Guest Editors' Introduction: Special Issue on Advances in Management of Softwarized Networks

Filip De Turck, *Senior Member, IEEE*, Prosper Chemouil, *Fellow, IEEE*, Wolfgang Kellerer, *Senior Member, IEEE*, Raouf Boutaba, *Fellow, IEEE*, Kohei Shiomoto, *Senior Member, IEEE*, Roberto Riggio, *Senior Member, IEEE*, and Rafael Pasquini, *Member, IEEE*

I. Introduction

SOFTWARIZATION of networks is an important trend, enabled by the NV (Network Virtualization), SDN (Software-Defined Networking), and NFV (Network Function Virtualization) paradigms and offers many advantages for network operators, service providers and datacenter 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 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 [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, optimizations for 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 "Management of Softwarized Networks" as a title [3]. The main reported research contributions were: SDN control planes optimizations, improvements of OpenFlow network traffic balancing and resilience, SDN traffic management optimizations, novel virtual network embedding algorithms, including algorithms for reliable embedding, efficient NFV resource management and advanced platforms for management of softwarized network systems.

There are many more interesting challenges currently being addressed by the research community, which aim at efficient management of softwarized networks. Examples of these current challenges include: management of softwarized datacenter networks, performance characterization and optimization of softwarized networks, advanced softwarized wireless networks, security in softwarized networks, and management of softwarized content distribution networks.

The current special issue reports upon recent advances in management of softwarized networks, addressing amongst others the above mentioned challenges.

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 three editions were respectively held in London, U.K. in 2015, in Seoul, South Korea in 2016 and in Bologna, Italy in 2017. Each of these editions attracted 180+ participants from academia and industry. IEEE NetSoft 2018 will be organized in Montreal, Canada.

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 been considered as well.

Eighty five 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 papers and to address in detail the concerns raised by the reviewers. It was finally decided to accept twenty eight papers for inclusion in this special issue.

The time between initial submission and online publication of the revised papers in this special issue was at most six months.

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F. De Turck is with imec, Ghent University, 9052 Ghent, Belgium (e-mail: filip.deturck@ugent.be).

P. Chemouil is with Orange Labs, 92320 Paris, France (e-mail: prosper.chemouil@orange.com).

W. Kellerer is with the Technical University of Munich, 80333 Munich, Germany (e-mail: wolfgang.kellerer@tum.de).

R. Boutaba is with the University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: rboutaba@uwaterloo.ca).

K. Shiomoto is with Tokyo City University, Tokyo 158-8557, Japan (e-mail: shiomoto@tcu.ac.jp).

R. Riggio is with FBK, CREATE-NET, 38123 Trento, Italy (e-mail: rriggio@fbk.eu).

R. Pasquini is with the Federal University of Uberlândia, Uberlândia 38408-100, Brazil (e-mail: rafael.pasquini@ufu.br).

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III. Accepted Papers

From the selected papers in this special issue, five papers deal with management of softwarized datacenter networks (Section III-A), four papers focus on VNF management in NFV-based networks (Section III-B), four papers present recent research on performance characterization and optimization of NFV-based networks (Section III-C), five papers report upon novel techniques for Software-Defined Networking (Section III-D), three papers focus on advanced softwarized wireless networks (Section III-E), three papers present recent results on security and verification in softwarized networks (Section III-F) and finally four papers report recent advances in management of softwarized content distribution networks (Section III-G).

A. Management of Softwarized Datacenter Networks

Efficient management of datacenter resources is an important research topic. The papers in this category focus on load balancing and application-aware network management in datacenters, orchestration for edge data centers, routing and channel allocation in hybrid datacenter networks and optimal flow routing in Clos topologies.

In "OFLoad: An OpenFlow-based Dynamic Load Balancing Strategy for Datacenter Networks", Trestian *et al.* [item 1) in the Appendix] present an intelligent network management system that makes the best use of the available bisection bandwidth abundance in datacenter networks to achieve high utilization and performance. An experimental prototype is built and the proposed solution is compared against other solutions from the literature in terms of load-balancing efficiency.

In "Application-Aware Network Design for MapReduce Optimization Using Software-Defined Networking", Zhao and Medhi [item 2) in the Appendix] focus on measuring the usage of resources for MapReduce workloads using the HiBench benchmark suite to identify traffic patterns, and apply an adaptive traffic engineering mechanism. Evaluation results show that the job completion time can be noticeably improved.

In "VirtPhy: Fully Programmable NFV Orchestration Architecture for Edge Data Centers", Dominicini *et al.* [item 3) in the Appendix] propose VirtPhy, a programmable approach to orchestrate Small-Scale Data Centers for edge and fog computing and present a real implementation in a datacenter testbed using the OpenStack cloud platform in a hypercube topology.

In "Online-Batch Joint Routing and Channel Allocation for Hybrid Data Center Networks", Dab *et al.* [item 4) in the Appendix] focus on augmenting the wired data center network with 60 GHz wireless communication technology and deal with optimization of multi-hop routing and channel allocation in such hybrid infrastructures.

In "Flow Optimization in Data Centers with Clos Networks in Support of Cloud Applications", Sehery and Clancy [item 5) in the Appendix] study Clos networks in data centers, whose topology provides many benefits. However, the routing of diverse traffic flows still remains an issue in Clos networks. The authors formulate optimal flow routing in these networks as a Binary Multi-commodity Flow Problem, and present a modified version that uses a heuristic-based approach to minimize hash collisions.

B. VNF Management in NFV-Based Networks

Four papers deal with resource efficient management of Virtual Network Functions (VNFs) in NFV-based networks, taking performance-related constraints into account.

In "On the Interplay Between Network Function Mapping and Scheduling in VNF Based Networks: A Column Generation Approach", Alameddine *et al.* [item 6) in the Appendix] present the formulation of the service function chaining scheduling (SFCS) problem, which exploits interactions between mapping onto virtual network functions, service scheduling and traffic routing. They introduce a novel primal-dual decomposition using column generation, which solves exactly a relaxed version of the problem and can serve as a benchmark. Furthermore, a diversification technique is presented to further improve the quality of the obtained solutions.

In "On the Placement of VNF Managers in Large-Scale and Distributed NFV Systems", Abu-Lebdeh *et al.* [item 7) in the Appendix] focus on the placement of VNF managers and aim at minimizing the operational cost without violating the performance constraints. An integer linear programming formulation is presented and a tabu search algorithm is proposed to solve larger problem instances.

In "A Graph Partitioning Game Theoretical Approach for the VNF Service Chaining Problem", Leivadeas *et al.* [item 8) in the Appendix] deal with improving the overall allocation performance of deploying service chains in a cloud environment to meet server affinity, collocation, and latency constraints. The proposed method is based on a partitioning game, and the authors prove that a Nash equilibrium exists corresponding to an optimal solution. By means of experimental validation, it is shown that the proposed algorithm converges to the optimal solution.

In "Service Mapping and Orchestration over MultiTenant Cloud-Enabled RAN", Khodashenas *et al.* [item 9) in the Appendix] study service mapping and quality of service assurance from a 5G perspective, and present a solution designed within the context of the EU H2020 SESAME (Small Cells coordination for Multi-tenancy and Edge services) project.

C. Performance Characterization and Optimization of NFV-Based Networks

Benchmarks for characterizing NFV-based networks are very useful for the research community. Three papers focus on benchmark design and one paper deals with efficient state migration of virtual network functions.

In the paper entitled "Evaluation of Forwarding Efficiency in NFV-nodes toward Predictable Service Chain Performance", Kawashima *et al.* [item 10) in the Appendix] present a common benchmark to predict the hop-by-hop performance in a service chain. Performance characteristics of packet forwarding in NFV nodes are investigated for three packet I/O architectures (NAPI, netmap, and DPDK), three virtual I/O

mechanisms (vhost-net, vhost-user, and SR-IOV), and four practical forwarding programs (Open vSwitch, OVS-DPDK, xDPd-DPDK, and Lagopus).

In "NFV-Bench: A Dependability Benchmark for Network Function Virtualization Systems", Cotroneo *et al.* [item 11) in the Appendix] propose a dependability benchmark to support NFV providers at making informed decisions about which virtualization, management, and application-level solutions can achieve the best dependability. The benchmark is applied to both hypervisor-based and container-based use cases.

In "NFV-Throttle: An Overload Control Framework for Network Function Virtualization", Cotroneo *et al.* [item 12) in the Appendix] detail a novel overload control framework to protect NFV services, by filtering the incoming traffic towards VNFs in order to make the best use of the available capacity, and to preserve the QoS of traffic flows admitted in the network. The framework has been designed to support the VNFaaS and NFVIaaS service models.

In "Statelet-Based Efficient and Seamless NFV State Transfer", Nobach *et al.* [item 13) in the Appendix] propose a novel approach for efficient NFV state transfers, The approach is based on the concept of statelets, which are compact representations of information in incoming packets that change the state of a Virtualized Network Function (VNF).

D. Novel Techniques for Software-Defined Networking

SDN control plane optimizations are required to ensure scalability and service guarantees. Four papers present specific control plane optimizations, and one paper focuses on advanced availability modeling of software-defined networks.

In "ParaCon: A Parallel Control Plane for Scaling Up Path Computation in SDN", Qiu *et al.* [item 14) in the Appendix] study path computation in the control plane. A significant computational load is required for path computation in large scale networks with frequent path requests from applications. The authors build a high-performance control plane using multiple controllers by distributing the load of path computation, and address the consistency problem and synchronization overhead.

In "Deterministic Quality of Service Guarantee for Dynamic Service Chaining in Software-Defined Networking", Chen *et al.* [item 15) in the Appendix] present an analytical method to characterize the delay performance of the control plane when handling traffic with different priorities, according to network calculus and queuing theory. By taking into account the estimated delay in the control plane, the authors propose a novel service traversal mechanism to calculate the optimal traversal path for a service chain.

In "DetServ: Network Models for Real-Time QoS Provisioning in SDN-based Industrial Environments", Guck *et al.* [item 16) in the Appendix] focus on industrial networks, which require real-time guarantees for the network flows. Network models are needed for the computation of worst-case delays and for access control. Two novel network models are presented, based on network calculus theory for providing deterministic services (DetServ).

In "Inter-Controller Traffic to Support Consistency in ONOS Clusters", Muqaddas *et al.* [item 17) in the Appendix] consider the state-of-art ONOS controller, designed to scale to large networks, based on a cluster of self-coordinating controllers. The inter-controller control traffic due to the consistency protocols is studied. Empirical models are developed to quantify the traffic exchanged among the controllers, depending on the considered shared data structures, the current network state and the particular network events.

In "Including Failure Correlation in Availability Modelling of a Software-Defined Backbone Network", Nencioni *et al.* [item 18) in the Appendix] deal with quantitative assessment of SDN backbone networks to determine whether they can provide similar availability to the traditional IP backbone networks. The authors have formalized a two-level availability model that captures the global network connectivity and includes a failure correlation assessment.

E. Advanced Softwarized Wireless Networks

The papers in this category focus on enhanced programmability in wireless networks, cost optimal design of 5G networks and QoS negotiation in combined wired and wireless networks.

In "Unified Programmability of Virtualized Network Functions and Software-Defined Wireless Networks", Schulz-Zander *et al.* [item 19) in the Appendix] present and evaluate OPENSDWN, a novel WiFi architecture based on a joint SDN and NFV approach. OPENSDWN introduces datapath programmability to enable service differentiation and fine-grained transmission control, and facilitates the prioritization of critical applications.

In "Towards a Cost Optimal Design for a 5G Mobile Core Network based on SDN and NFV", Basta *et al.* [item 20) in the Appendix] propose three optimization models that aim at minimizing the network load cost as well as data center resources cost by finding the optimal placement of the data centers as well the SDN and NFV mobile network functions in 5G networks. A Pareto-optimal multi-objective model is presented, which achieves a balance between network and data center cost.

In "A Dynamic QoS Negotiation Mechanism between Wired and Wireless SDN Domains", Das *et al.* [item 21) in the Appendix] consider use cases where flows connect devices passing through a wired and a wireless domain having separate SDN controllers and propose a novel QoS negotiation mechanism between them. A generic mechanism is defined to map QoS parameters from one domain to the other, and a Mixed Integer Program is proposed.

F. Security and Verification in Softwarized Networks

Security management in softwarized networks is currently a very hot topic. Two papers focus on countermeasures for attacks on softwarized networks. One paper presents a data plane verification technique.

In "Mitigating the Table-Overflow Attack in Software-Defined Networking", Xu *et al.* [item 22) in the Appendix] study a countermeasure to table-overflow attacks in SDN-enabled switches. A practical monitoring and mitigation

method is proposed, based on a mathematical model for the flow table consumption and a flow entry token bucket.

In "Deceiving Network Reconnaissance Using SDN-Based Virtual Topologies", Achleitner *et al.* [item 23) in the Appendix] define network deception to defend reconnaissance and develop a reconnaissance deception system for software-defined networks. Deception is achieved by simulating virtual topologies. The designed system provides malicious network discovery and reconnaissance techniques with virtual information, while limiting the information an attacker is able to obtain from the system under attack.

In "An Efficient Framework for Data-Plane Verification with Geometric Windowing Queries", Inoue *et al.* [item 24) in the Appendix] present a novel framework for data-plane verification. Two window-based algorithms are proposed and a theoretical analysis is presented. The obtained verification times are characterized.

G. Management of Softwarized Content Distribution Networks

Multimedia content delivery is an important use case in softwarized networks. One paper presents a survey on Content Centric Networks combined with SDN/OpenFlow. Two papers focus on optimized multimedia content delivery in softwarized networks and one paper deals with the design of a Protocol-Oblivious Forwarding switch for efficient caching.

In "Content-Centric Networking Management Based on Software Defined Networks: Survey", Jmal and Fourati [item 25) in the Appendix] present a survey of Content-Centric Networks and their combination with SDN and OpenFlow. The most prominent approaches combining the Content-Centric Networks and OpenFlow are analyzed in detail.

In "An SDN/NFV Platform for Personal Cloud Services", Bruschi *et al.* [item 26) in the Appendix] detail results from the INPUT project to support Future Internet personal cloud services in a scalable and sustainable way. By means of a virtual Set-Top-Box use case, the platform benefits are characterized in terms of obtained Quality of Experience (QoE).

In "NFV-based Scalable Guaranteed-Bandwidth Multicast Service for Software-Defined ISP Networks", Soni *et al.* [item 27) in the Appendix] propose a scalable multicast group management mechanism for Software-Defined ISP networks. Multicast services on the network edge are designed, and a Lazy Load balancing Multicast (L2BM) routing algorithm is presented for sharing the core network capacity between guaranteed bandwidth multicast traffic and best-effort traffic.

In "A Split Architecture Approach to Terabyte-Scale Caching in a Protocol Oblivious Forwarding Switch", Ding *et al.* [item 28) in the Appendix] focus on Protocol-Oblivious Forwarding (POF), which is an enhancement to the current OpenFlow-based SDN forwarding architecture. The authors propose a novel split architecture design of a POF switch to solve the problem of speed mismatch between packet forwarding and blocked I/O operations.

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APPENDIX
RELATED WORK

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Filip De Turck received the M.Sc. and Ph.D. degrees from Ghent University, Belgium, in 1997 and 2002, respectively. He is currently a Full Professor with the Network and Service Management Research Group, Department of Information Technology, Ghent University, Belgium, and imec. He has (co)-authored over 450 peer reviewed papers. His research interests include telecommunication network and service management, design of efficient virtualized network systems, and data analytics. He is involved in several research projects with industry and academia. He serves as the Chair of the IEEE Technical Committee on Network Operations and Management, and is on the TPC of many network and service management conferences and workshops. He serves on the editorial board of several network and service management journals. He is also a member of steering committee of the IEEE NetSoft conference.

Prosper Chemouil (F'03) received the M.Sc. and Ph.D. degrees in control theory from École Centrale de Nantes, in 1976 and 1978, respectively. He is a Research Director on Future Networks with Orange Labs. His research interests are with the design and management of new networks and technologies and their impact on network architecture, traffic engineering and control, and performance, with significant involvement in standardization at ITU-T. For several years, he has been focusing on network softwarization and cognitive management. In 2016, he has become the Co-Chair of the IEEE SDN Initiative and a member of the IEEE ComSoc Industry Communities Board, representing the SDN/NFV/Cloud area. Within the IEEE SDN Initiative, he launched NetSoft, the IEEE International Conference on Network Softwarization, in 2015 and the General Co-Chair of NetSoft 2018. He was a recipient of several awards, such as the Blondel Medal in 1996, the Ampère Medal in 2003, the Salah Aidarous Memorial Award in 2014, and the Arne Jensen Lifetime Achievement Award in 2015. He was nominated as French Senior Engineer of the Year in 1995. He has served as a Board Member, an Associate Editor, and the Guest Editor of various journals, including the *IEEE Communications Magazine*, the IEEE TRANSACTIONS ON NETWORK AND SERVICE MANAGEMENT, IEEE NETWORKS, and *Annals of Telecommunications*. He has been involved as the general or TPC co-chair in many events dealing with network performance and management. He is a fellow of SEE and the Electrical and Electronical Society of France.

Wolfgang Kellerer received the Dr.-Ing. (Ph.D.) and Dipl.-Ing. (Master) degrees from the Technical University of Munich, Germany, in 1995 and 2002, respectively, where he is a Full Professor, heading the Chair of Communication Networks with the Department of Electrical and Computer Engineering. He was with NTT DOCOMO's European Research Laboratories for ten years in leading positions, contributing to research and standardization of LTE-A and 5G technologies. In 2001, he was a Visiting Researcher with the Information Systems Laboratory, Stanford University, CA, USA. His research has resulted in over 200 publications and 35 granted patents. He was awarded with an ERC Consolidator Grant from the European Commission for his research project FlexNets "Quantifying Flexibility in Communication Networks" in 2015. He currently serves as an Associate Editor for the IEEE TRANSACTIONS ON NETWORK AND SERVICE MANAGEMENT and on the Editorial Board of the IEEE COMMUNICATIONS SURVEYS AND TUTORIALS. He is a member of ACM and VDE ITG.

Raouf Boutaba (M'93–SM'01–F'12) received the M.Sc. and Ph.D. degrees in computer science from the University Pierre and Marie Curie, Paris, in 1990 and 1994, respectively. He is currently a Professor of computer science with the University of Waterloo, Canada, and the Associate Dean Research with the Faculty of Mathematics. His research interests include resource and service management in networks and distributed systems. He served as a Distinguished Speaker for the IEEE Computer and the IEEE Communications Societies. He is the founding Editor-in-Chief of the IEEE TRANSACTIONS ON NETWORK AND SERVICE MANAGEMENT, from 2007 to 2010, and on the editorial boards of other journals. He was a recipient of several best paper awards and other recognitions, such as the Premiers Research Excellence Award, the IEEE Hal Sobol Award in 2007, the Fred W. Ellersick Prize in 2008, the Joe LociCero and the Dan Stokesbury awards in 2009, the Salah Aidarous Award in 2012, and the McNaughton Gold Medal in 2014. He is a fellow of the Engineering Institute of Canada and the Canadian Academy of Engineering.

Kohei Shiomoto received the B.E., M.E., and Ph.D. degrees in information and computer sciences from Osaka University, Osaka, in 1987 1989, and 1998, respectively. He is a Professor of Tokyo City University, Tokyo Japan.

His current interest research areas include software-defined networking, network function virtualization, machine-learning, and network management. From 1989 to 2017, he was engaged in research and development of high-speed networks, including ATM networks, IP/MPLS networks, GMPLS networks, network virtualization, traffic management, and network analytics with NTT Laboratories. From 1996 to 1997, he was engaged in research in high-speed networking as a Visiting Scholar with Washington University, St. Louis, MO, USA. He has co-authored the book entitled *GMPLS Technologies: Broadband Backbone Networks and Systems (Optical Engineering)* (Marcel Dekker). He is a fellow of IEICE and a member of ACM.

Roberto Riggio is a Chief Scientist with FBK CREATE-NET and a Guest Lecturer with the University of Trento. His research interests include network operating systems for wireless and mobile networks, active network slicing in 5G systems, and distributed management and orchestration of network services. He is the Creator of 5G-EmPOWER the first Network Operating System for Mobile Networks. 5G-EmPOWER is currently used in several EU H2020 Projects and Research Institutions worldwide. He is currently involved in several EU-5G-PPP projects, including COHERENT and SESAME. He was a recipient of several awards, including the IEEE INFOCOM 2013 Best Demo Award, the IEEE ManFI 2015 Best Paper Award, and the IEEE CNSM 2015 Best Paper Award. He has one granted patent on network virtualization and has published 81 papers in internationally refereed journals and conferences. He serves as an Associate Editor for the *International Journal of Network Management* (Wiley), the *Wireless Networks* journal (Springer), and the IEEE TRANSACTIONS ON NETWORK AND SERVICE MANAGEMENT. He is a Co-Founder of the IEEE Workshop on Software Defined 5G Networks (IEEE Soft5G) and of the IEEE Workshop on Management of 5G Networks (IEEE 5GMan).

Rafael Pasquini received the M.Sc. and Ph.D. degrees in computer engineering from the State University of Campinas in 2006 and 2011, respectively. From 2015 to 2017, he was a Visiting Researcher with the Department of Network and Systems Engineering, KTH Royal Institute of Technology. Since 2011, he has led the Distributed Systems and Networks Research Group with the Department of Computer Science, Federal University of Uberlândia. His research interests include network management, machine learning, cloud computing, and software defined networks. He is involved in research projects with industry and academia, served as the chair of conference tracks and demo sessions, and acts as a TPC member for several conferences.