Adaptive and Scalable Communication Networks

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In this special issue, we have collected and presented recent works on innovative approaches and emerged technologies for coping with dynamicity, heterogeneity, and the scale, which have been central to (or even enablers of) recent advances in communications and networking technologies. At a time of an ever-increasing demand for networking resources and a larger scale, communication networks have faced challenges due to the heterogeneity of the demands, the diversity of communication mechanisms, the high dynamicity of the environments, the virtualization of functions, and the stringent and dynamic quality requirements. In recent years, there have been notable advancements in research and development of concepts and methods for highly adaptive and scalable communication networks.

This special issue focuses on recent advances in the field of adaptive and scalable communications.

I. SCALABLE AND ADAPTIVE COMMUNICATIONS

While communication networks themselves are becoming increasingly seamless to their users, they have become an integral part of human society and are deployed in increasingly challenging network scenarios, such as the Internet of Things (IoT), smart cities, big data systems, and multimedia systems. Key to the success of communication networks is their ability to adapt and cope with the broad challenges due to the increase in the scale. This way communication networks can meet a variety of demands of a wide range of sophisticated and challenging network scenarios. Adaptive communication networks have the ability to change network configurations, the usage of network resources, or the network mechanisms themselves. This allows for meeting the demands of the applications in the presence of dynamics associated with changes in the workload, in the usage of the communication media, in the context (such as user mobility), or in the demands of the applications. Not surprisingly, networked systems, such as the Internet, are considered an innovation driver in the more general field of adaptive systems.

An additional requirement that has become critical in many recently evolved networking scenarios is that of ensuring the scalability of the involved communication networks. *Scalable and adaptive communication networks* ensure that the ability of the network to meet demands degrades gracefully with the dynamics of the system. Although the Internet is already considered to be a highly scalable communication network in terms of devices that can be connected, it is important to note that the underlying adaptation mechanisms and its architecture are not fulfilling the demands of many challenging networking scenarios in a scalable way. This has triggered many research efforts centered on

Digital Object Identifier 10.1109/JPROC.2019.2904751

many distinct networking scenarios aiming at improving adaptivity and scalability. For example, a scalable adaptive data processing system should be capable of analyzing data with only minor variation in delay, independently of whether the number of information producers is in the order of hundreds, thousands, or millions of interconnected devices. Similarly, the quality of experience (QoE) of users in video streaming systems should degrade only slightly as the number of clients watching a video massively grows or decreases.

The goal of this special issue on Adaptive and Scalable Communication Networks is to acknowledge and comprehensively present the recent research progress observed in this field in order to support such demands of increasingly complex networking scenarios. We introduce within important and representatively chosen networking scenarios and enabling networking technologies recent advances and recurring adaptation methods for scalable and adaptive communication networks. To give the reader of the journal a comprehensive overview of the field, we have selected and structured contributions along the following dimensions: *networking scenarios*, to understand the distinct demands of applications and the implications of such demands on building scalable adaptive networking; and *enabling network technologies and mechanisms*, to present the recent technologies that implicitly or explicitly cope with the need for adaptation and the increase in the scale. Some of these technologies like software-defined networking and network function virtualization (NFV), provide for unprecedented flexibility in the usage and the on-demand allocation of resources. Other approaches advance key technologies, such as wireless communication media, by addressing innovative challenges posed by the need for a broad adaptation capability. Finally, we aim to give the readers an overview of *recurring principles in the adaptation of scalable and adaptive networks*, as well as provide material (concepts/approaches/methodologies/tools) for understanding and analyzing their performance. For instance, some approaches focus on self-adaptation principles that expose scalability, and other approaches focus on general adaptation methods that improve flexibility, which can be exploited to enhance scalability.

II. ARTICLES IN THE SPECIAL ISSUE

As part of this issue, we have collected 13 contributions from excellent and well-known scientists in the broad areas of communications, networks, and related subfields in computer science and electrical engineering, who have made recent (and sometimes longer term) contributions that fit in the theme of "adaptive and scalable communication networks."

A. Five Contributions Address Novel and Challenging Networking Scenarios, the Respective Requirements, and Present Appropriate Adaptation Methods to Address the Challenges of the Respective Demands

"Scalable 360° video stream delivery: Challenges, solutions, and opportunities" introduces a very novel networking scenario, namely 360° video streaming. This has evolved to be a hot topic in the context of multimedia systems with severe challenges on scalable distribution and streaming to ensure for users appropriate QoE. The article presents challenges of 360° video streaming systems, gives an overview of existing approaches for 360° video streaming, and outlines research opportunities enabled by 360° video.

"Web AR: A promising future for mobile augmented reality—State of the art, challenges, and insights" addresses, in the context of mobile augmented reality, a challenging network scenario that requires adaptation in the usage of computing, storage, and communication resources. The authors introduce and review a variety of different deployment approaches ranging from 5G networks, devices-to-device communications, and the Edge/Cloud infrastructure.

"Will serverless computing revolutionize NFV?" explores a network scenario that is emerging as a different type of a novel cloud computing paradigm in which applications are decomposed into smaller and modular functions. The article provides for a classification of the intricate landscape of the existing serverless deployment strategies, advantages and limitations of these approaches, and discusses the tradeoffs involved in developing applications for the serverless environment.

"Modeling of aggregated IoT traffic and its application to an IoT cloud" provides a survey on traffic models for the IoT, a challenging network scenario comprising of highly varying load characteristics and interconnections of devices. The traffic models are derived from real-world examples with a focus on periodic traffic patterns that are typical of those generated by IoT.

"Scalable personalized IoT networks" surveys, in the context of the IoT, the readiness and interplay of various distinct technologies that are likely to be necessary in order to enable personalized IoT networks. The surveyed technologies include scalable sensing, information-centric networks, and artificial intelligence (AI).

B. Four Contributions Focus on Enabling Networking Technologies That Provide for New Ways of Coping With Scalability Through Adaptation of Communication Systems

"Adaptable and data-driven softwarized networks: Review, opportunities, and challenges" reviews and analyzes adaptation opportunities and the potential for building scalable communication systems by means of software-defined networking (SDN) and NFV. The article outlines a data-driven approach in exploiting the flexibility exposed by these important paradigms in networking.

"Scaling millimeter-wave networks to dense deployments and dynamic environments" discusses, in the context of millimeter-wave networks, an important wireless technology that will further increase the communication bandwidth and data rates. The article surveys adaptive communication techniques that relate to the coordination of antennas and beams that allow millimeter-wave networks to operate at scale.

"Survey of performance acceleration techniques for network function virtualization" discusses, in the context of NFV, ways of realizing network functions in a scalable way. The authors introduce techniques for hardware and software acceleration that allow for removing inherent bottlenecks in the deployment of network functions.

"Energy-adaptive error correcting for dynamic and heterogeneous networks" reviews adaptive coding techniques for achieving energy efficiency in wireless communications. The work analyzes and presents fundamental limits of adaptive coding techniques.

C. Four Contributions Focus on Recurring Adaptation Principles and Methods That Can Be Used to Design and Implement Scalable and Adaptive Communication Systems

"Learning and management for Internet of Things: Accounting for adaptivity and scalability" illustrates, in the context of online learning and management policies, ways of dealing with extreme heterogeneity, massive number of devices, and unpredictable dynamics in the context of the IoT. To adapt to changing environmental conditions, the article outlines a unifying framework through contemporary communication, networking, and optimization advances.

"Elements of application-layer internetworking for adaptive self-organizing networks" presents an internetworking approach based on self-organizing application-layer networks. Toward this goal, the article surveys and presents findings related to scalability, the ability to adapt after disruptions, heterogeneous substrate networks, distributed security, and the dynamic creation of network services.

"Self-organization and resilience for networked systems: Design principles and open research issues" reviews and proposes research on the twin fields of self-organization and resilience for networked systems. A combination of methods in both fields is an important foundation for networked scenarios that underpin critical physical infrastructures such as electricity, water, and transport requiring high availability of many distributedly managed networking components.

"Transitions: A protocol-independent view of the future internet" provides a taxonomy of an adaptation principle, named transition. The concept of a transition aims at increasing the flexibility and scale at which communication networks can be adapted by introducing the possibility to change between the existing protocols and technologies while the network is in operation. To this end, a classification of transition approaches is provided.

ABOUT THE AUTHORS

Ralf Steinmetz (Fellow, IEEE) has been the Managing Director of the Multimedia Communications Lab, Darmstadt, Germany, since 1996. He was the Director of the Fraunhofer Institute, Darmstadt, until the end of 2001. In 1999, he founded the Hessian Telemedia Technology Competence Center httc, Darmstadt, where he holds a Chair position. For more than 10 years, he has served as the Advisor for information and communications technology with the Hessian Telemedia Technology Competence Center. He is currently a Full Professor with the Department of Electrical Engineering and Information Technology and the Department of Computer Science, Technische Universität Darmstadt, Darmstadt. Together with more than 30 researchers, he works toward his vision of seamless adaptive multimedia communications. With his team, he has contributed more than 900 refereed publications. He has edited and co-authored a set of multimedia books that reflected the major issues; the initial version was the worldwide first in-depth technical book on multimedia technology.

Prof. Steinmetz is a member of the Scientific Council and the President of the Board of Trustees of the International Research Institute IMDEA Networks, Madrid, Spain. He was awarded the Chair of Excellence at the University Carlos III de Madrid. In 2016, he was awarded with the first Athene Award for Knowledge and Technology Transfer at TU Darmstadt for his visionary and successful establishment of startup activities. In 2017, he was among the first three scientists being awarded a fellowship of the VDE ITG. As first German scientist, he was awarded the honors of Fellow of both the IEEE and the ACM. He has served as the Editor-In-Chief and an Editor for various IEEE, ACM, and other journals.

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Dr. Stavrakakis has served in NSF and EU-IST proposal panels and in the organization of conferences sponsored by IEEE, ACM, ITC, and IFIP. He served as the Chairman of IFIP WG6.3 and the Officer for the IEEE Technical Committee on Computer Communications (TCCC). He served on the editorial boards of the PROCEEDINGS OF IEEE, ACM/IEEE TRANSACTIONS ON NETWORKING, and *Computer Communications Journals*.

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During his master's thesis, he worked on fixed mobile convergence and mobility management, and was engaged in R&D activities on converged access networks (ScaleNet) and self-optimizing radio access networks at Deutsche Telekom, Darmstadt. During his Ph.D., he worked on probabilistic data structures applied to packet forwarding in content-centric networks, was a visiting researcher at Ericsson Research Nomadic Lab, Jorvas, Finland, in 2008, and contributed to the EU FP7 Publish/Subscribe Internet Routing Paradigm (PSIRP) project. From 2010 to 2013, he was a Senior Research Scientist of IP Systems and Networking with the CPqD Research and Development Center, Telecommunications, Campinas. He is currently an Assistant Professor (tenure track) and the Head of Information and Networking Technologies Research and Innovation Group (INTRIG), UNICAMP. He has authored or co-authored more than 90 publications, including in scientific journals and top-tier networking conferences such as SIGCOMM and INFOCOM. He holds two international patents.

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Dr. Koldehofe serves in several program committees and as a reviewer for high reputational journals. He served in the organizing committee of the ACM DEBS Conference, as the TPC Co-Chair in 2017 and as the General Chair in 2019. He has served as a Tutorial Speaker for the ACM/USENIX Middleware, ACM DEBS, GI, and NetSys conferences.