Guest Editors' Introduction: Special Issue on Recent Advances in the Design and Management of Reliable Communication Networks

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***Abstract*—This Special Issue contains a collection of outstanding papers covering several recent advances in the design and management of reliable communication networks. Papers are organized into five categories: resilience in network functions virtualization based networks, application-aware solutions for network resilience, resilience of transport networks, secure and reliable communications, wireless and radio-access network resilience. In this editorial, a brief overview of the field is given, followed by a summary of the twenty nine papers, accepted for publication in this special issue.**

***Index Terms*—Resilience, NFV, optical networks, wireless networks, network management, network design, critical services.**

I. Introduction

This Special Issue (SI) features the latest research contributions regarding recent advances in the design and management of reliable communication networks. Communication networks are constantly increasing their complexity and scale to satisfy the requirements of network services. The current trend of convergence of networking and computing infrastructures (as in today's cloud systems and softwarized networks) calls for novel advanced strategies and solutions to support reliable services, as the development of new data-driven solutions for reliable network automation and self-diagnostic tools to ensure resilient network management.

In current 5G-network deployments, major network upgrades are on-going, or soon to be implemented, to support the new Ultra-Reliable Low-Latency Communication (URLLC) services with availabilities of up to 6 nines to be guaranteed jointly with exceptionally low latencies. Looking ahead, the envisioned 6G communication networks will support network services with even more critical requirements, such as smart mobility, e-health, industrial control, and pave the way to immersive environments with application in remote education, working and entertainment.

Several new technical developments are hence under investigation to allow network providers to achieve the desired levels of resilience: network functions virtualization (NFV), which enables shorter provisioning times and more flexible use of physical network resources; the synergistic collaboration of different technologies (optical, wireless satellite, datacenter networks); enhanced forms of data/service replication, supported by cloud and edge computing; network slicing, which allows to define highly-reliable logical partitions of network, computing and storage resources. These and other technological innovations can be used as facilitators for the deployment of high-reliability networks and are discussed in the articles published in this Special Issue.

II. Overview of Special Issue

The Special Issue received sixty-three submissions. After a thorough and timely review process, twenty-nine papers were accepted for publication in this Special Issue. The twenty-nine accepted papers have been classified into five categories: (i) resilience in NFV-based networks; (ii) application-aware solutions for network resilience (iii) resilience of transport networks; (iv) secure and reliable communications (v) wireless and radio-access network resilience.

A. Resilience in NFV-based networks

NVF strongly contributes to attaining the required resilience of future networks, as illustrated in the following works.

A critical concerns of cloud operators is how to increase the service reliability to at least 4 nines. Ref. [1] proposes to use Function Choreographies (FC) to orchestrate several network functions in the same workflow and maintain the service reliability in federated clouds. The proposed approach outperforms existing solutions (e.g., AWS Step Functions) and it also survives massive failures.

Similarly, 5G mobile networks are being softwarized to enable a more efficient use of resources. A compromise between the high reliability requirements (up to 6 nines) and the fallible nature of servers has to be found. In paper [2], authors analyze an auto-scaling mechanism to de/activate servers and propose an algorithm to optimally configure these thresholds as a function of the server performance. The performance evaluation compares different server configurations in terms

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of failure probabilities and power consumption for different arrival rates.

The resilience of the control plane in virtualized 6G core networks is addressed in [3]. An Integer Linear Program (ILP) and a heuristic for latency-aware hypervisor placement for protection against single-link and hypervisor failures are presented. Results illustrate the impact of three hypervisor placement methods on the acceptance ratio of virtual SDN requests.

In [4], the fault tolerance for highly-available NFV in LTE is studied. The authors address three critical issues to provide high availability in LTE: fast failure detection, recovery of lost states and messages, and overhead minimization. Their design implemented over OpenAirInterface is LTE standard-compliant and works as a plug-and-play without modifying existing LTE implementations.

Finally protection is also investigated in the context of Multi-access Edge Computing (MEC). A protection scheme, designated 1:N:K, for placement of MECs and slices in a 5G infrastructure is proposed and analyzed in [5]. The objective is to achieve low latency and high reliability at minimum cost.

B. Application-aware solutions for network resilience

Network resilience is ultimately aimed at supporting the requirement of a specific service or application. More and more, in the last years, the specific application requirements shape the strategies for network resilience. For example, Internet of Things (IoT)-based applications need secure, low-cost real-time data sharing mechanisms, while E-health applications are particularly sensitive with respect to data privacy and Industrial Control applications focus on real-time communications with high reliability.

Authors in [6] propose to transfer a distributed membership detection algorithm for networking servers to IoT, in order to contribute to reliability in the IoT domain. Evaluations based on analysis, simulation, and hardware test shows that both detection time and communication traffic can be optimized.

The authors of [7] leverage fog computing (FC) to deliver reliable remote health monitoring and propose a reliable health monitoring framework operating under uncertain FC conditions. A problem is formulated to assign tasks of remote sensors attached to patients to their applications deployed in fog nodes aiming to maximize the number of satisfied tasks with respect to the fog nodes' availability and communication latency constraints. Authors propose as a solution a differential evolution-based algorithm enhanced by reinforcement learning to deploy applications in fog nodes.

In [8] authors present Reparo, a new framework that leverages Hidden Markov Model (HMM) enhanced with adversarial autoencoders to perform predictions at the application-layer and enable fast detection and restoration of lost packets. Using realistic traffic traces, Reparo is shown to satisfy the requirements of a telemedicine use case in terms of throughput and latency.

Paper [9] presents an approach to manage communication resilience for the healthcare domain in presence of available heterogeneous networks. Specifically, the authors propose a portable assisted living system and show that it performs well in terms of delay, throughput, and communication resilience.

In [10], the authors propose a trust management method against abnormal behavior of industrial control networks. For that purpose, trust information and trust relationship of abnormal behaviors are used to establish a trust update and decision-making mechanism under the availability constraints of industrial control networks.

For critical wireless networks, Ref. [11] evaluates a forecast-based recovery mechanism for real-time remote control in robotic environments, using simulation and hardware experimentation. The authors show that the mechanism reduces the robots' trajectory error in RF-interference situations significantly.

C. Resilience of transport networks

Transport networks are the core of the Internet infrastructure and their resilience has always been a major concern for network operators. To achieve a more efficient and flexible use of installed capacity, new technologies have been recently developed, such as elastic optical networks (EON) and new advanced forms of satellite networking exploiting inter-satellite laser links to increase global connectivity.

As EONs offer a flexible platform to deal with massive failures, authors in [12] develop new efficient protection mechanisms for disaster mitigation in EONs. They propose the new concept of mitigation zone, i.e., a region, close to the disaster, where lightpaths may accept degraded service. An ILP and a heuristic algorithm are proposed and simulation results demonstrate lower penalty and blocking ratio with respect to conventional algorithms.

Also leveraging EON flexibility, authors in [13] address the problem of service degradation. In case of failures, lightpath capacity is adjusted to reduce network blocking probability. The paper introduces a service-degradation algorithm, which combines the requirements and characteristics of the optical and the application domain.

Ref. [14] focuses on Flex Ethernet (FlexE), a novel technology to to realize deterministic and ultra-low latency in transport networks. Authors provide ILP models and heuristics, representing various flavours of cross-layer restoration in a FlexE-over-EON architecture. Authors' proposal is corroborated on the specific scenario of FlexE switch outage using extensive network-level numerical simulations.

For satellite networks, Ref. [15] proposes and assesses an algorithm that removes optical inter-satellite links for bandwidth efficiency of satellite networks, while maintaining reliability and availability. A simulation study shows that the selective removal of inter-satellite links can improve the bandwidth efficiency of optical satellite networks significantly.

Authors in [16] present a cloud-based network telemetry system, called BigBen, for accurate and timely detection of failure events in the Internet. BigBen differs from other detection systems as it uses passive measurements of network time protocol (NTP) traffic. A cloud-based implementation of BigBen is developed to process terabytes of NTP data and provide accurate event reporting.

A topology-agnostic multipath source routing, based approach for reliable communications designated Multipath Polynomial Key-based Architecture (M-PolKA), is described in [17]. The proposed scheme reduces the size of routing tables through path encoding in the packet header. The numerical evaluation of M-Polka is carried on using two prototypes: an emulated setup and a physical setup based on Netronome SmartNICs.

Software-Defined Wide Area Network (SD-WAN) is promising technology for enterprise networking as it is more cost-effective than other traditional solutions. In [18] a performance evaluation is carried out on two experimental SD-WAN testbeds, demonstrating a significant increase service availability while satisfying the rigorous requirements of delay-sensitive services.

D. Secure and reliable communications

Security concerns are transversal to communication networks and are becoming more and more intertwined with network reliability.

The interconnection of smart devices and authentication requirements to enable secure communication is addressed in [19]. The authors note that traditional certificate-based authentication scheme can no longer meet the requirements of massive device deployment. Ref. [19] introduces a Blockchain technology to establish trust in an untrusted environment and share cross-domain certificate information among multiple domains.

Along the same lines, authors of [20] exploit Blockchain to enhance performance and security in IoT-based Federated learning (FL) systems. As directly integrating Blockchains in large systems still faces many limitations in terms of scalability and privacy, they proposed μDFL, a novel hierarchical IoT network fabric for decentralized FL atop of a lightweight blockchain called microchain. These microchains are federated via a high-level inter-chain network, which adopts an efficient Byzantine Fault Tolerance consensus protocol to achieve scalability and security.

Ref. [21] contributes to the field of quantum key distribution (QKD), a recent technology that ensures unconditional secure physical communication. This study analyzes performance bounds of the Bennett–Brassard-84 (BB84) QKD protocol, and also introduces a new grouped BB84 protocol to deal with changing channel conditions. Based extensive simulation study, the grouped BB84 protocol is shown to guarantee high accuracy in eavesdropping detection even under rapidly varying channel conditions.

Machine Learning (ML)-based techniques have been shown to be good candidates as security diagnosis tools as they can detect and identify the nature of existing attacks. However, to cope with unknown attacks, paper [22] proposes a Distance-Based Root Cause Analysis (DB-RCA), which is applied to optical physical layer attacks. The proposed framework is also validated on an experimental physical-layer security dataset.

E. Wireless and radio-access network resilience

Wireless networks are increasingly ubiquitous, so their resilience is of the utmost importance.

The next generation of cellular networks will have to cope with an increasing number of users and, hence, power and bandwidth resources have to be efficiently managed. In [23], the integration of traditional (i.e., grid-based) and renewable (e.g., solar-based) power sources is proposed in a smart city scenario. Authors propose a pricing model and a cost optimization based on a game-theoretic analysis. The Nash Equilibrium is verified for two defined games, and an optimal cost solution is proposed for green base stations.

The authors in [24] enhance and expand on traditional availability modeling used in cognitive radio networks. The new concepts of connection availability and service maintainability are introduced and, to test them, a new channel reservation algorithm is proposed and an analytical model is introduced. Valuable tradeoffs among the newly-introduced metrics are explored using numerical evaluations.

Ref. [25] focuses on Multi-access Edge Computing (MEC). Resource allocation scheduling in MEC is addressed by decomposing the problem in a pre-processing phase and an assignment phase. In the pre-processing phase, several clustering models are considered to group access points, then the assignment phase selects the MEC hosts, taking into account the MEC capacity constraints. Results show that the proposed approach reduces both memory usage and execution time.

In [26], the authors investigate underwater optical wireless communication as an enabling technology for underwater applications that require high bandwidth links. A dual-hop hybrid free-space optical communication link integrated with an underwater visible light communication system is investigated. This proposal enables a high data rate with minimal delay in real-time monitoring scenarios as compared to traditional underwater wireless communication technologies.

Ref. [27] proposes an Intelligent Control for Self-driving RAN (ICRAN) to maximize the radio resources utilization while minimizing the performance degradation. ICRAN involves two deep reinforcement learning approaches, one for centralized and a second for distributed RAN control planes. The evaluation show that ICRAN is able to satisfy the Service Level Agreement (SLA) requirements while maximizing the radio resource utilization.

In [28] the authors tackled the problem of public street coverage for 5G deployments in urban areas using a data-driven methodology. Starting from 3D digital maps, the problem of antenna placement is formulated as a set coverage problem and the authors leveraged powerful heuristics to allows the exploration of different policies, returning the detailed coverage, the antenna placement, and the cost of the coverage.

In [29] the authors considered the issue of deploying UAVs as aerial base stations to establish wireless communication networks in various challenging scenarios, and addressed the reliability of the communication when one or more UAVs are compromised. The authors leverage Deep Reinforcement Learning (DRL) to achieve a reliable backhauling that survives even under various random and/or targeted UAV node failures.

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