This article has been accepted for publication in IEEE Transactions on Network and Service Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TNSM.2024.3469308

Guest Editors' Introduction: Special Issue on Robust and Resilient Future Communication Networks

I. Introduction

This Special Issue (SI) features research contributions in the area of robust and resilient future communication networks. Network resilience is a topic of investigation that has been attracting sustained interest in the network-management research community, as confirmed by the renewed success of this fourth consecutive annual special issue on this topic in IEEE Transactions on Network and Service Management. Novel methodologies and solutions to guarantee system resilience need to be constantly investigated to keep pace with the never-ceasing evolution of network and cloud systems. As the computing and communication domains of today's cloud systems become evermore entwined, network softwarization, originally intended as a technical facilitator to quickly and flexibly deploy new services, has emerged also as an enabling technology to increase and ensure service continuity in cloud systems. Such evolution requires investigating the resilience aspect of modern resource allocation problems as network slicing, Virtual Network Embedding (VNE) and Service Function Chaining (SFC).

Moreover, due to the huge amount of monitoring information available in today's networks, from which the relevant. data can be extracted, novel solutions for automated network resilience with the support of artificial intelligence (AI) are being put forward. These AI-based proposals are based on various tools, such as neural networks, federated learning and deep reinforcement learning (DRL). The application of machine-based management is expected to be widely adopted in future communication networks, contributing to more robust and resilient networks. In several papers of this SI, network resilience is tackled using AI tools.

Ultra-reliable and low latency communication (URLLC) services are starting to be deployed on several use cases, e.g., for the operation of warehouses and industrial facilities. Proposals for minimizing the amount of resources to satisfy the stringent requirements of URLLC services are presented in this special issues. Another topic that is being subject of renewed interest in the networking community is energy conservation in network and cloud systems. Energy consumption within data centers and communication network keeps steadily increasing due to never-ceasing demand for processing-intensive and bandwidth hungry services (as, e.g, distributed training of large machine learning models). Guaranteeing energy efficiency while coping with such increasing demands, and while also ensuring high degrees of resilience, is a multi-faceted and challenging problem. Several solutions for reducing energy consumption (and cost for network providers) are discussed in this special issue. Last but not least, service providers are becoming increasingly aware of the need to ensure security and privacy to their services. Novel solutions for detecting and mitigating attacks and mitigating are examined., as well as novel blockchain based proposals to increase network privacy and security.

II. Overview of Special Issue

The Special Issue received sixty-two submissions. Additionally, nine manuscripts were re-submitted from the previous SI. After a thorough and timely review process, thirty-four papers (twenty-seven papers submitted for this SI plus seven papers from the previous SI), were accepted for publication in this Special Issue. The thirty-three accepted papers have been classified into five categories: (i) Robust Network Management and Optimization, (ii) Energy-Efficient and Resilient Network Operations, (iii) Secure and Trustworthy Network Systems, (iv) Resilient and Reliable Network Architectures, and (v) AI and Machine Learning for Network Resilience.

A. Robust Network Management and Optimization

Robust resource management in modern softwarized networks requires novel approaches for joint optimization of computing and communication resources, to solve problems of rising importance as Virtual Network Embedding (VNE) and Service Function Chaining (SFC).

Minardi et al. [1] propose to address the VNE problem by leveraging real-time traffic statistics. Their proposed VNE solution is formulated as a Mixed Binary Linear Programming (MBLP) problem and as its relaxed version. These solutions jointly minimize the load balancing and the data rate assignment to each virtual-network request based on their priority level, i.e., tolerated queuing delay and user satisfaction probability. The proposed solution outperforms several state of-the-art solutions in terms of acceptance ratio and average queueing delay, specially in heavy-loaded use cases.

Mohamad et al. [2] focus on SFC for ultra-low latency applications at the network edge, where resources are more limited compared to virtually-unlimited cloud resources. This paper proposes a novel solution for SFC of time-critical services leveraging the sharing of virtual-network functions and prioritizing time-critical premium services by pre-mepting best-effort services. Numerical results show a reduction of premium services rejection rate to 0% while minimizing the disturbance to best effort services. The integration of segment routing over IPv6 (SRv6) and in-band network telemetry (INT) for SFC deployment is considered

Yan et al. [3]. A self-adaptative SRv6-INT-driven SFC deployment system, that can orchestrate network and

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computing resources to adapt to bursty traffic and dynamic network changes, is experimentally demonstrated. Additionally, a closed-loop system is designed to manage SFCs locally (servers can make their own decisions) and globally (using the control plane, which oversees the SFC deployment). A prototype that experimentally demonstrates its effectiveness is presented.

Also Medagliani et al. [4] consider Segment Routing (SR) to increase network robustness, specifically, by offloading traffic from congested links in the presence of congestion. The authors introduce an efficient algorithm for the computation of alternative paths and two methods for computing the weights of the Unequal Cost Multipath. It is shown that the knowledge of remote link loads and per-destination traffic is key to mitigating congestion in loaded scenarios.

Moreover, novel methodologies to ensure service robustness in cloud systems are also investigated in the following two papers. Considering that Distributed Cloud Networks (DCNs) are vulnerable to large-scale disasters, Miao et al. [5] formulate a DCN recovery problem to identify which links should be repaired in case of large-scale damage. The proposed computation-aware link repair (CALR) algorithm seeks to guarantee network repair performance, and a Benders decomposition-based resolution approach is developed to cope with the complexity of the problem.

Instead, considering the multi-domain nature of today’s cloud systems, Koulougli et al. [6] investigate the resilience of intra-domain and inter-domain paths under limited resources and information sharing. In this study, the authors harness FlexEthernet (FlexE) on interdomain links to maximize the restoration at minimum cost. FlexE enables effective network reutilization by leveraging time division multiplexing (TDM), but the scheduling of traffic in FlexE is a challenging and underinvestigated research topic. In this paper, authors formulate the FlexE-based traffic restoration problem as a Mixed Integer Non-Linear Program (MINLP) and then introduce an approximation algorithm to efficiently solve this problem in polynomial time. Numerical results show that the proposed solution restores up to 14% more traffic than a state-of-the-art approach.

B. Energy-Efficient and Resilient Network Operations

Energy efficiency is paramount to preserving our planet’s resources and reducing energy costs for network providers. Unfortunately, achieving reliable network operation typically involves redundant resource utilization and/or operation, which induces extra energy consumption, going in the opposite direction to energy efficiency. In the first part of this section, we mention the works that address possible balances between energy efficiency and resilient network operations.

Ho et al. [7] proposed a Deep Reinforcement Learning (DRL) technique to maximize the long-term energy efficiency of a 5G mission-critical swarm of robots. The scenario is an automated grid-based warehouse, where authors aim to meet the energy consumption constraint of the robots as well as the ultra-reliable and low latency communication (URLLC) requirements between robots and the central controller. As the presented non-convex optimization did not scale, the authors propose a DRL-based approach using a deep deterministic policy gradient method and convolutional neural network (CNN) to achieve the optimal control policy. The proposed solution is compared with three other solutions showing the increase on energy efficiency, especially for low bandwidth systems.

Khoramnejad et al. [8] address the combination of edge computing and unmanned aerial vehicles for monitoring in smart agriculture environments. Specifically, the joint power minimization and offloading problem is studied and formulated as a mixed integer multi-objective optimization problem. A combination of reinforcement learning and graph convolutional neural networks together with a selected algorithm from literature have been employed to solve the problem. Simulation results demonstrate that the consumed energy can be reduced by 45% using the approach proposed by the authors.

Reddy et al. [9] focus on a performing task mapping in many-core processors in fault tolerant manner, while enhancing performance and reducing communication energy consumption. The proposed algorithm maps tasks onto two specific network-on-chip (NoC) platforms, guaranteeing surviving operation in the presence of faults, but at the same time allocating spare cores minimizing communication energy. Simulative results against several benchmarks showed that the proposed algorithm leads to improved performance and communication energy reductions. Moreover, an experiment with Field Programmable Gate Array (FPGA) was tested, showing significant improvements to existing approaches.

The authors of [10] considered a robust energy-efficient reconfigurable intelligent surface (RIS)-aided multi-antenna decode-and-forward (DF) relay cooperative multiple-input multiple-output (MIMO) system. Owing to the passive characteristic of RIS, it is challenging to obtain perfect channel state information (CSI) and the channel estimation error (CEE) is inevitable in practice. Therefore, taking into account the imperfect CSI, the authors used methodologies for robust optimization to achieve energy efficiency under bounded CEE and statistical CEE models. The problem is solved by the alternating optimization (AO)-based Dinkelbach algorithm in an iterative manner. Numerical simulations demonstrate that the EE performance of the considered scheme outperforms the benchmarks. While the previous four papers explicitly relate their contribution to energy efficiency, reliable network operation is also addressed in the following papers, with no explicit reference to energy aspects.

Abdullah et al. [11] propose a novel resource allocation framework that minimizes the allocated resources while meeting the strict requirements of Ultra Reliable Low Latency Communications (URLLC). The authors develop a discrete time queuing model for latency-critical mobile service as well as a control scheme that dynamically updates the amount of resources to be allocated per time slot. The proposed framework is evaluated in terms of violation probability and cost in terms of used resources.

A graph-based approach for Beyond Line of Sight (BVLoS) drone operation is proposed in [12]. The authors use a multi-layer framework to represent real-world scenarios and challenges. The developed graph allows us to solve the Maximum Dependability Path Problem (MDP2) using Dijkstra’s algorithm. As the built graph can become very large, a new lightweight graph-based corridor model, which considers a limited part of the original graph, is also presented. However, this lighter model will result in a sub-optimal solution to MDP2. Results are presented that illustrate the performance of the proposed resolution approaches.

Finally, Eltokhey et al. [13] investigate the role of an emerging technology, Visible Light Communication (VLC), in resolving radio-frequency (RF) spectrum congestion, especially in indoor scenarios. VLC offers many advantages, e.g., usage of unlicensed spectrum and inherent physical layer security, but efficient handover techniques are required. The authors proposed efficient soft-handover solutions allowing improved network performance based on joint transmission of adjacent Access Points (APs). The proposed schemes improve by 30% the users regaining the throughput compared with non-coordinated based schemes. The increase in throughput is related to higher link reliability and more efficient resource allocation.

C. Secure and Trustworthy Network Systems

The importance of security and trustworthiness to build reliable and robust communication systems is growing, together with the awareness of the interdependence across these three fundamental network requirements. The Special Issue has received several submissions in the area of secure and trustworthy network systems.

Noh et al. [14] investigate the Hyperledger Fabric (HF), a well-known blockchain platform. As HF has limitations in terms of the integrity of distributed ledgers, simple consensus mechanism, and deployment in a single data center/cloud, authors propose a solution for multi-cloud environments that leverages a resilient peer-to-peer technology to deal with network congestion and delay in a multi-cloud environment. Experimental results show a reduction of the maximum block arriving time among all the participating nodes by approximately 50% 95% compared to the existing algorithms, and improved resilience to various network-layer vulnerabilities and attacks.

Liu et al. [15] address blockchain oracles to connect blockchains to external systems in the Industrial Internet of Things (IIoT). Rapid data changes as well as network and device heterogeneity in IIoT can impair the quality of services of blockchain oracles. A two-step approach is proposed, which implements (i) a node selection algorithm to combine a reputation mechanism and a verifiable random function to select nodes with a high reputation secretly and (ii) a data filtering algorithm based on a sliding window to improve the consistency and efficiency of data collection. Simulation results show that the proposed approach can effectively improve the service quality in terms of data accuracy and data variance.

The article of Prateek et al. [16] deals with the important topic of cybersecurity for smart metering infrastructures. The authors propose the ‘]lq Quantum-Secure Privacy-Preserving Smart Meter Authentication (Q-Secure P2-SMA)” protocol to address the competing targets of privacy and practicality and to ensure security against quantum computer threats. Q-Secure P2-SMA implements a semi-quantum key distribution and a hash function to protect against a large set of security and privacy threats such as replay attacks and message unlinkability. A detailed analysis of the communication, computation, and energy overheads shows that Q-Secure P2-SMA is superior to existing protocols. Its performance and implementation features could lead to practical use soon. In payment channel networks (PCNs) handling a large number of transactions, existing distributed routing algorithms struggle to efficiently manage multiple simultaneous transactions due to the risk of deadlocks.

Sharma and Kapoor [17] demonstrated the potential for deadlocks in these algorithms and proved that routing two transactions in a PCN is an NPcomplete problem. Their work focuses on developing routing algorithms that avoid deadlock conditions and enhance routing choices to minimize the number of saturated links that can lead to deadlocks. Threat hunting aims to uncover attacks that might evade standard detection methods by generating and refining attack hypotheses. Typically, this process is manual, requiring significant expertise and often resulting in irrelevant hypotheses. Nour et al. [18] introduce AUTOMA, an automated solution that improves hypothesis generation by leveraging system telemetry and a knowledge base of attacks. AUTOMA generates relevant hypotheses and their variants using advanced evaluation techniques like similarity, success, likelihood, and criticality assessments. It also uses sequence and hierarchical similarity methods to account for attack variations. Evaluations on a dataset of 284 attack campaigns show that AUTOMA effectively generates relevant hypotheses with up to 99% fewer irrelevant results and a rapid execution time, taking as little as 8 minutes for hypothesis generation and 10 seconds for variant creation.

Masuduzzaman et al. [19] propose a Deep Learning (DL) model incorporating information from smartwatches with Heart Rate (HR) for determining if soldiers are injured. The authors use unmanned aerial vehicles (UAVs) to get images, obtain the data from the smartwatches, and then offload the data to the edge cloud where the DL model runs and the HR is analyzed. To ensure the security of the transmitted information the authors use secure access control with blockchain technology. The proposed system is implemented and experimental results are discussed.

In [20], Albinaliet al. conduct a comprehensive literature review covering 175 papers on attacks against routing protocol over LLNs (Low Power and Lossy Networks), short for RPL, and their mitigation solutions. A rigorous selection process provides a deep understanding of how RPL is exploited for different attacks and the solutions designed to mitigate such attacks. In their study, the authors proposed a taxonomy where RPL attacks are classified based on the attack vector, such as generating, dropping, modifying, or replaying specific control messages. The mitigation solutions surveyed include authenticating, updating, discarding, encrypting, and isolating attacking nodes. The authors also presented evaluation metrics in the literature to evaluate the performance of mitigation solutions. Further, an efficiency criteria to assess mitigation solutions’ efficiency is also proposed. This review aims to uncover innovative techniques that can effectively safeguard networks against routing attacks.

Yang et al. [21] investigated the problem of resilient optimal bipartite tracking control for heterogeneous multi-agent

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systems with multiple targets under denial-of-service (DoS) attacks. They devised a bipartite tracking mechanism that enables the agents to track the targets under bipartite consensus control, making the system non-autonomous. Numerical simulations verified the effectiveness of their proposed tracking mechanism.

D. Resilient and Reliable Network Architectures

This section explores key advancements at the architectural level in designing robust communication systems. The studies address diverse applications, including power grid communication, 5G networks, IoT, and Time-Sensitive Networking (TSN).

Volkova et al. [22] address the design of communication networks for the restoration procedure in distributed power grids. Assuming likelihoods for communication node failures, the restoration problem is formulated as a multi-objective optimization problem to find the optimal subgraph with sufficient node-disjoint paths between the communicating power grid assets. A genetic algorithm is used to solve the problem and its effectiveness is evaluated based on benchmark models developed in the article. The authors analyze the results based on the trade-offs between the robustness and the network size.

To ensure latency guarantees in layer-3 networks without any time synchronization among nodes, Miserez et al. [23] propose control and routing strategies, namely network protocols based on network calculus, queue information and budgets as well as ingress traffic shaping. The strategies are evaluated by simulations based on representative study networks. The results show that the control messaging and memory overheads scale appropriately, while acceptance rate, network utilization, and path dissemination times are nearly stable in larger networks. Time-Sensitive Networking (TSN) enhances Ethernet for real-time communication, using mechanisms like Credit-Based Shaper (CBS) for priority scheduling and Time-Aware Shaper (TAS) for scheduled traffic. TSN requires explicit admission of streams and uses Per-Stream Filtering and Policing (PSFP) to ensure traffic compliance. While traditional token bucket policers handle credit-based metering, time-based metering demands precise time synchronization.

Ihle et al. [24] introduce a P4-based PSFP implementation on a 100 Gb/s switch, detailed in the provided GitHub code. The implementation supports credit-based and time-based policing and scales to 35,840 streams. It offers a practical solution for TSN switches lacking these features and can aid other P4-based hardware needing time synchronization.

Simone et al. [25] introduce a stochastic method to evaluate resilient 5G architectures, focusing on performance and availability. Performance is assessed by analyzing Packet Data Unit session establishment delays using non-product-form queueing networks, modeling 5G nodes as G/G/m queues. Availability is modeled with a hierarchical approach combining Reliability Block Diagrams and Stochastic Reward Networks. This method identifies an optimal 5G configuration that meets performance and availability constraints at minimal cost. The approach is validated with empirical data from an Open5GS testbed.

To address the challenge of unstable IoT network management, where devices can move, appear, or vanish unpredictably, Chambon et al. [26] propose a novel architecture based on a selection process of dominant devices acting as gateways, ensuring continuity of service. The authors investigate two selection processes based on Connected Dominating Sets and Deep QNetwork techniques, to optimize energy consumption while providing high QoS and extending network access to offline devices within predefined zones of interest. The authors use emulation tools to measure metrics like dominant device proportions, energy savings, and service quality. They then offer recommendations for system selection based on system's needs. The special issue also accommodates a paper of tutorial nature.

Tipper et al. in [27] describe the current challenges that network operators face in ensuring end-to-end connectivity, especially across the backhaul network, during equipment failures and power outages. Key factors impacting resilience include the shift to commodity hardware, disaggregation of the radio access network, edge computing, network densification, and rising power demands. The paper explores strategies to address these challenges, including cooperative techniques between operators and extending resilient overlays to the wireless edge.

E. AI and Machine Learning for Network Resilience

This section highlights cutting-edge applications of AI and machine learning techniques to enhance network reliability, security, and performance across various network domains. These studies demonstrate how advanced machine learning models like GANs, Deep Reinforcement Learning, and Graph Neural Networks can tackle challenges in network slicing, failure management, and spectrum sharing, offering timely solutions for improving network resilience in complex, dynamic environments.

Murmu et al. [28] introduced a reliable technique called Customized Inequality-Aware Federated Learning (CusIAFL) for securing color images transmitted over wireless networks. This technique personalizes federated learning by adjusting data sampling based on the availability of labels on each client's device. They also employ a hybrid approach to ensure consistency in time-series data and use a Pix2Pix Generative Adversarial Network (GAN) to generate realistic images.

In the smart agriculture context, Cui et al. [29] investigate object detection methods on drones. For instance, since detection on drones can control pesticide spraying, the amount of unnecessary spraying can be reduced. A recent convolutional neural network detection algorithm is used together with an adaptive backbone network, an attention mechanism, and a rapid convergence function. Experimental results show that the approach surpasses the previous algorithms in terms of overall detection effectiveness and other parameters.

Rabbani et al. [30] developed an approach to detect malicious lateral movement paths by leveraging authentication events and graph learning techniques. Their approach involves constructing a heterogeneous graph and employing DeepWalk for node embedding. Combining node embedding features with the temporal information of authentication events generates feature vectors for each authentication request.

Jiao et al. [31] presents a novel framework designed to localize failed optical layer device boards in an Optical Transport Network (OTN), that correlates failed boards and alarms. Furthermore, to identify all possible failures, various dimensions, are considered including time, network topology, traffic distribution, and board/alarm attributes. Extensive case studies demonstrate the superior results of the framework in terms of metrics evaluating the identified failed boards and root alarms.

Ahmadi et al. [32] jointly addresses admission control and RAN/MEC slicing, to maximize Infrastructure Provider (InP) revenue through the application of multi-agent Deep Reinforcement Learning (DRL) and Graph Neural Networks (GNNs). The approach uses Graph Attention Networks (GATs) and a new neural network architecture, allowing it to be applied to larger and unknown topologies without re-training or model tuning. Furthermore, the authors introduce a new application of attention maps within GATs to identify network bottlenecks. Through GATs, InPs can better understand the model decision-making process and upgrade resources only in critical network parts, thus increasing their revenue. The extreme reliability requirements of microwave links, as part of the backhaul of mobile traffic, demand prompt failure management.

In [33] the authors develop Machine learning (ML) based hardware failure classifiers. They designate their methodology for ML-based As-Soon-As-Possible (ASAP) hardware failure-cause. ASAP seeks to give quick predictions, based on as little network information as possible. Additionally, using Venn-Abbers predictors, a prediction is obtained jointly with the probability of being correct above a given threshold. The authors validate their proposal against the state-of-the-art and show their approach produces better probabilistic predictions.

Nasr and Sanusi [34] investigate spectrum sharing for Device-to-Device (D2D) Ultra Reliable Low Latency Communication (URLLC) services. The authors propose a reinforcement learning approach to distributed self-organizion of spectrum resources, called Reinforcement Learning Based Matching (RLBM). Compared with existing schemes, simulation results show better performance in key parameters of throughput, spectrum utilization, signaling overheads, and computation complexity. For instance, RLBM needs _ 38% less signaling overhead than the deferred acceptance algorithm.

ACKNOWLEDGMENT

The editors would like to sincerely thank all authors who submitted papers to this special issue and all reviewers for their relevant comments, constructive suggestions, and timely submission of their reviews. Finally, we appreciate the support of the Editor-in-Chief, Hanan Lutfiyya, and Janine Bruttin, IEEE TNSM Administrative Assistant, for their precious help in the preparation of this SI. Teresa Gomes, was partially funded by the Portuguese Foundation for Science and Technology under the project grant UIDB/00308/2020 with the DOI 10.54499/UIDB/00308/2020. Massimo Tornatore acknowledges support by the PRIN PNRR project GASTON, funded by Italian Ministry of University and Research.

APPENDIX: RELATED ARTICLES

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This article has been accepted for publication in IEEE Transactions on Network and Service Management. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TNSM.2024.3469308

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