PM is open sourced to provide a reproducible data plane environment for performance monitoring systems.

In "In-Band Network Monitoring Technique to Support SDN-Based Wireless Networks," Haxhibeqiri *et al.* [item 48) in the Appendix] present a novel and low-overhead in-band network telemetry and monitoring technique for wireless networks focusing on IEEE 802.11 networks. Essentially, most industrial applications demand determinism in terms of latency, reliability, and throughput, but the first cornerstone of network verification ability is to enable end-to-end network monitoring, including end devices too. The paper brings the design of in-band network telemetry enabled node architecture and its proof-of-concept (PoC) implementation. The PoC realization is used to monitor a real-life SDN-based wireless network, enabling on-the-fly (re)configuration capabilities based on data monitoring. It is shown that the proposed in-band monitoring technique has six times lower overhead than other active monitoring techniques on a single-hop link. Besides this, it is demonstrated that (re)configuration decisions taken based on monitored data fulfill targeted application requirements, validating the suitability of the proposed monitoring technique.

In "A Novel Autonomous Profiling Method for the Next Generation NFV Orchestrators," Moazzeni *et al.* [item 49) in the Appendix] propose a Novel Autonomous Profiling (NAP)

method for creating VNF profiles that describe a set of resource configurations for meeting the given performance targets. They provide an optimal solution for predicting network loads and required resources for VNFs. In addition, they evaluate the proposed NAP using real datasets from two well-known VNFs (SNORT and vFW).

In "Assessing Container Network Interface Plugins: Functionality, Performance, and Scalability," Qi *et al.* [item 50) in the Appendix] focus on the networking component of Kubernetes, and specifically on the choice of implementing solutions of its Container Network Interface (CNI). They compare the various open source CNI plugins available from the community, analyzing the overheads and bottlenecks for each CNI plugin, as a result of the interaction with the datapath/iptables as well as the host network stack. Scalability aspects with increasing number of Pods as well as with HTTP workloads are also considered.

In "Joint Monitorless Load-Balancing and Autoscaling for Zero-Wait-Time in Data Centers," Desmouceaux *et al.* [item 51) in the Appendix] propose a unified and centralized monitoring-free architecture for autoscaling and load balancing. This joint monitorless load-balancing and autoscaling reduce operational overhead while increasing response time performance. An analytical model of the system is derived and proves that the proposed technique achieves asymptotic zero-wait time with high probability.

In "Software Physical/Virtual Rx Queue Mapping Toward High-Performance Containerized Networking," Kawashima [item 52) in the Appendix] presents a novel approach, IOVTee, to tackle performance degradations of virtualized network functions due to packet copy operations. Focus is set on improving compatibility, manageability and performance compared to other related zero-copy/pass-through acceleration approaches. In a broad evaluation study, the performance of IOVTee is detailed and the approach is compared to related approaches.

G. Security

Security is one of the most critical aspects of network softwarization. The papers in this category focus on different aspects of this topic, ranging between authentication aspects and protocol misuse. More specifically, the first paper regards authentication in 5G systems, while the second and the third paper regard formal verification and security in software-defined networks. Finally, the last two papers deal with security problems caused by TCP protocol misuse.

In "Cross-Network-Slice Authentication Scheme for the 5th Generation Mobile Communication System," Fan *et al.* [item 53) in the Appendix] aim at demonstrating a new authentication technique suitable for effective communication in the 5G network. The scheme is based on the concept of the elliptic curve cryptography (ECC) encryption strategy. It leverages the functionalities of the edge cloud and the center cloud to reduce the latency for 5G communication. Further, it shows an efficient handover mechanism where IoT devices need to switch network slices based on the requirement.

In "Improving the Formal Verification of Reachability Policies in virtualized Networks" Bringhenti *et al.* [item 54) in the Appendix] study anomalies detection in the data plane in virtualized network, presenting a formal verification approach of reachability policies.

In "MLSNet: A Policy Complying Multilevel Security Framework for Software Defined Networking," Achleitner *et al.* [item 55) in the Appendix] propose to extend multi-level security to network access with efficient route flows and low security cost. They formulate a policy compliance problem as an optimization problem to maximize the number of policies and rules, and to minimize the security cost. Various multilevel security policies are constructed using the well adopted notions and frameworks using multilevel security lattices and then translated to OpenFlow rules.

In "AEGIS: Detection and Mitigation of TCP SYN Flood on SDN Controller," Ravi *et al.* [item 56) in the Appendix] propose a method called AEGIS to detect and respond to SYN flood attacks against an SDN controller. The proposed algorithm reduces the DDoS attack caused by TCP SYN flood by identifying the spoofed addresses and deleting the spoofed addresses. The authors evaluate AEGIS by a testbed and an emulator, and show that malicious SYN can be identified with 97.78% accuracy.

In "Mitigating TCP Protocol Misuse With Programmable Data Planes," Laraba *et al.* [item 57) in the Appendix] propose a new approach for detecting and mitigating the impact of misbehaving TCP end-hosts using programmable data planes. For that, they address the challenges imposed by the restricted data plane programming model by relying on extended finite-state machine abstractions for modeling stateful protocol behavior and a mapping of this abstraction to programmable data plane primitives. Evaluation results demonstrate the applicability of the approach to restore the throughput loss caused by misbehaving end-hosts that manipulate TCP congestion control.

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APPENDIX
RELATED WORK

1) 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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