A CRITICAL ANALYSIS AND REVIEW OF THE CONTROLLER PLACEMENT PROBLEM IN 5G SDN SECURED NETWORKS. OPEN ISSUES AND POSSIBLE SOLUTIONS

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Abstract: *This paper attempts a critical analysis of the Controller Placement Problem (CPP) in Software-Defined Networking (SDN) environments, identifies open issues and exploring potential solutions. The strategies to solve the CPP are examined aiming to enhance network performance, scalability, and resilience. SDN is a powerful technology used more and more in different networks. In particular the SDN control is a strong candidate proposed in 5G architectures. This study considers various aspects of CPP, including latency, reliability, and effective load distribution, which are also important in the context of 5G networks. The analysis reviews existing literature, revealing gaps in current strategies, particularly in addressing the dynamic nature of 5G architectures. Special attention is given to the multi-Controller contexts encountered in large networks, where Multi-controller Placement Problem (MCPP) emerges. This overview not only underscores the criticality of CPP in 5G SDN but also outlines some future research directions by our original proposal for a generic architecture for dynamic optimization in CPP.*

Keywords*: 5G networks, Software-defined networking (SDN), Controller placement problem (CPP), Multi-Controller Placement Problem (MCPP), network performance, latency in SDN, 5G SDN scalability*

1. INTRODUCTION

The complex 5G networks, currently developed in the real world, need powerful management and control systems. The integration of Software-Defined Networking (SDN) and Network Function Virtualization (NFV) technologies offer a flexible solution, already adopted in 5G architectures and standards. Usage of intensive virtualization techniques in both SDN and NFV offer the possibility of integration with cloud computing. However, the challenge of effectively integrating SDN and NFV within 5G framework remains a vital topic. This evolution is not limited to just improving the existing infrastructure but marks a strategic transition to more flexible and adaptable network systems, enhanced with cloud computing capabilities.

In SDN based networks a major problem is where to place the SDN controller. This is called controller placement problem (CPP). In large networks where multiple controllers are used, the problem is still more important. Multi-controller implementation of the SDN control plane for large networks can solve the scalability and reliability issues introduced by the SDN centralized logical control principle.

Note that multiple criteria may exist in selection of a particular solution for a Multi-Controller Placement Problem (MCPP). Therefore, a critical analysis of challenges and potential solutions is necessary, to offer the basis for an appropriate design, aiming to meet the requirements and assure the scalability and flexibility. This includes investigating optimal strategies for placing the SDN controller. Such optimizations have as objectives a well-balanced load among the controllers in set, a good real-time response to network events and adaptation to the dynamic requirements of data traffic and services in 5G networks.

This article explores and addresses several challenges in the deployment and optimization of 5G networks using SDN technology. It aims to provide insights into optimizing controller deployment for efficient network management and performance in the rapidly evolving 5G landscape.

Section 2 presents a short overview of related literature. Section 3 outlines the SDN–NFV cooperation within 5G Architectures, to illustrate the role of the SDN control. In Section 4 a few network security and performance issues are summarized. Section 5 defines the CPP topic while Section 6 identifies and analyses the applicable strategies. Section 7 summarizes the conclusions.

2. LITERATURE REVIEW

The study by Kumari and Sairam [1] was one of the first to approach CPP from an optimization perspective, identifying four main areas of criteria considered in the literature: reliability, latency, cost, and multiple objectives. They analyzed specific algorithms for various application scenarios, highlighting the complexity and diversity of this issue [2].

The research conducted by Fancy and Pushpalatha [3] examined different CPP resolution techniques, focusing on various metrics and the characteristics of the proposed solutions. The study also emphasized the importance of optimizing the relationship between controllers and switches, considering this an essential aspect for the efficiency of SDN networks.

The work [4] by Ayo et al. explored CPP in two distinct scenarios: minimizing the number of controllers and optimizing their locations. Their approach highlighted the complexity and tradeoff in choosing between a low number of controllers with extended capabilities versus a broader distribution with reduced individual capacity. This indicates that solutions for CPP must consider a wide range of factors, including the communication latency between switches and controllers, as well as among the controllers themselves.

Another essential aspect in CPP is the dependence of the optimal solution, on topology and the controller load factor. This is an example of the multi-criterial characteristics of the CP problem. The study by Rahman et al. [5] demonstrated the usefulness of a heuristic algorithm to dynamically manage the controller load, taking into account the average flow requests between switches and controllers. This highlights that the proposed solutions for CPP must be flexible and adaptable to different network configurations and traffic variations.

Richard Wang et al. [6] proposed using wildcard rules in the matching tuple to reduce the load on the controller. Wildcard rules in OpenFlow switches are used to handle large volumes of client traffic without involving a central SDN controller for each connection. These rules are generated by algorithms such as "partitioning algorithms" to efficiently distribute traffic across server replicas.

During conversion, microflow rules are temporarily installed by the controller to ensure that ongoing connections on the original replica are intact, thereby reducing interruptions and controller involvement in routine traffic processing. This approach minimizes the load on the SDN controller and enables scalable and adaptive server load balancing

A persistent challenge in the field of CPP is determining the optimal number of controllers and also their strategic placement in the network. Studies [7] and [8] have addressed these aspects, emphasizing that the placement and number of controllers are essential for balancing the load in the network and ensuring efficient traffic distribution. This is crucial to ensure optimal performance and enhanced resilience in 5G networks.

The study [9] revealed that HTTP applications constitute a significant proportion of internet traffic, necessitating a strategic approach in managing this traffic through OpenFlow switches. This underscores the importance of considering the predominant types of traffic in the design and implementation of CPP solutions.

The proposed approaches the CPP from heuristic solutions to optimized algorithms for controller load management, demonstrating the complexity and multidimensional nature of CPP. It is evident that any viable solution for CPP must be robust, flexible, and consider a multitude of factors, including network topology, data traffic, and controller capacity. Last but not least the scalability of solution should be considered.

3. SDN – NFV COOPERATION WITHIN 5G ARCHITECTURES

The SDN and NFV - based management and control entities are proposed as main cooperating functional components in 5G architectures [10], [11], [12]. This approach is also used in 5G network slicing. Two types of SDN of controllers are embedded in the general NFV reference architecture. Each controller centralizes the control plane functionalities and provides an abstract view of all the connectivity-related components it manages (Fig. 1).

- *Infrastructure SDN controller (IC)- sets up and manages the underlying networking resources* to provide the required connectivity for communicating the virtualised network functions VNFs (and their components); The Virtual Infrastructure Manager (VIM) manages the ICs; the IC may change on-demand the infrastructure behaviour, according to VIM specifications, adapted from tenant requests. IC provides an underlay to support the deployment and connectivity of VNFs.
- *Tenant SDN controller (TC)-* (Note that the tenant is defined as a generic user of a slice) is instantiated in the tenant domain - as one of the VNFs, or as part of the Network Management System (NMS); *TC dynamically manages the pertinent VNFs* used to realize the tenant's network service(s). These VNFs play the role of an underlying forwarding plane resources of the TC. The applications running on top of TC (e.g., the Operation System Support - OSS) triggers the operation and management tasks that the TC carries out. Each tenant can independently manage on its slice(s). TC provides an overlay comprising tenant VNFs that, properly composed, define the network service(s).

The controllers' southbound interfaces can use programmable protocols (e.g., OpenFlow, NETCONF or I2RS).

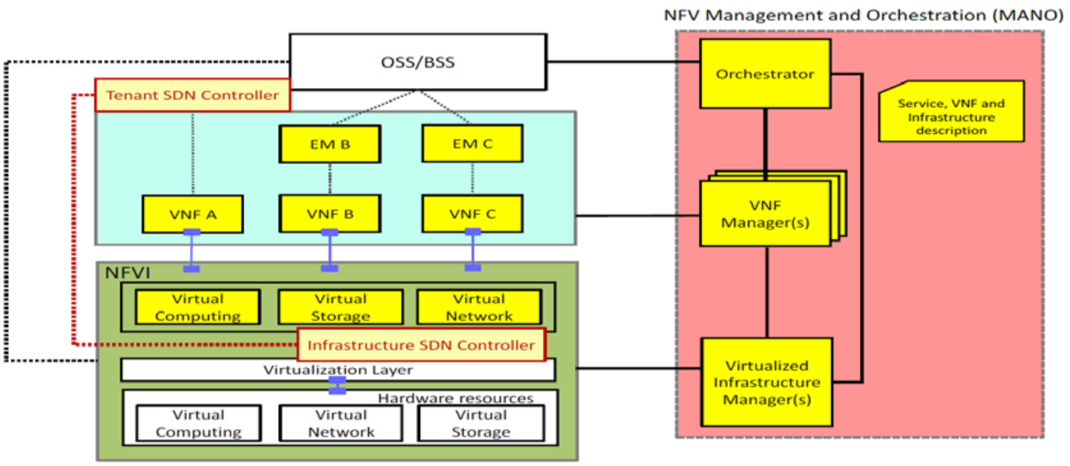

FIG. 1. Two levels of SDN controllers in 5G NFV-SDN based architecture (to achieve slicing) [source: ONF-2016-TR256]

The SDN have controller's different views on resources. The IC is not aware of the number of slices that utilize the VNFs it connects, nor the tenant(s) which operates such slices. For the TC the network is abstracted in terms of VNFs. The TC does not know how those VNFs are physically deployed. However, the IC and TC have to coordinate and synchronize their actions. The service and tenant concept mentioned here can be extended to higher abstraction layers by applying the recursion principle.

The problem placement of SDN controllers (CPP) is particularly of interest for Infrastructure Controllers (IC) in large 5G networks, given the geographical distribution of the network regions.

4. NETWORK SECURITY AND PERFORMANCE

Enhanced network security directly influences performance, ensuring reliability. It involves protective measures, like firewalls and intrusion detection systems, guarding data integrity and confidentiality. Encryption, e.g., SSL/TLS, secures data in transit. High-performance networks feature swift data transfer, low latency, and minimal errors. Software-Defined Networking (SDN) and Network Function Virtualization (NFV) enhance performance. Balancing security with performance is essential. Latency, crucial in SDN, varies based on factors like controller placement. Researchers propose solutions, such as considering propagation latency, integrating metrics like throughput, and reducing controller-switch latency.

As for 5G, the 5th generation of mobile communications brings numerous improvements compared to the previous generation such as:

- Use of AES-256 versus AES-128 used for data encryption and privacy within 4G;
- Network segmentation to isolate different parts of the network;
- Optimized support for IoT communication;
- Mutual authentication between device and network;
- "Lightweight" encryption to facilitate secure communication between IoT devices with low power consumption. Among the standardized algorithms, we mention SIMON and SPECK (NSA, 2014).

In CPP placement context, securing the control architectural plane involves protecting and securing the communication channels for messages exchanged between network devices and the controller, implementing strong authentication mechanisms within the control plane to prevent unauthorized access and implement security measures to protect the controller as it manipulates the entire network.

5. CONTROLLER PLACEMENT PROBLEM IN SDN

SDN Controller Placement Problem (CPP) has as main target to find an appropriate distribution of controllers, while meeting different criteria of optimization. A single controller is insufficient to manage large-scale networks, necessitating the use of multiple controllers to ensure proper network control and scalability. The CPP result is to determine the optimal number of controllers [13] and their strategic locations within the SDN network, while meeting the requirements and, in particular, specific scalability and Quality of Service (QoS) needs.

Fig.2 illustrates the architecture of a multi-controller SDN network still able to construct a logically centralized vision on the network. In this configuration, the data path is marked with a red line, while the control path is represented with dashed lines, demonstrating a clear and efficient separation between the two essential functions in the SDN network architecture [14]. Therefore, addressing CPP in SDN requires careful analysis of the network topology and specific requirements to ensure efficient and scalable network management.

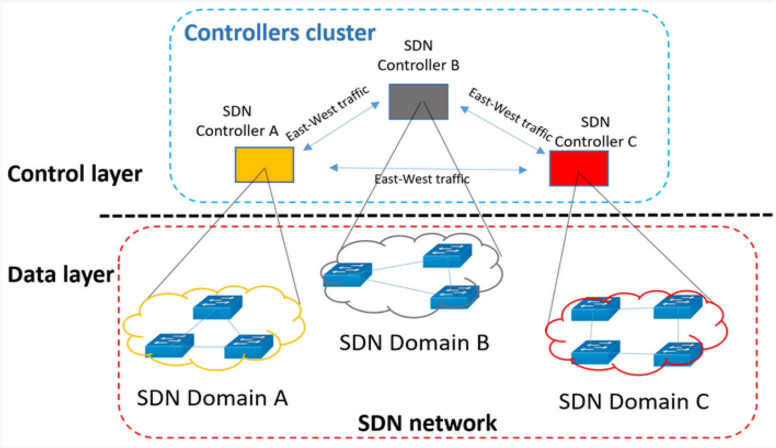

FIG. 2. Multi-controller SDN architecture

In an SDN controller’s distributed architecture, network performance fundamentally depends on controller placement. This problem is still valid in a single physical controller case, though the problem is less impactful. Heller, Sherwood, and McKeown formulated the CPP in [15] as a facility location issue. They use metrics such as average latency and worst-case latency to optimize controller layout. Through a comprehensive topology analysis, they show that in many cases a single controller is sufficient to achieve response time targets. The study highlights the trade-offs between optimizing for average and worst-case latency and provides practical guidance for SDN deployments. According to [16], a single controller is deemed sufficient for managing networks in most SDN-based networks. A significant issue in the single controller system is a single point of failure. Conversely, in large-scale networks, a single controller can act as a network bottleneck and create performance issues.

Hence, in larger networks, multiple controllers are necessary. This point is vital for enhancing network performance, latency between forwarding elements and controllers, network reliability and robustness, and scalability.

The core of CPP lies in determining the optimal number and locations of controllers within an SDN network, a challenge that significantly impacts performance, reliability, and efficiency. The infrastructure is commonly modeled as a graph, $G = (V, E, U)$, where V represents the set of switches, E the set of physical links, and U the set of controllers [17]. The goal is to optimize the value of k (number of controllers) and the $U \rightarrow V$ mapping, aiming to minimize, e.g., switches-controllers communication latency as the primary objective.

CPP studies often consider the shortest path lengths between each pair of nodes, with the minimization of delay as a key goal in the optimization function [18]. The CPP is an optimization challenge that can be based on data or various metrics to find the minimum or maximum cost like the optimal number of controllers, SC delay, or controller synchronization time [19][20]. This approach aids in determining the number, types, and placement locations of controllers, crucial for network performance and service quality.

CPP is recognized as a non-deterministic NP-hard problem, similar to the facility location problem, necessitating intelligent planning and decision-making to achieve optimal placement and satisfactory results [21][22].

In the placement of multiple controllers, several factors impact SDN performance, including reliability, controller load balancing, latency, operational costs, and event response time. These factors can be explored in more detail as follows:

→ Latency in the control plane is a crucial factor in CPP, heavily influenced by the distance between network nodes. Propagation and processing times are significant for packet transmission. Propagation latency is the response time between controllers or switches, affected by their distance. Additionally, processing latency is strongly affected by controller load. Optimizing latencies affects both controller-to-controller (CC) and switch-controller (SC) delays. SC latency exceeding a threshold leads to increased network latency, affecting network responsiveness.

→ Controller load balancing is essential as an increasing number of switches controlled by a single controller can overload it, resulting in queuing delays and unprocessed requests. Achieving balanced load distribution among SCs is challenging when minimizing controllers and switch allocations.

→ Fault tolerance is vital, as the loss of a controller directly impacts the switches it controls, hindering network functions. Reducing the number of controllers while ensuring reliability is critical in order to maintain continuous network functionality and minimizing **downtime.**

→ Determining the optimal number of controllers becomes complex with unplanned switches linked to a controller, impacting network performance. Various approaches, such as traversal searching, are time-consuming when seeking optimal performance.

→ Cost considerations play a significant role in deploying controllers efficiently, affecting overall expenditure. Balancing CAPEX and OPEX is essential in minimizing costs.

→ Inter-controller communication is essential for maintaining global consistency in SDN. Communication between controllers influences the end-to-end communication performance among switches under different controllers. Optimizing the controllers' placements in such a context is necessary, in order to achieve a high efficiency of the control plane, seen as a whole.

Several specific algorithms have been developed to find an optimum solution for a single given criterion; however, the optimization for MCPP problem is natively a multi-criteria one, (as it was shown above). The objective is to achieve an overall optimization on controller placement, by applying multi-criteria decision algorithms (MCDA) [23][24]. The input of MCDA is a set of candidates (here an instance of controller placement is called a candidate solution). In the optimization process different criteria can be assigned different weights, depending on particular objectives of the network owner.

6. STRATEGIES

Software-Defined Networking (SDN) faces complex challenges, including controller scalability, network latency, load balancing, and cost-efficiency.

Addressing the challenges in SDN networks involves complex issues such as scalability, reliability, and delay optimization.

For these types of problems, there are some possible solutions as shown in the following table:

Table 1. Overview of some problems

Problem	Possible solution
Scalability	Distributed controller deployment
Reliability	Redundant controller configurations
Delay optimization	Strategic controller placement

One of the primary challenges in SDN networks is ensuring that the architecture can scale effectively to accommodate growing network demands. As networks expand, the centralized control plane may become overwhelmed, leading to performance bottlenecks and decreased network efficiency.

One solution to address scalability challenges is the deployment of multiple distributed controllers. Each controller is responsible for a specific segment or domain of the network; thus, the load on any individual controller is lower. The controllers can handle a portion of the network's traffic independently.

A unique controller in an SDN network is a single point of failure). To enhance reliability, redundant controller configurations can be implemented. This involves setting up backup controllers that are ready to take over in the event of a primary controller failure. These backup controllers are kept synchronized with the primary controller's state so that they can seamlessly assume control of the network if needed. This approach minimizes downtime and ensures continuous network operation, even when the primary controller encounters issues.

Minimizing delay or latency in SDN networks is crucial for delivering real-time services and improving the overall user experience. High latency can lead to delays in data transmission and processing, negatively impacting applications like video conferencing and online gaming these latencies are related to data plane operations, distinct from the communication processes done in the control plane.

Strategic controller placement is essential for optimizing delay in SDN networks. This approach involves carefully selecting the locations where controllers are deployed within the network. To achieve this, network traffic patterns must be thoroughly analyzed to identify hotspots or areas with high traffic. Controllers should be strategically placed closer to these hotspots to reduce the distance that control messages need to travel, thus minimizing latency.

By analyzing network data and understanding the flow of traffic, network operators can determine the optimal placement of controllers to ensure minimal delay. This approach can significantly enhance the performance of latency-sensitive applications and services.

Addressing the challenges in SDN networks requires a multi-faceted approach. Scalability can be improved through the deployment of distributed controllers, while reliability is enhanced by implementing redundant controller configurations. Delay optimization relies on strategic controller placement to minimize latency. By adopting these solutions, SDN networks can overcome these challenges and provide efficient and reliable communication services to users. The continued development of SDN technologies and innovative solutions will play a pivotal role in shaping the future of networking and addressing the evolving needs of modern communication systems.

7. CONTRIBUTION –AN ARHITECTURE FOR DYNAMIC OPTIMIZATION IN CPP

In this chapter we propose a generic SDN management and control architecture aiming to optimize the controller's placement through a SDN network, in a dynamic way, based on integrating advanced traffic analysis capabilities. The architecture is shown in the Fig. 3.

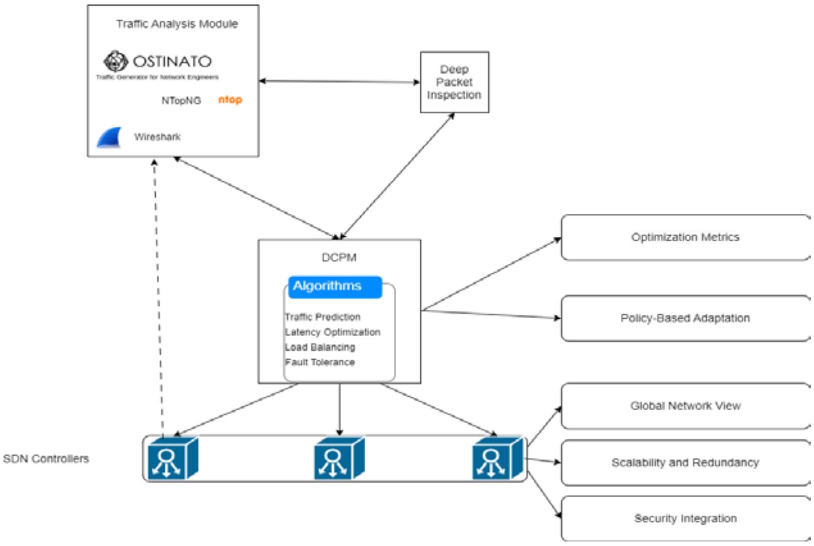

Fig. 3. System architecture proposal for dynamic optimization in CPP

Our proposal integrates a TAM (Traffic Analysis Module) working together with a DPI (Deep Packet Inspection) in order to analyze network traffic. TAM has the role of providing flow-level visibility and DPI conducts in-depth analysis of packet content. The connection between them is bidirectional suggesting the traffic analysis capability by interacting between flow-level and packet-level.

The DCPM (Dynamic Controller Placement Manager) will use the information provided by DPI and TAM to place the SDN controller dynamically, by using algorithms such as Round Robin (for uniform traffic distribution between the controllers), network latency-based algorithms, genetic algorithms and so on.

The Optimization Metrics could be QoS based, but as well other criteria could be considered, having different priorities They are connected to the DCPM and influence the optimization of network performance.

Connected to the DCPM and the Optimization Metrics block, the Policy-Based Adaptation provides policy definition using the YANG modeling language.

SDN controllers (e.g., ONOS, ODL, RYU, etc.) enable communication between various network devices and applications, incorporating dynamic adjustments to the flow tables to accommodate real-time traffic requirements. Even more, in order to obtain a much scalable architecture, the controller can provide traffic information to the TAM, avoiding the overloading of the DCPM by letting it to collect information about all traffic in the network.

The Global Network View represents a centralized database connected to the SDN controllers that has the purpose of maintaining a real-time global view of the network. This offers the controller a perspective that helps it in the decision-making process.

The component of Scalability and Redundancy employs a microservices approach and active-standby configurations for redundant controllers by using Kubernetes orchestration, which plays a pivotal role by automating the deployment, scaling, and management of these microservices. This integration ensures that the SDN controller operates within a scalable and resource-efficient network environment.

The Security Integration block (SI) provides secure communication using OVS (Open vSwitch) security features, through using TLS (Transport Layer Security) protocol.

Our study addressed the CPP problem in SDN context, proposing an architecture which can provide an adaptive optimization for CPP. Featuring key modules as DPI, Traffic Analysis and Dynamic Controller Placement, resulted a holistic and dynamic optimization strategy for the controller placement. To emphasize the importance of security integrations, QoS and policy-based adaption the architecture encapsulates a comprehensive solution. The microservices-oriented design assures scalability while the efficiency over the resource’s usage is handled by Kubernetes. Our SDN architecture provides an efficient and solid resolution to the CPP, promoting a robust and high-performing network infrastructure.

8. CONCLUSIONS

Placing the controller efficiently can significantly improve performance metrics such as propagation latency, reliability, load distribution, and failure resilience. This study provides a brief introduction to Software-Defined Networking (SDN), examines its architecture, reviews related work, and identifies weaknesses in both single-controller SDN and multi-controller (distributed) SDN evolution. As a result, it becomes evident that, in order to ensure scalability and reliability, large-scale SDN networks necessitate multiple controllers. Such comparisons can aid in progressing towards a dependable solution for CPP in SDN.

Future research must pivot towards developing dynamic load balancing strategies, integrating Machine Learning for load prediction, and enhancing security in 5G-integrated SDN environments. Key areas like IoT, satellite networks, and IoV also require novel controller placement techniques. The ultimate goal is to optimize controller distribution for improved network performance, scalability, and reliability.

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