Indonesian Journal of Electrical Engineering and Computer Science
Vol. 34, No. 3, June 2024, pp. 1800∼1813
ISSN: 2502-4752, DOI: 10.11591/ijeecs.v34.i3.pp1800-1813

Optimizing high availability multi-controller placement in SDN/NFV 5G networks: a survey

Samer Mohammed Rasool[1,2], Yassine Boujelben[2], Faouzi Zarai[2]
[1]National University of Science and Technology, Dhi Qar, Iraq
[2]NTS'COM Research Unit, National School of Electronics and Telecommunications of Sfax (ENET COM), University of Sfax
Sfax, Tunisia

Article Info

Article history:

Received Dec 19, 2023
Revised Jan 29, 2024
Accepted Feb 22, 2024

Keywords:

Availability
Controller placement problem
Distributed control
Network function virtualization
Resilience
Software defined networking

ABSTRACT

In meeting the diverse and occasionally conflicting quality of service (QoS) requirements associated with modern communication networks, 5G technology has emerged as a pivotal player. In its architecture, 5G has adopted network function virtualization (NFV) and cloud-based approaches, aiming to simplify network and service deployment, operational processes, and management. The convergence of software defined networking (SDN) and NFV offers an effective solution, enabling scalable and high-performance 5G networks. However, this integration poses critical challenges, with the placement of SDN controllers being a central concern due to its significant impact on network performance, covering aspects such as latency, costs, and energy efficiency. This challenge is known as the controller placement problem (CPP). The central theme of this paper revolves around the intricate relationship between 5G core networks, virtualization technology, and the pressing concern of SDN controller placement, underscoring its significance in the modern networking landscape. We provide a survey of recent methodologies aimed at solving the CPP within the realm of SDN, with a particular focus on resiliency and high availability.

Corresponding Author:

Samer Mohammed Rasool
NTS'COM Research Unit, National School of Electronics and Telecommunications of Sfax (ENET COM)
University of Sfax
Road of Tunis, City el Ons, Technopole of Sfax, Tunisia
Email: samermoon53@gmail.com

1. INTRODUCTION

Internet protocol (IP) networks are supervised using decentralized control and distributed network protocols, operating on the network switches [1]. This design complicates network administration, requiring the individual application of overarching rules to each device, depending on vendor-specific commands [2]. In the conventional setup, the control plane and data plane are situated within switches or routers in traditional architectures, lacking the adaptability necessary for effective network management [3]. With the increasing use of IP technology and the expanding influence of digital applications in daily society, networks must be flexible and dynamic [4]. This flexibility enables them to promptly adapt to changing scenarios, including fluctuating traffic patterns, network glitches, security vulnerabilities, and more [5].

With the goal of addressing the limitations inherent in traditional network setups, the concepts of software defined networking (SDN) and network function virtualization (NFV) have emerged to simplify network intricacies [6] and facilitate the effective utilization of resources [7]. SDN represents a flexible networking approach that permits centralized control over networks in a programmable manner [8]. NFV is a networking concept that seeks to decrease the quantity of intermediary devices by converting network operations into software-based functions [9].

Despite the benefits offered by SDN, it has been observed that the segregation of the control plane can directly impact network performance [10]. Consequently, identifying the optimal quantity and placement of controllers to enhance performance and availability has become a core research challenge within SDN, often referred to as the controller placement problem (CPP) [11]. Distributing user requests across cluster controllers is vital to ensure a balanced distribution of workloads among them [12]. When aiming to reduce the overall response time for delegated tasks, careful attention must be paid to anticipating the necessary requirements for traffic volume and tools controlling service requests [13].

Several surveys proposed in the literature have provided insights into CPP-related research issues and solutions. The studies in [14]–[16] have surveyed state-of-the-art methods and solutions, focusing on their objectives and the impact of multi-controller placement on SDN network performance. These studies have presented existing works in the CPP based on different strategies and techniques. Additionally, they have identified numerous open issues and research challenges related to the CPP problem that should be considered in future research. Furthermore, other works have presented optimizations of the CPP issue, which are utilized in the latest studies to extract strategies, techniques of optimization, solutions, and objective functions [17], [18]. These works have provided a taxonomy of studies related to solutions for CPP optimization in SDN from dissimilar perspectives and dimensions.

The demand for reliability and high availability has been increasing over the years, with information and communication technologies (ICTs) playing central roles in modern life. Hence, in this paper, our focus will be on works related to CCP, specifically addressing solutions for resilient networks. The originality of our work is highlighted through the following key contributions:

– Providing a comprehensive review of SDN, NFV, and 5G technologies.
– Identifying and outlining key challenges within SDN, NFV, and 5G that necessitate further study for resolution, ultimately enhancing network performance.
– Presenting state-of-the-art methods and techniques that uniquely address CPP challenges under the resiliency constraint.

The rest of this paper is organized as follows. Section 2 gives an overview of SDN and NFV. Section 3 provides the single and multi-controller architectures in the SDN and the comparison between them. Section 4 presents the literature survey for works related to the CPP. Section 5 provides an overview of techniques used to enhance resiliency in multi-controller SDN environments. Section 6 provides a discussion on previous works and lists open issues. Finally, section 7 presents the conclusion and future directions.

2. OVERVIEW OF SDN AND NFV

Within service provider networks, the tasks of efficiently establishing, removing, adjusting, and directing traffic are effectively accomplished through the application of SDN and NFV technologies [19], pivotal networking models. In other words, the chaining of hardware middle-boxes can be achieved by utilizing NFV, which significantly simplifies and reduces costs [20]. Consequently, SDN is utilized to coordinate virtual network functions, providing a centralized logical control mechanism and facilitating the configuration of service chains [21]. In this section, we will present a brief overview of the SDN and NFV technologies in the subsequent sections, respectively.

2.1. Software defined networking

SDN entails the segregation of the control plane and data plane in networking devices. In contrast to conventional non-SDN networks, where the coupling of control and data planes in a single device results in issues like intricate management and scalability challenges [22]. By employing centralized network control through SDN controllers, service deployment and management become more straightforward [23]. This enables efficient traffic direction between network functions (NFs) by distributing the load across multiple physical machines.

Furthermore, the SDN architecture facilitates direct interaction between applications and the network through application programming interfaces [24]. Through SDN, network administrators gain the ability to directly adjust and update routing regulations and guidelines [11]. The SDN architecture is typically organized into three distinctive planes: the data plane, the control plane, and the application plane [25], [26]. Each plane consists of specific components. The data plane incorporates forwarding devices, the control plane hosts the SDN controller, while the application plane accommodates SDN applications [27], [28]. These various planes within SDN interact with each other through programming interfaces [29].

The application layer consists of diverse network applications providing network services. These applications utilize northbound interfaces to communicate with higher-level applications, sending requests to the control plane and embodying centralized logical control [30]. The SDN controller plays a crucial role in overseeing a comprehensive perspective of the network infrastructure. It is tasked with managing network functions, responding to requests from network applications, and issuing instructions to the network's data plane for packet processing [31]. Two widely recognized open-source controllers are OpenDaylight [32] and POX [33].

2.2. Network function virtualization

For service providers, employing proprietary network hardware often entails substantial expenses, including procurement, security, configuration, scalability, and maintenance costs [34]. To address these challenges, the European Telecommunications Standards Institute (ETSI) introduced an advanced NFV architectural framework [35]. This framework envisions the implementation of network functions in the form of software, operating on a network function virtual infrastructure (NFVI), which can be hosted on a general-purpose server. This suggestion was presented to leverage hardware virtualization [36]. NFV adoption streamlines the deployment of network services by reducing the need for acquiring new hardware middle-boxes. Virtualizing and deploying multiple middle-boxes on either single or multiple general-purpose servers can lead to cost savings and improved efficiency [37].

The NFV framework outlined by ETSI includes essential components such as operations support system (OSS), business support system (BSS), virtualized network functions (VNFs), virtualized computing infrastructure managed by VIM, and service orchestration performed by NFVO and MANO. VNFs represent various network functionalities, and the orchestration layer, led by NFVO, plays a key role in mapping VNFs to physical resources and managing services. The MANO component is instrumental in orchestrating VNFs and establishing service chains, particularly in scenarios involving service function chaining [38]–[40].

2.3. SDN/NFV architecture in 5G networks

The advent of the fifth generation (5G) has triggered a swift increase in data traffic, accompanied by widespread application adoption and diverse service characteristics, including enhanced mobile broadband (eMBB), ultra-reliable low latency communications (URLLC), and massive machine type communications (mMTC) [41]. These use cases bring forth a heterogeneous landscape, adding complexity to the administration and coordination of 5G wireless networks. Consequently, addressing quality of service (QoS) management becomes imperative to meet the unique requirements of each use case and ensure optimal network performance [42].

The progression of the 5G network towards reconfiguring the existing network infrastructure is achieved by effectively utilizing intelligent systems across both the access and core networks through the implementation of SDN and NFV technologies. The 5G network's capabilities encompass a broad spectrum of networks, offering highly flexible control over the network and efficient allocation of cloud resources [43]. This is vital to cater to diverse network traffic operations and the substantial demands of handling large volumes of data [44]. With SDN as the foundation, the control functions of the network's control plane are separated from the forwarding abilities of physical layer components such as firewalls and routers. These control functions are then centralized within an SDN controller. The virtualization of the control plane is achieved by integrating new NFs into the software infrastructure, avoiding the need to modify any of the hardware switches [45]. Effective resource slice separation can be achieved through the dynamic deployment of NFs.

The idea of network function (NF) chaining provides a means to introduce adaptability and enhance flexibility within the 5G network structure. This concept allows for the allocation of virtualized services in the 5G core cloud network, which can then be replicated across different networks for consistency [46]. In simpler terms, NFV plays a crucial role in the 5G infrastructure by virtualizing various appliances in the network. Within the context of 5G, NFV facilitates network slicing which defines a virtual network architecture that enables the creation of multiple virtual networks on a shared physical infrastructure. Figure 1 illustrates the integration of NFV and SDN in the 5G network. The synergy of SDN and NFV in 5G is envisioned as a multi-tenant solution, allowing multiple independent network operators and service providers to utilize the same physical infrastructure and computing platforms [47]. This results in the existence of a streamlined virtual layer between the control plane and the forward paths, defining the path for traversing the virtual network [48].

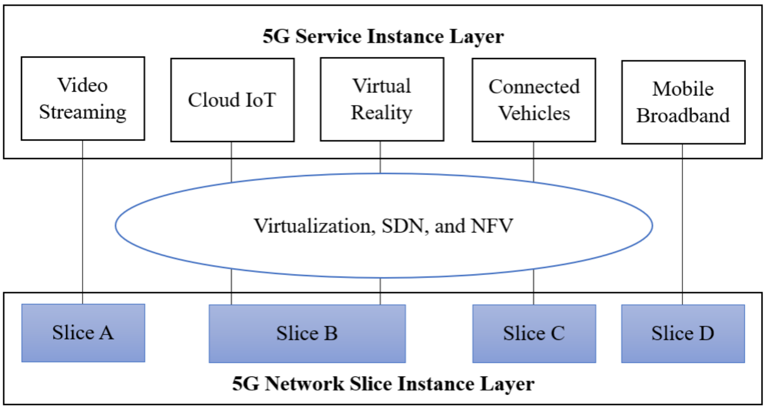

Figure 1. The NFV and SDN in 5G network

3. SINGLE AND MULTI CONTROLLER ARCHITECTURES

The control plane is centered around a central controller, serving as the core of the SDN system and overseeing the entire network's operations. Simultaneously, the application plane falls under the administration of the application administrator, responsible for handling policies that are governed and enforced by the controller [49]. The controller holds the authority to both remove and introduce rules and policies within the SDN networks, thereby enhancing network programmability and streamlining network management processes [50]. Typically, the entire SDN network is governed through a single SDN controller. However, such single SDN controllers are primarily suitable for networks with limited coverage, such as local area networks [51]. The structure of a single controller SDN is depicted in Figure 2. Previous studies have employed single SDN controllers for these smaller networks. Nevertheless, these approaches face challenges related to single-point failures and scalability problems [52].

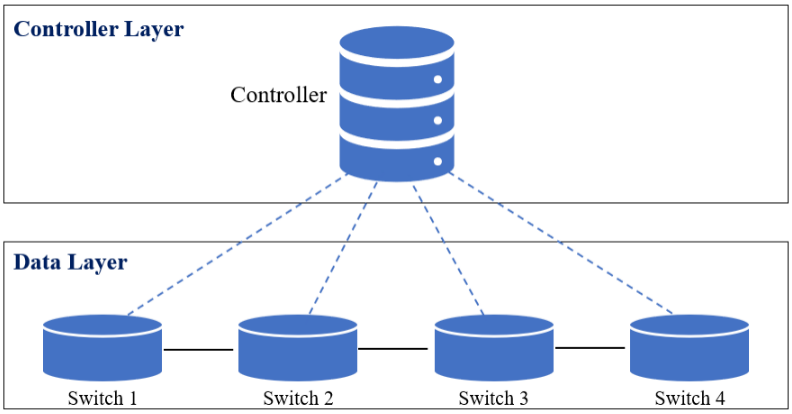

Figure 2. The structure of single controller SDN

Certainly, utilizing a single SDN controller for a large area network presents limitations such as high latency, congestion, and vulnerability to link failures, all adversely affecting network performance [53]. To address challenges related to scalability and latency inherent in single SDN controllers, the concept of multi-controller systems has been introduced. By adopting this approach, challenges linked to single-point failures are alleviated, offering a distributed and responsive solution for SDN networks while minimizing latency [54]. Recent studies have explored the multi-controller SDN concept and have succeeded in alleviating traditional drawbacks to a certain extent. The structure of a multi-controller SDN is illustrated in Figure 3. As mentioned earlier, the use of multiple SDN controllers collectively constitutes what is known as the CPP [55]. This raises questions about the optimal number of controllers required to deliver adaptable services to the SDN network [56], as well as which controllers should be selected for deployment within the network [57].

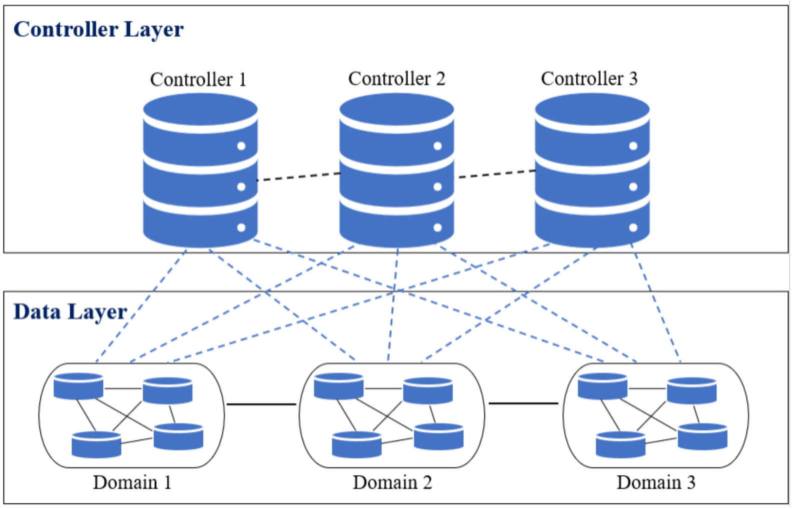

Figure 3. The structure of multi-controller SDN

Determining the optimal number of controllers required for delivering adaptable services to the SDN network is closely linked to selecting the optimal positions for controllers that meet switch requirements and choosing highly fault-tolerant controllers. Identifying and situating controllers in optimal locations results in reduced latency between multiple controllers and switches [58]. In a study by Calle *et al.* [59], heuristic approaches were employed to address the CPP, but their methods have limitations in accounting for critical constraints. Specifically, they overlook controller fault tolerance and neglect switch requirements. The parameters of current heuristic algorithms present challenges in achieving convergence, affecting both controller placement and network performance [60]. The problem of controller placement in a multi-controller environment remains an open issue, requiring thorough investigation to improve performance in SDN networks. Table 1 summarizes the comparison of single and multi-controllers in SDN networks.

Table 1. Comparison between single and multi-controllers in the SDN networks

Single SDN controller	Multi SDN controller
Provides an encompassing perspective of the entire network's overview	Lacks an encompassing perspective of the entire network
There is a single point of failure	No single point of failure
Lacks scalability.	Higher scalability
Easy deployment in legacy environments	Supports SDN and legacy environments
Suffers from high latency	Less latency
Not appropriate for mobile environments	Appropriate for mobile environments
High possibility of link failure rate	No link failure rate
Faces high congestion within the network	No congestion within the network

4. CONTROLLER PLACEMENT PROBLEM

In recent decades, there has been a significant surge of interest among various researchers and developers in the field of SDN technology, particularly in the context of both single and multi-controllers concerning 5G technology. Furthermore, the integration of SDN with NFV has introduced numerous valuable opportunities for enhancing network performance. This review aims to examine state-of-the-art methods and techniques that leverage the synergies of SDN, 5G, and NFV, all with the goal of optimizing network performance.

Various techniques and methods have been developed to tackle challenges linked to the CPP, including dynamic scenarios for switch allocation and strategies for switch migration. However, it's important to note that the capacity of each controller to effectively manage the increasing volume of traffic requests is limited [61], and switches are dynamically arranged and allocated to different controllers as traffic patterns fluctuate, as exemplified in [62], [63]. While other researchers have discussed such problems based on load balancing (LB) [64], [65], the previously mentioned research endeavors presented various methods for addressing CPP as a problem of locating resources. In this context, the key parameter was the count of switches, emphasizing the significance of accurately choosing controller placements and assigning switches with weights based on latency or distance. Nonetheless, the majority of past studies approached CPP within a solitary domain, with their primary focus on achieving load distribution without precisely evaluating the necessary number of controllers in relation to the load imposed by network traffic [66].

The study in [67] addresses the challenge of switch migration within 5G networks built on the foundations of SDN and NFV. Specifically, SDN controllers are deployed as VNFs. The primary focus is on efficiently rerouting traffic from specific SDN switches to one or more virtualized SDN controllers, aiming to manage traffic fluctuations and adapt to changes in the network layout. Given the dynamic nature of 5G networks, the task involves balancing competing goals, including load distribution among controllers and maintaining network stability. The work formulates this challenge as a computationally demanding mixed integer non-linear Program with multiple objectives. To tackle this, the study proposes a mathematically based solution approach using the successive convex approximation (SCA) technique for the single-objective case. The approach considers preference parameters that define the relative importance of objectives. Acknowledging the practical efficiency needed, an extended deep learning (DL) method is introduced to generate multiple mappings for multiple objectives.

Another study, presented in [68], focuses on augmenting SDNs with intelligent controllers to enhance the processing period of the first packet. The study introduces a new approach specifically designed to minimize the time required for a host to send its initial data packet. The proposed method involves proactively incorporating essential flow entries into the flow table of the OpenFlow switch before the arrival of traffic from the host. Implemented using Python, the technique is evaluated through experimentation on a Mininet network emulator, utilizing the RYU controller. The experimental results demonstrate a substantial reduction of over 83% in the time taken to handle the first data packet. However, it's noted that the proposed method does not provide a blueprint for locating hosts, and it does not consider the necessary rules and controls before traffic creation through the linked host.

The study in [69] introduces a method utilizing SDN and NFV in the next-generation time and wavelength division multiplexing-passive optical network (TWDM-PON). The primary objective is to establish an elastic access network with multi-tenancy capabilities. This integration not only aims to enhance virtual unbundling for broadband access networks but also facilitates cost-sharing and introduces dynamic competitiveness to the network environment. Simulation results indicate that the proposed architecture and approach exhibit improved performance, particularly in multi-tenancy scenarios. These enhancements maintain quality-of-service requirements, including factors such as throughput, jitter, packet loss ratio, and mean packet delay. However, it's noted that this method requires specialized components, potentially leading to higher initial capital expenditure. Additionally, the proposed architecture may take a longer time to realize the benefits associated with reductions in operational and maintenance costs.

Qaffas *et al.* [70] have presented a technique for selecting the optimal placement of SDN controllers to enhance the performance of wireless sensor networks. They address the multi-objective optimization problem considering constraints such as time, reliability, and cost. The introduced method, adaptive population-based Cuckoo optimization (APB-CO), is employed for optimizing controller placement. The effectiveness of APB-CO is discussed without providing specific numerical results. The proposed model's performance is compared to existing methods, including the greedy approach and simulated annealing, demonstrating favorable results. However, it is noted that the proposed method still requires improvements in terms of flexibility.

Praveen *et al.* [71], a strategy involving multiple SDN controllers for dynamic LB is presented. This method efficiently shifts workload from heavily burdened controllers to less burdened ones based on the load status of each controller. To measure its effectiveness, the approach uses parameters such as response time, throughput, and resource consumption. Practical tests using projectors have shown that this system autonomously allocates workload across controllers, reducing LB duration. However, it's noted that this method does not account for controller cost and fault tolerance.

Sreekanth *et al.* [72] have introduced an architecture that combines SDN and NFV on an edge node server tailored for internet of things (IoT) devices, aiming to alleviate computational complexity in cloud-based fog computing. SDN establishes a separation between the forwarding and control planes, offering a structured forwarding framework. NFV, focusing on virtualization, merges the forwarding model with VNFs. This integration ensures interoperability and consistency. The proposed architecture features an orchestrator layer tasked with real-time responsibilities, utilizing an edge node server via the SDN controller for creating tasks, amendments, operation, and completion. Simulations using the EstiNet simulator are conducted, employing metrics like total time delay, reliability, and satisfaction for evaluation. However, it's noted that this method has ignored the usage of multi-SDN controllers, and the optimal placement of the controller is not considered.

A resolution is presented for addressing the challenge of controller placement within SDN networks [73]. The study employs nature-inspired algorithms, specifically the manta ray foraging optimization (MRFO) and the slap swarm algorithm (SSA), to tackle CPPs. To enhance the efficacy of these individual algorithms, a process of discretization is executed using triple operators. The discretized algorithms are then combined in a hybrid fashion to handle controller placement. The primary aim of this study was to resolve the CPP with a specific emphasis on minimizing network latency. However, it is important to note that other factors, such as switch requirements, fault tolerance, and additional constraints, should also be taken into consideration to achieve optimal placement of controllers.

In addition, an optimization algorithm to address the CPP in SDN networks is presented in [74]. This study has employed two distinct algorithms for the controller placement task: the particle swarm optimization (PSO) algorithm and the genetic algorithm (GA). The PSO algorithm is used initially to identify the most suitable controller based on fitness values, taking into account delay constraints. Subsequently, the GA algorithm is employed to update the position and velocity of controllers. In other words, this work leveraged both algorithms for controller placement. However, it is noted that the GA algorithm is limited by high computational time consumption.

Dhar *et al.* [75] have presented a novel approach to controller placement within an SDN network by employing an optimization algorithm. In their method, a controller is strategically positioned for each cluster, with the objective of minimizing latency between switches and controllers. The proposed technique determines the maximum distance that ensures reduced latency between switches and their respective controllers. This method effectively reduces latency across diverse scenarios involving different types and quantities of controller placements. Experimental results substantiate the effectiveness of the proposed approach in terms of fault tolerance, outperforming its comparatives. Nevertheless, it is noted that there are some network controllers that failed with respect to path reliability.

A potent technique for addressing the CPP is presented in [76], employing heuristic algorithms. The initial step involves analyzing the latency between switches and controllers, resulting in the creation of a delay-aware model. This model's efficacy is evaluated using three optimization algorithms: the Bat optimization (BO) algorithm, the varna-based optimization (VBO) algorithm, and the firefly algorithm (FA). To enhance performance, all parameters of these three optimization algorithms are fine-tuned using the PSO algorithm. However, it is noted that this method attempted to solve the CPP using limited network indicators.

The traffic engineering (TE) for 5G networks based on the integration of SDN-NFV techniques is presented in [77]. In this method, the TE framework is designed to facilitate effective resource management among slices, aiming to prevent congestion and maintain QoS performance. The framework leverages an NFV architecture that incorporates two-level SDN controllers situated in both tenant and infrastructure domains, facilitating the implementation of the proposed TE framework. The evaluation includes aspects such as ensuring QoS performance, enhancing resource utilization, and minimizing reconfiguration overhead. However, the performance of the presented method in terms of the end-to-end (E2E) delay is degraded with the increase in traffic burstiness, and the method has not addressed the problem of controller placement. Table 2 provides a summary of related works on these methods and techniques, emphasizing the architecture type, denoted as D for distributed, C for centralized, and H for hybrid. It also indicates whether a load balancer (LB) is employed.

5. RESILIENCY IN SDN CPP

In computer networks, resilience is paramount, given that even a brief failure lasting a few milliseconds in a high-speed connection can result in significant packet losses reaching the scale of terabytes. In traditional networks, where both data and control packets utilize the same transmission link, the vulnerability to network failures is equal for both control and data information. This is due to the shared resilience characteristics of the control plane and the data plane [78]. Network resilience, in essence, involves the ability to recover logical control within a specific time window following the detection of a failure. The core concept of SDN addresses this challenge by isolating the control plane from the data plane, centralizing control logic [79]. This centralization yields resilience benefits by reducing reliance on brief control messages, which are particularly vulnerable to disruption caused by network failures [80]. The resilient CPP adds additional complexity to resilient routing, as the locations of server replicas are not predetermined [81].

Table 2. Summary of related works

Reference	Year	Problems	Type	LB	Contributions	Limitations
[67]	2023	The challenge of switch migration	D	Yes	Can produce high-quality Pareto Fronts	Did not surpass the performance of the current state-of-the-art algorithms
[68]	2023	The processing period of the first packet	C	No	More than 83% of the time taken is reduced to handle the first data packet	Lacks the ability to provide a blueprint for host location and overlooks essential rules and controls required before generating traffic through the connected host
[69]	2023	Providing a flexible access network multi-tenancy	C	No	Enhances performance, particularly in multi-tenancy scenarios, while preserving QoS requirements	Requires specialized components, possibly leading to a higher initial capital expenditure
[70]	2023	CPP	D	Yes	The performance outperformed the greedy approach and simulated annealing	The flexibility in this method needs enhancements
[71]	2022	Dynamic LB	D	Yes	Can autonomously allocate the workload across controllers	The system has ignored controller cost and fault tolerance
[72]	2022	The computational complexity in cloud-based fog computing	C	No	The analysis reveals that the proposed architecture exhibits superior performance in terms of total time delay, satisfaction, and reliability	This method has ignored the usage of multi-SDN controllers. Hence, the optimal placement of the controller is not considered
[73]	2021	CPP in SDN networks	H	Yes	Solved the CPP issue while focusing on minimizing network latency	Important factors, including switch requirements and fault tolerance are not considered
[74]	2021	CPP in SDN networks	D	Yes	This work based on the PSO and GA algorithms obtained an optimal placement for the SDN controller	The GA algorithm is constrained by high computational time consumption
[75]	2021	CPP in SDN network	D	No	This method effectively reduces latency across diverse scenarios involving different types and quantities of controller placements	Some network controllers failed with respect to the path reliability
[76]	2020	CPP	H	No	The method has solved the issue of the controller placement and the network performance is enhanced	The method used limited network indicators
[77]	2020	Prevention of congestion and maintaining the QoS performance	D	Yes	The method has maintained QoS performance, enhanced resource utilization, and minimized reconfiguration overhead	When the traffic burstiness increased, the performance of the presented method in terms of the E2E delay is degraded

The resilient CPP can be characterized as an optimization challenge aimed at satisfying resilience constraints while concurrently managing considerations of performance, cost, and capacity limitations [82]. Despite the centralized architecture of SDN, resilience-related challenges persist, primarily driven by a significant increase in data generated by diverse smart devices [83]–[86]. Notably, the resilience of the control plane is intricately linked to the matter of controller placement, which involves organizing and allocating controllers to forwarding devices, such as switches. Tackling the resilient CPP involves the assignment of multiple controllers to a switch, ensuring the fulfillment of specific quality of service requirements [87].

Numerous recent studies are addressing SDN controller placement, with a specific emphasis on solutions aimed at improving resilience in controller placement. For example, the investigation conducted in [88] delves into the CPP, taking into consideration factors such as the control path rerouting count and the delay between the controller and the switch in the event of each link failure. This problem is formulated as a multi-objective optimization challenge. The study employs a heuristic approach, specifically PSO.

Killi and Rao [89] have proposed three methods for placing controllers and associating switches with multiple controllers. These approaches, named resilient multi-controller mapping with minimum cost (RMM-MC), RMM with minimum backup capacity (RMM-MB), and RMM with latency minimization (RMM-LM), are designed to minimize network cost, reserved backup capacity at controllers, and latency from switches to controllers. The main goal is to guarantee full resilience in the event of a predefined number of controller failures.

In a different study, a framework for controller placement has been introduced, considering both the control plane architecture and the relationship between the control and data planes [13]. This framework is formulated as a multi-objective optimization model with two goals: minimizing inter-controller latency and reducing flow setup time. Furthermore, within this framework, the best–worst multi-criteria decision-making method, considering hop count and propagation latency, is employed to allocate switches to controllers. Finally, a heuristic approach is utilized to assign a path between a switch and its controller based on the path reliability. The proposed model is executed iteratively to determine the optimal controller location, switch assignment to the controller, and the best route within the network.

Dou *et al.* [90], have introduced Matchmaker, an adaptive approach designed to restore offline flows in SD-WANs in the event of controller failures. Matchmaker intelligently adjusts the routes of specific offline flows, modifying the control cost of offline switches based on the established control capacity of active controllers. As a result, it allocates offline switches to active controllers in an efficient way, leading to a substantial improvement in the number of recovered flows.

Guozhu *et al.* [91], explain the study first reviews and examines resiliency technologies in military SDNs, exploring the fundamental architecture of the SDN paradigm and its key features. Notably, the analysis points out that there are currently no typical applications of SDN in military information and communication networks. The second key observation emphasizes the critical need to address SDN's reliability challenges and susceptibility to single points of failure, given its requirement for centralized control. Lastly, the study highlights the potential to expedite the development of military information and communication networks by drawing on successful practices from both domestic and international internet companies. Overall, the emphasis is on enhancing network resilience and readiness for future intelligent warfare scenarios through the deployment of SDN architecture networks.

Gholamrezaei *et al.* [92], present a learning-based strategy known as multi-constraint resilient controller placement and assignment (MCRCPA). This approach incorporates a comprehensive set of constraints, including resiliency, switch-to-controller delay, switch-to-controller reliability, inter-controller delay, and controller capacity in both primary and backup modes. The method employs a structure called constraint covering graph (CCG) to evaluate reliability and incorporate the specified constraints. The CCG is then transformed into a distributed learning model to accurately determine controller locations.

6. DISCUSSION AND OPEN ISSUES

Although SDN, NFV, and 5G technologies offer numerous advantages, they also present various challenges that need careful consideration. The challenge of optimal controller placement in SDN networks remains an open issue, necessitating further in-depth investigation to determine the best placement for achieving high network performance. Minimizing delays between switches is a critical consideration in SDN networks.

Designing SDN networks requires careful consideration of parameters to enhance controller fault tolerance. The selection and number of SDN controllers need to be carefully evaluated to optimize network efficiency. Some studies still face challenges related to high network traffic loads.

The integration of NFV in 5G networks poses challenges due to its inherent complexity. Ensuring the security of NFV in the 5G network is essential and requires measures comparable to those in proprietary hosting environments designed for network functions. As NFV represents a significant generational shift in network technology, real-world experiments are essential to measure, enhance, and better understand the consequences and implications. Limited research exists on security issues relevant to SDN networks. While SDN and NFV show promise in reducing operational expenditures (OPEX) and enhancing customer experience, challenges arise from the limited availability of vendor solutions and the slow adoption of technologies necessary for fully realizing the capabilities of SDN/NFV.

7. CONCLUSION AND FUTURE DIRECTIONS

The integration of 5G communication with SDN and NFV techniques represents a substantial advancement in modern communication technology. SDN introduces significant innovation in network programmability, while NFV networks have the potential to achieve heightened security levels compared to hardware-based networks. The synergy created by the combination of NFV and SDN in 5G networks is noteworthy. However, it is crucial to acknowledge that these techniques come with limitations, necessitating comprehensive studies and a focus on their challenges. This paper has explored the concepts of 5G, SDN, and NFV techniques, delving into associated challenges and open issues. A notable challenge discussed is the optimal placement of controllers (CPP). The drawbacks and contributions of state-of-the-art methods and techniques have been thoroughly examined.

Future work in this domain involves addressing the challenges and issues facing SDN networks, particularly concerning CPP. Developing an effective method for optimizing the placement of multiple controllers in a flexible manner is a crucial and demanding task in this intricate environment. Therefore, optimizing the deployment of multiple controllers within an SDN network is of utmost importance. Another avenue for future research is the investigation of the optimal number of SDN controllers required in the network to achieve energy and cost savings.

In conclusion, while SDN, NFV, and 5G technologies offer numerous advantages, recognizing and addressing their associated limitations and challenges is essential for their successful implementation. The open issue of optimal controller placement in SDN networks remains a focal point, requiring further investigation for achieving high network performance. Minimizing delays, enhancing fault tolerance, and carefully evaluating controller parameters are vital considerations. Challenges related to high network traffic loads and the integration of NFV in 5G networks also pose complexities. Real-world experiments and increased research efforts are necessary to overcome these challenges and fully realize the potential benefits of SDN, NFV, and 5G technologies.

REFERENCES

[1] R. Roux, T. O. Olwal, and D. S. P. Chowdhury, "Software defined networking architecture for energy transaction in smart microgrid systems," *Energies*, vol. 16, no. 14, p. 5275, 2023, doi: 10.3390/en16145275.

[2] D. Kreutz, F. M. V Ramos, P. E. Verissimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig, "Software-defined networking: a comprehensive survey," *Proceedings of the IEEE*, vol. 103, no. 1, pp. 14–76, 2014.

[3] F. Hu, Q. Hao, and K. Bao, "A survey on software-defined network and openflow: From concept to implementation," *IEEE Communications Surveys & Tutorials*, vol. 16, no. 4, pp. 2181–2206, 2014, doi: 10.1109/COMST.2014.2326417.

[4] T. Semong *et al.*, "Intelligent load balancing techniques in software defined networks: a survey," *Electronics*, vol. 9, no. 7, p. 1091, 2020, doi: 10.3390/electronics9071091.

[5] T. Das, V. Sridharan, and M. Gurusamy, "A survey on controller placement in SDN," *IEEE Communications Surveys & Tutorials*, vol. 22, no. 1, pp. 472–503, 2019, doi: 10.1109/COMST.2019.2935453.

[6] A. Bradai, M. H. Rehmani, I. Haque, M. Nogueira, and S. H. R. Bukhari, "Software-defined networking (SDN) and network function virtualization (NFV) for a hyperconnected world: challenges, applications, and major advancements," *Journal of Network and Systems Management*, vol. 28, no. 3. pp. 433–435, 2020, doi: 10.1007/s10922-020-09542-z.

[7] M. S. Kumar, "Analysis of network function virtualization and software defined virtualization," *JOIV: International Journal on Informatics Visualization*, vol. 1, no. 4, pp. 122–126, 2017, doi: 10.30630/joiv.1.4.40.

[8] R. Salam and A. Bhattacharya, "Efficient greedy heuristic approach for fault-tolerant distributed controller placement in scalable SDN architecture," *Cluster Computing*, vol. 25, no. 6, pp. 4543–4572, 2022, doi: 10.1007/s10586-022-03694-0.

[9] W. Kellerer, P. Kalmbach, A. Blenk, A. Basta, M. Reisslein, and S. Schmid, "Adaptable and data-driven softwarized networks: review, opportunities, and challenges," *Proceedings of the IEEE*, vol. 107, no. 4, pp. 711–731, 2019, doi: 10.1109/JPROC.2019.2895553.

[10] M. Karakus and A. Durresi, "A survey: control plane scalability issues and approaches in software-defined networking (SDN)," *Computer Networks*, vol. 112, pp. 279–293, 2017, doi: 10.1016/j.comnet.2016.11.017.

[11] M. Dhar, A. Debnath, B. K. Bhattacharyya, M. K. Debbarma, and S. Debbarma, "A comprehensive study of different objectives and solutions of controller placement problem in software-defined networks," *Transactions on Emerging Telecommunications Technologies*, vol. 33, no. 5, p. e4440, 2022.

[12] D. Kumar and C. Sharma, "Improved Load balancing for large-scale smart cities in SDN-IoT networks," in *2022 Second International Conference on Advanced Technologies in Intelligent Control, Environment, Computing & Communication Engineering (ICATIECE)*, 2022, pp. 1–5, doi: 10.1109/ICATIECE56365.2022.10047351.

[13] A. Jalili, M. Keshtgari, and R. Akbari, "A new framework for reliable control placement in software-defined networks based on multi-criteria clustering approach," *Soft Computing*, vol. 24, no. 4, pp. 2897–2916, 2020, doi: 10.1007/s00500-019-04070-8.

[14] G. Deep, V. Tripathi, and A. Dumka, "A review on controller placement problem in software defined networking," in *AIP Conference Proceedings*, 2023, vol. 2521, doi: 10.1063/5.0113880.

[15] B. Isong, R. R. S. Molose, A. M. Abu-Mahfouz, and N. Dladlu, "Comprehensive review of SDN controller placement strategies," *IEEE Access*, vol. 8, pp. 170070–170092, 2020, doi: 10.1109/ACCESS.2020.3023974.

[16] J. Lu, Z. Zhang, T. Hu, P. Yi, and J. Lan, "A survey of controller placement problem in software-defined networking," *IEEE Access*, vol. 7, pp. 24290–24307, 2019.

[17] A. Shirmarz and A. Ghaffari, "Taxonomy of controller placement problem (CPP) optimization in software defined network (SDN): a survey," *Journal of Ambient Intelligence and Humanized Computing*, vol. 12, no. 12, pp. 10473–10498, Jan. 2021, doi: 10.1007/s12652-020-02754-w.

[18] G. Wang, Y. Zhao, J. Huang, and W. Wang, "The controller placement problem in software defined networking: a survey," *IEEE Network*, vol. 31, no. 5, pp. 21–27, 2017, doi: 10.1109/MNET.2017.1600182.

[19] A. M. Medhat, G. A. Carella, M. Pauls, M. Monachesi, M. Corici, and T. Magedanz, "Resilient orchestration of service functions chains in a NFV environment," in *2016 IEEE Conference On Network Function Virtualization And Software Defined Networks (NFV-SDN)*, 2016, pp. 7–12, doi: 10.1109/NFV-SDN.2016.7919468.

[20] D. E. Sarmiento, A. Lebre, L. Nussbaum, and A. Chari, "Decentralized SDN control plane for a distributed cloud-edge infrastructure: a survey," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 1, pp. 256–281, 2021, doi: 10.1109/COMST.2021.3050297.

[21] S. Ahmad and A. H. Mir, "Scalability, consistency, reliability and security in SDN controllers: a survey of diverse SDN controllers," *Journal of Network and Systems Management*, vol. 29, no. 1, p. 59, Nov. 2021, doi: 10.1007/s10922-020-09575-4.

[22] M. Hamdan *et al.*, "A comprehensive survey of load balancing techniques in software-defined network," *Journal of Network and Computer Applications*, vol. 174, p. 102856, 2021, doi: 10.1016/j.jnca.2020.102856.

[23] Y. E. Oktian, S. Lee, H. Lee, and J. Lam, "Distributed SDN controller system: a survey on design choice," *Computer Networks*, vol. 121, pp. 100–111, 2017, doi: 10.1016/j.comnet.2017.04.038.

[24] K. M. Modieginyane, B. B. Letswamotse, R. Malekian, and A. M. Abu-Mahfouz, "Software defined wireless sensor networks application opportunities for efficient network management: a survey," *Computers & Electrical Engineering*, vol. 66, pp. 274–287, 2018, doi: 10.1016/j.compeleceng.2017.02.026.

[25] R. Masoudi and A. Ghaffari, "Software defined networks: a survey," *Journal of Network and Computer Applications*, vol. 67, pp. 1–25, 2016.

[26] E. O. Zaballa, D. Franco, E. Jacob, M. Higuero, and M. S. Berger, "Automation of modular and programmable control and data plane SDN networks," in *2021 17th International Conference on Network and Service Management (CNSM)*, 2021, pp. 375–379, doi: 10.23919/CNSM52442.2021.9615508.

[27] M. Caprolu, S. Raponi, and R. Di Pietro, "Fortress: an efficient and distributed firewall for stateful data plane sdn," *Security and Communication Networks*, vol. 2019, 2019, doi: 10.1155/2019/6874592.

[28] M. Bhuyan, S. Kashihara, D. Fall, Y. Taenaka, and Y. Kadobayashi, "A survey on blockchain, SDN and NFV for the smart-home security," *Internet of Things*, p. 100588, 2022.

[29] G. Ramya and R. Manoharan, "Traffic-aware dynamic controller placement in SDN using NFV," *The Journal of Supercomputing*, vol. 79, no. 2, pp. 2082–2107, 2023, doi: 10.1007/s11227-022-04717-8.

[30] S. P. Biswal and S. Patel, "Introduction to software defined networking," *Software Defined Networks: Architecture and Applications*, pp. 1–27, 2022.

[31] T. Zhang, L. Linguaglossa, P. Giaccone, L. Iannone, and J. Roberts, "Performance benchmarking of state-of-the-art software switches for NFV," *Computer Networks*, vol. 188, p. 107861, 2021, doi: 10.1016/j.comnet.2021.107861.

[32] J. Medved, R. Varga, A. Tkacik, and K. Gray, "Opendaylight: towards a model-driven SDN controller architecture," in *Proceeding of IEEE international symposium on a world of wireless, mobile and multimedia networks 2014*, 2014, pp. 1–6, doi: 10.1109/WoWMoM.2014.6918985.

[33] H. U. Adoga and D. P. Pezaros, "Network function virtualization and service function chaining frameworks: a comprehensive review of requirements, objectives, implementations, and open research challenges," *Future Internet*, vol. 14, no. 2, 2022, doi: 10.3390/fi14020059.

[34] M. Pattaranantakul, R. He, Q. Song, Z. Zhang, and A. Meddahi, "NFV security survey: From use case driven threat analysis to state-of-the-art countermeasures," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 4, pp. 3330–3368, 2018, doi: 10.1109/COMST.2018.2859449.

[35] Q. Duan, N. Ansari, and M. Toy, "Software-defined network virtualization: an architectural framework for integrating SDN and NFV for service provisioning in future networks," *IEEE Network*, vol. 30, no. 5, pp. 10–16, Sep. 2016, doi: 10.1109/MNET.2016.7579021.

[36] A. Binu and G. S. Kumar, "Virtualization techniques: a methodical review of XEN and KVM," in *Advances in Computing and Communications: First International Conference, ACC 2011, Kochi, India, July 22-24, 2011. Proceedings, Part I 1*, 2011, pp. 399–410, doi: 10.1007/978-3-642-22709-7_40.
[37] S. K. N. Rao, "SDN and its use-cases-NV and NFV," *Network*, vol. 2, p. H6, 2014.
[38] J. Gil-Herrera and J. F. Botero, "A scalable metaheuristic for service function chain composition," in *2017 IEEE 9th Latin-American Conference on Communications (LATINCOM)*, 2017, pp. 1–6, doi: 10.1109/LATINCOM.2017.8240194.
[39] A. M. Medhat, T. Taleb, A. Elmangoush, G. A. Carella, S. Covaci, and T. Magedanz, "Service function chaining in next generation networks: state of the art and research challenges," *IEEE Communications Magazine*, vol. 55, no. 2, pp. 216–223, 2016.
[40] B. Koné and A. D. Kora, "Management and orchestration for network function virtualization in a VoIP testbed: a multi-domain case," in *2021 44th International Conference on Telecommunications and Signal Processing (TSP)*, 2021, pp. 372–376.
[41] Y. O. Imam-Fulani *et al.*, "5G frequency standardization, technologies, channel models, and network deployment: advances, challenges, and future directions," *Sustainability*, vol. 15, no. 6, p. 5173, 2023, doi: 10.3390/su15065173.
[42] Y. Boujelben, "Scalable and QoS-aware resource allocation to heterogeneous traffic flows in 5G," *IEEE Internet of Things Journal*, vol. 8, no. 20, pp. 15568–15581, 2021, doi: 10.1109/JIOT.2021.3074111.
[43] G. Nencioni, R. G. Garroppo, A. J. Gonzalez, B. E. Helvik, and G. Procissi, "Orchestration and control in software-defined 5G networks: research challenges," *Wireless Communications And Mobile Computing*, vol. 2018, 2018, doi: 10.1155/2018/6923867.
[44] T. Taleb, A. Ksentini, and R. Jantti, "'Anything as a service' for 5G mobile systems," *IEEE Network*, vol. 30, no. 6, pp. 84–91, 2016, doi: 10.1109/MNET.2016.1500244RP.
[45] S. Clayman, E. Maini, A. Galis, A. Manzalini, and N. Mazzocca, "The dynamic placement of virtual network functions," in *2014 IEEE Network Operations And Management Symposium (NOMS)*, 2014, pp. 1–9, doi: 10.1109/NOMS.2014.6838412.
[46] P. Schulz *et al.*, "Latency critical IoT applications in 5G: perspective on the design of radio interface and network architecture," *IEEE Communications Magazine*, vol. 55, no. 2, pp. 70–78, 20177, doi: 10.1109/MCOM.2017.1600435CM.
[47] P. Yang, N. Zhang, Y. Bi, L. Yu, and X. S. Shen, "Catalyzing cloud-fog interoperation in 5G wireless networks: an SDN approach," *IEEE Network*, vol. 31, no. 5, pp. 14–20, 2017, doi: 10.1109/MNET.2017.1600078.
[48] B. Han, J. Lianghai, and H. D. Schotten, "Slice as an evolutionary service: genetic optimization for inter-slice resource management in 5G networks," *IEEE Access*, vol. 6, pp. 33137–33147, 2018, doi: 10.1109/ACCESS.2018.2846543.
[49] A. Moradi, A. Abdi Seyedkolaei, and S. A. Hosseini, "Controller placement in software defined network using iterated local search," *Journal of AI and Data Mining*, vol. 8, no. 1, pp. 55–65, 2020, doi: 10.22044/JADM.2019.7934.1931.
[50] X. Zhang, L. Li, and C. Yan, "Robust controller placement based on load balancing in software defined networks," in *2020 IEEE International Conference on Networking, Sensing and Control (ICNSC)*, 2020, pp. 1–6, doi: 10.1109/ICNSC48988.2020.9238066.
[51] Y. Fan, L. Wang, and X. Yuan, "Controller placements for latency minimization of both primary and backup paths in SDNs," *Computer Communications*, vol. 163, pp. 35–50, 2020, doi: 10.1016/j.comcom.2020.09.001.
[52] N. Lin, Q. Zhao, L. Zhao, A. Hawbani, L. Liu, and G. Min, "A novel cost-effective controller placement scheme for software-defined vehicular networks," *IEEE Internet of Things Journal*, vol. 8, no. 18, pp. 14080–14093, 2021, doi: 10.1109/JIOT.2021.3069878.
[53] B. Balakiruthiga and P. Deepalakshmi, "A distributed energy aware controller placement model for software-defined data centre network," *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, vol. 45, no. 4, pp. 1083–1101, 2021, doi: 10.1007/s40998-021-00425-w.
[54] B. R. Killi and S. V. Rao, "Poly-stable matching based scalable controller placement with balancing constraints in SDN," *Computer Communications*, vol. 154, pp. 82–91, 2020, doi: 10.1016/j.comcom.2020.02.053.
[55] D. Santos, T. Gomes, and D. Tipper, "SDN controller placement with availability upgrade under delay and geodiversity constraints," *IEEE Transactions on Network and Service Management*, vol. 18, no. 1, pp. 301–314, 2021, doi: 10.1109/TNSM.2020.3049013.
[56] A. Alowa and T. Fevens, "Towards minimum inter-controller delay time in software defined networking," *Procedia Computer Science*, vol. 175, pp. 395–402, 2020, doi: 10.1016/j.procs.2020.07.056.
[57] E. Amiri, E. Alizadeh, and M. H. Rezvani, "Controller selection in software defined networks using best-worst multi-criteria decision-making," *Bulletin of Electrical Engineering and Informatics*, vol. 9, no. 4, pp. 1506–1517, 2020, doi: 10.11591/eei.v9i4.2393.
[58] A. Dvir, Y. Haddad, and A. Zilberman, "The controller placement problem for wireless SDN," *Wireless Networks*, vol. 25, pp. 4963–4978, 2019, doi: 10.1007/s11276-019-02077-5.
[59] E. Calle, D. Martínez, M. Mycek, and M. Pióro, "Resilient backup controller placement in distributed SDN under critical targeted attacks," *International Journal of Critical Infrastructure Protection*, vol. 33, p. 100422, 2021, doi: 10.1016/j.ijcip.2021.100422.
[60] D. Santos and T. Gomes, "Joint optimization of primary and backup controller placement and availability link upgrade in SDN networks," *Optical Switching and Networking*, vol. 42, p. 100634, 2021, doi: 10.1016/j.osn.2021.100634.
[61] G. Yao, J. Bi, Y. Li, and L. Guo, "On the capacitated controller placement problem in software defined networks," *IEEE Communications Letters*, vol. 18, no. 8, pp. 1339–1342, 2014, doi: 10.1109/LCOMM.2014.2332341.
[62] M. He, A. Basta, A. Blenk, and W. Kellerer, "Modeling flow setup time for controller placement in SDN: evaluation for dynamic flows," in *2017 IEEE International Conference on Communications (ICC)*, 2017, pp. 1–7, doi: 10.1109/ICC.2017.7996654.
[63] T. Wang, F. Liu, J. Guo, and H. Xu, "Dynamic SDN controller assignment in data center networks: stable matching with transfers," in *IEEE INFOCOM 2016-The 35th Annual IEEE International Conference on Computer Communications*, 2016, pp. 1–9, doi: 10.1109/INFOCOM.2016.7524357.
[64] G. Li, X. Wang, and Z. Zhang, "SDN-based load balancing scheme for multi-controller deployment," *IEEE Access*, vol. 7, pp. 39612–39622, 2019, doi: 10.1109/ACCESS.2019.2906683.
[65] T. Wang, F. Liu, and H. Xu, "An efficient online algorithm for dynamic SDN controller assignment in data center networks," *IEEE/ACM Transactions on Networking*, vol. 25, no. 5, pp. 2788–2801, 2017, doi: 10.1109/TNET.2017.2711641.
[66] A. A. Z. Ibrahim, F. Hashim, N. K. Noordin, A. Sali, K. Navaie, and S. M. E. Fadul, "Heuristic resource allocation algorithm for controller placement in multi-control 5G based on SDN/NFV architecture," *IEEE Access*, vol. 9, pp. 2602–2617, 2020, doi: 10.1109/ACCESS.2020.3047210.

[67] E. Vaezpour, "Deep learning-driven multi-objective dynamic switch migration in software defined networking (SDN)/network function virtualization (NFV)-based 5G networks," *Engineering Applications of Artificial Intelligence*, vol. 125, p. 106714, 2023, doi: 10.1016/j.engappai.2023.106714.

[68] R. C. Meena *et al.*, "Enhancing software-defined networks with intelligent controllers to improve first packet processing period," *Electronics*, vol. 12, no. 3, p. 600, 2023, doi: 10.3390/electronics12030600.

[69] A. F. Pakpahan and I. S. Hwang, "Flexible access network multi-tenancy using NFV/SDN in TWDM-PON," *IEEE Access*, vol. 11, pp. 42937–42948, 2023, doi: 10.1109/ACCESS.2023.3271142.

[70] A. A. Qaffas, S. Kamal, F. Sayeed, P. Dutta, S. Joshi, and I. Alhassan, "Adaptive population-based multi-objective optimization in SDN controllers for cost optimization," *Physical Communication*, vol. 58, p. 102006, 2023, doi: 10.1016/j.phycom.2023.102006.

[71] S. P. Praveen, P. Sarala, T. N. S. K. M. Kumar, S. G. Manuri, V. S. Srinivas, and D. Swapna, "An adaptive load balancing technique for multi SDN controllers," in *2022 International Conference on Augmented Intelligence and Sustainable Systems (ICAISS)*, 2022, pp. 1403–1409, doi: 10.1109/ICAISS55157.2022.10010881.

[72] G. R. Sreekanth, S. A. N. Ahmed, M. Sarac, I. Strumberger, N. Bacanin, and M. Zivkovic, "Mobile fog computing by using SDN/NFV on 5G edge nodes," *Computer Systems Science and Engineering*, vol. 41, no. 2, pp. 751–765, 2022, doi: 10.32604/csse.2022.020534.

[73] N. Firouz, M. Masdari, A. B. Sangar, and K. Majidzadeh, "A novel controller placement algorithm based on network portioning concept and a hybrid discrete optimization algorithm for multi-controller software-defined networks," *Cluster Computing*, vol. 24, pp. 2511–2544, 2021, doi: 10.1007/s10586-021-03264-w.

[74] L. Liao, V. C. M. Leung, Z. Li, and H.-C. Chao, "Genetic algorithms with variant particle swarm optimization based mutation for generic controller placement in software-defined networks," *Symmetry*, vol. 13, no. 7, p. 1133, 2021, doi: 10.3390/sym13071133.

[75] M. Dhar, B. K. Bhattacharyya, M. Kanti Debbarma, and S. Debbarma, "A new optimization technique to solve the latency aware controller placement problem in software defined networks," *Transactions on Emerging Telecommunications Technologies*, vol. 32, no. 10, p. e4316, 2021, doi: 10.1002/ett.4316.

[76] Y. Li, S. Guan, C. Zhang, and W. Sun, "Parameter optimization model of heuristic algorithms for controller placement problem in large-scale SDN," *IEEE Access*, vol. 8, pp. 151668–151680, 2020, doi: 10.1109/ACCESS.2020.3017673.

[77] K. Qu, W. Zhuang, Q. Ye, X. Shen, X. Li, and J. Rao, "Traffic engineering for service-oriented 5G networks with SDN-NFV integration," *IEEE Network*, vol. 34, no. 4, pp. 234–241, 2020, doi: 10.1109/MNET.001.1900508.

[78] M. D'Arienzo, M. Napolitano, S. Pietro Romano, and others, "Controller placement problem resiliency evaluation in SDN-based architectures," *International Journal Of Computer Networks And CommunicationS*, vol. 14, no. 5, pp. 101–116, 2022, doi: 10.5121/ijcnc.2022.14507.

[79] F. J. Ros and P. M. Ruiz, "On reliable controller placements in software-defined networks," *Computer Communications*, vol. 77, pp. 41–51, 2016, doi: 10.1016/j.comcom.2015.09.008.

[80] M. Guo and P. Bhattacharya, "Controller placement for improving resilience of software-defined networks," in *2013 Fourth International Conference on Networking and Distributed Computing*, 2013, pp. 23–27, doi: :10.1109/ICNDC.2013.15.

[81] P. Vizarreta, C. M. Machuca, and W. Kellerer, "Controller placement strategies for a resilient SDN control plane," in *2016 8th International Workshop On Resilient Networks Design And Modeling (RNDM)*, 2016, pp. 253–259, doi: 10.1109/RNDM.2016.7608295.

[82] M. Tanha, D. Sajjadi, and J. Pan, "Enduring node failures through resilient controller placement for software defined networks," in *2016 IEEE Global Communications Conference (GLOBECOM)*, 2016, pp. 1–7, doi: 10.1109/GLOCOM.2016.7841786.

[83] R. Chaudhary and N. Kumar, "PARC: placement availability resilient controller scheme for software-defined datacenters," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 8, pp. 8985–9001, 2020, doi: 10.1109/TVT.2020.2999072.

[84] N. Perrot and T. Reynaud, "Optimal placement of controllers in a resilient SDN architecture," in *2016 12th International Conference on the Design of Reliable Communication Networks (DRCN)*, 2016, pp. 145–151, doi: 10.1109/DRCN.2016.7470849.

[85] J. Liu, J. Liu, and R. Xie, "Reliability-based controller placement algorithm in software defined networking," *Computer Science and Information Systems*, vol. 13, no. 2, pp. 547–560, 2016, doi: 10.2298/CSIS160225014L.

[86] F. Bannour, S. Souihi, and A. Mellouk, "Scalability and reliability aware SDN controller placement strategies," in *2017 13th International Conference on Network and Service Management (CNSM)*, 2017, pp. 1–4, doi: 10.23919/CNSM.2017.8255989.

[87] M. Tanha, D. Sajjadi, R. Ruby, and J. Pan, "Capacity-aware and delay-guaranteed resilient controller placement for software-defined WANs," *IEEE Transactions on Network and Service Management*, vol. 15, no. 3, pp. 991–1005, 2018, doi: 10.1109/TNSM.2018.2829661.

[88] Z. Fan, J. Yao, X. Yang, Z. Wang, and X. Wan, "A multi-controller placement strategy based on delay and reliability optimization in SDN," in *2019 28th Wireless And Optical Communications Conference (WOCC)*, 2019, pp. 1–5, doi: 10.1109/WOCC.2019.8770551.

[89] B. P. R. Killi and S. V. Rao, "Towards improving resilience of controller placement with minimum backup capacity in software defined networks," *Computer Networks*, vol. 149, pp. 102–114, 2019, doi: 10.1016/j.comnet.2018.11.027.

[90] S. Dou, G. Miao, Z. Guo, C. Yao, W. Wu, and Y. Xia, "Matchmaker: maintaining network programmability for software-defined WANs under multiple controller failures," *Computer Networks*, vol. 192, p. 108045, 2021, doi: 10.1016/j.comnet.2021.108045.

[91] Y. A. N. Guozhu, Q. Wu, R. Chen, L. Du, and S. Ren, "A Literature review of resiliency technologies in military software defined networks," in *2022 5th International Conference on Data Science and Information Technology (DSIT)*, 2022, pp. 1–7, doi: 10.1109/DSIT55514.2022.9943919.

[92] R. Gholamrezaei, G. Mirjalily, and S. Emadi, "Learning-based multi-constraint resilient controller placement and assignment in software-defined networks using covering graph," *Transactions on Emerging Telecommunications Technologies*, vol. 34, no. 4, p. e4742, 2023, doi: 10.1002/ett.4742.

BIOGRAPHIES OF AUTHORS

Samer Mohammed Rasool received his B.Sc. degree in Computer Engineering from the Islamic University of Najaf, Iraq, in 2011, and M.Sc. degree in Computer Science (Internetworking Technology) from Universiti Teknikal Malaysia Melaka (UTeM) in 2015. Since February 2021, he is pursuing a doctorate program in Science and Technologies of Information and Communication (STIC) at the École Nationale d'Électronique et des Télécommunications de Sfax (ENETCom), University of Sfax, Tunisia. He is working at the National University of Science and Technology, Dhi Qar, Iraq, in the Faculty of Pharmacy. He has experience in computer science, with an emphasis on computer networks, security, embedded systems, and distributed computing. He can be contacted at email: samermoon53@gmail.com.

Yassine Boujelben is an associate professor at the École Nationale d'Électronique et des Télécommunications de Sfax (ENETCom), University of Sfax, Tunisia. He received the Dipl.-Ing. degree in Telecommunications from the École Supérieure des Communications de Tunis, Tunisia, in 1996, the M.Sc. degree in Systems Analysis and Digital Processing from the École Nationale d'Ingénieurs de Tunis, Tunisia, in 1996, and the Ph.D. degree in Telecommunications from the Institut National de la Recherche Scientifique, Centre Énergie Matériaux Télécommunications (INRS-EMT), University of Quebec, Montreal, Canada, in 2003. His current research interests include network support for cloud gaming, QoS management for multimedia services and resource optimization in IoT networks. He can be contacted at email: yassine.boujelben@enetcom.usf.tn.

Faouzi Zarai received the Engineering Diploma, Master Diploma, and Ph.D. in Information and Communication Technologies from the Engineering School of Communications (Sup'Com, Tunisia) in 2002, 2003, and 2007; respectively. From 2002 to 2005 he has worked for the National Digital Certification Agency (NDCA, Tunisia). Since 2011, he serves on the editorial boards of the International Journal of Communication Systems. He published one book and 5 chapters and co-authored more than 200 papers that have been published in international journals and conferences. Currently, he is serving as professor for the National School of Electronic and Telecommunications Sfax (ENET'COM). Since 2016, he is Director of the research unit of News Technologies and Telecommunications Systems (NTS'COM). He is conducting research activities in the areas of security and Quality of services in new generations wireless. He can be contacted at email: faouzi.zerai@enetcom.usf.tn.