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5G MEC-Based Networks Placement Problem with Protected SFC Distributions

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Abstract

This paper summarize the thesis "MEC Placement Problem in Protected 5G Networks". It investigates two distinct placement strategies: a centralized approach, where a single MEC node hosts an entire Service Function Chain (SFC) request, and a distributed approach, where Virtualized Network Functions (VNFs) forming SFC request are spread across multiple 5G-MEC based networks. The research analyzes the cost of traditional $1:1$ and $1:N$ protection schemes and introduces an 'enhanced shared protection scheme ($1:N:K$)' that provides additional redundancy. The evaluation, which considers varying levels of reliability, latency, and failure probability, demonstrates two key findings: the distributed placement of VNFs forming SFC requests can substantially increase network costs, and the enhanced shared protection scheme ($1:N:K$) is a more cost-effective solution.

Keywords: MEC location problem, protection schemes, VNF placement, 5G, NFV.

1 Introduction

The fifth-generation cellular network (5G) supports massive broadband applications, massive machine-type communication, and large-scale connectivity for the Internet of Things (IoT). As mobile data traffic continues to increase, there is a need for mechanisms that can improve network resilience and optimize the use of network resources. To support reliable Service Function Chains (SFC) requests, 5G network resources are divided into logical resources or slices using cloud-slicing. Multi-access Edge Computing nodes (MECs) leverage virtualization, thus, providing cloud slices to host VNF chains [1]. MECs usually have limited computational and storage capacities as well as bandwidth to handle the traffic generated by diverse service requests. Moreover, VNFs, slices, VMs, and MECs are prone to failures and malfunctions, which can compromise the reliability required for 5G services. Hence, achieving high levels of reliability in 5G networks with MECs is challenging.

This paper summarizes the thesis "MEC Placement Problem in Protected 5G Networks" [2] that attempted to answer the following question "Where to position MECs in 5G networks to achieve 5G reliability and latency requirements at a minimum cost". The work in the thesis considered a set of demand points requesting the execution of SFCs with stringent requirements in terms of latency and reliability and a set of locations that can host an MEC. The MEC placement problem in 5G network aims at devising locations to MECs and hosted slices so that the requirements of services can be supported and cost minimized.

The Infrastructure Provider (InP) must choose a protection scheme to support the 5G reliability and latency requirements at a minimum cost. Unlike existing works in the literature that consider reliability Constraints, this thesis evaluated different protection schemes and levels of reliability Constraints on the problem formulation.

The protection scheme in this paper provides different protection guarantees at different costs. In the dedicated protection scheme ($1:1$), each demand point is assigned a dedicated backup (secondary) in case of a primary slice failure. The backup (secondary) slice is reserved exclusively for one demand point. A demand point's primary and a backup slice cannot be hosted on the same MEC.

In the shared protection scheme ($1:N$), one primary slice is allocated to a single demand point, whereas the secondary slice is shared by several ($N < |V|$) demand points. At any given time, only one of the N

demand points can use the secondary slice, and if the shared secondary MEC node is already occupied by one of the other $N-1$ demand points, service can be denied in case of an MEC node failure.

indent The enhanced shared protection scheme $(1:N:K)$ consists of extending the shared protection scheme $(1:N)$ with $K-2$ additional redundant slices to mitigate the impact of failures of the MEC nodes. If the secondary slice fails, the demand point is still protected by additional $K-2$ redundant MEC nodes, increasing the level of protection. These $K-2$ backup slices are ordered for each demand point so that if the k-th node is unavailable, the VNFs will be transferred to the $k+1$-th slice. These redundant $K-2$ slices are not reserved for a specific number of demand points, although only a single demand point can occupy the slice at any given time. Moreover, no two redundant slices of a demand point can be placed at the same MEC node, nor can the primary slice be placed at the same MEC node as other redundant slices of the same demand point.

Moreover, the distribution of the VNFs that form SFCs can impact the number of MECs needed, and consequently the cost of provisioning 5G networks. Thus, the work in the thesis investigated the impact of the cost of different distribution of VNFs forming SFC requests for the MEC placement problem: i) centralized placement where Service Function Chain (SFC) request formed by multiple VNF chains are fully hosted in a single slice of an MEC, and ii) distributed SFC assumption in which the VNFs forming an SFC are hosted in different number of MECs. The centralized placement, all VNFs of an SFC request are hosted in a single slice; the distributed SFC placement (DSF) consists of all VNFs of an SFC request are distributed across multiple MECs located at different locations.

The contributions of the thesis are the following:

1. *A new enhanced share protection scheme, named* $1:N:K$.
2. *Evaluation of the impact of VNF distribution on the cost of provisioning a reliable 5G network with edge computing nodes.*
3. *Evaluation of the impact of traditional dedicated, shared and the new proposed enhanced shared protection schemes on the cost of provisioning a reliable 5G network with edge computing nodes;*

The relevance of the contributions of the thesis is related to the deployment of MEC nodes that should be carefully planned so that the low-latency and high-reliability requirements can be met simultaneously, since the replacement of a failed MEC by another one in a different location may lead to a violation of latency requirements. Most of the work on the support of 5G requirements neglects the reliability Constraints and assumes that latency requirements can be supported regardless of any failure that might happen, which is an unrealistic assumption.

The MEC placement problem with a protection scheme is a constrained bi-objective optimization NP-hard problem. The problem of locating a reliable MEC was formulated as a generalization of the classical Facility Location Problem [3]. All the feasible instances of this formulation were solved exactly using the Gurobi Optimizer solver. The metaheuristic NSGA-II was employed to solve the proposed formulation for networks larger than those with a feasible exact solution.

The remainder of this paper is organized as follows. Section 2 reviews related work. Section 3 introduces the MEC placement problem with the assumption that the VNFs forming SFC requests are located in a single slice that is deployed on one MEC. Section 4 presents the contributions of the thesis considering the MEC placement problem with SFCs hosted on distributed MECs assuming that the VNFs forming the SFC requests are distributed on different MEC nodes. Section 5 summarizes the main results of the thesis. Finally, Section 6 draws the conclusions.

2 Related Work

The MEC placement problem, investigated in the thesis, considered where to place MECs given a distribution of VNFs in a SFC. The placement of virtual network functions can be seen as a generalization of the virtual network embedding problem, an *NP*-hard problem. MEC placement promises to push the computation and communication resources from cloud to network edge. However, due to heterogeneity and variability in MEC nodes, a guarantee of high availability is a challenge for the InP.

The resources of MECs can be divided into cloud-slices [1], which are referred to interchangeably as 'cloud-slices' or 'slices' in the thesis. Some authors approach the network function placement problem by focusing only on QoS metrics while others also consider reliability. The authors of [4] proposed a virtual network function placement approach. However, early studies were focused on applying virtualization and network function decomposition on the mobile core gateways. Our work is different from [4] as we focus on placing VNFs in the mobile edge computing nodes near the end-users. In our MEC placement problem formulation, we consider the demands for reliability and latency required to provide a reliable 5G network with mobile edge computing nodes. For instance [5] proposed a VNF placement algorithm for virtual 5G networks to minimize the length of the paths between users and their associated data anchor gateways as well as to optimize their session's mobility. The work in [6] investigated VNF placement strategies, emphasizing potential issues that may disrupt VNF placement. The paper classifies the existing placement solutions based on the type (online or offline) and reliability-awareness and discusses metrics and objectives. The authors of [7] studied the problem of a redundant placement policy for the deployment of microservice-based applications at the distributed edge, modeling the distributed redundant placement as a stochastic discrete optimization problem and proposed a Genetic Algorithm-based server selection algorithms designed to optimize response time. However, the proposed problem does not consider the 5G requirements of services.

The authors of [8] addressed the problem of provisioning the data plane for MEC-based cellular networks to improve resiliency, reduce latency, and limit mobility-based service disruptions. However, their work did not address protection schemes, nor was the problem formulated as a multi-objective optimization problem.

The authors of [9] investigated the placement of virtual machine replicas to minimize the average response time of applications running on edges with numerous MEC nodes and considered different demands and heterogeneous MEC capacity Constraints. In [10], the authors have proposed a combinatorial optimization solution based on multiple k-redundancy for VM placement considering potential server failures. The proposal estimated the minimum number of VMs necessary to protect services, even with k server failures. However, latency was not considered in the solution. Although the mentioned studies considered VNF placement in 5G networks, none of the investigated work considered reliability and latency requirements in the VNF placement formulation, neither they considered the failure probability of slices and MECs. Our work differs from the existing placement problem, in the sense that we consider stringent requirements of 5G services simultaneously while minimizing the costs in terms of MEC nodes and slices needed to support the 5G services and application requirements. In our proposed work, the MEC placement problem is formulated as a bi-objective non-linear problem. In [11], optimal placement of virtual resources is proposed based on a canonical domain framework using the Schwartz-Christoffel conformal mapping in order to tackle the dynamic characteristics of mobile edge clouds. The proposed solution reduces the end-to-end latency as well as the total number of activated VMs. The study conducted in [11] fails to consider simultaneously the stringent requirements of reliability, and the low latency needed for the services or applications of 5G use cases. Our work differs from [11] since we formulate the MEC placement problem in 5G network considering both requirements of reliability and latency. The level of redundancy needed is part of the MEC nodes problem formulation. Our work evaluates the impact of the distribution of the VNFs composing the SFC request on the cost of provisioning reliable 5G network.

Redundancy is an essential aspect of service provisioning so that service resiliency can be assured. Service can be impacted by a failure of VNFs running on a VM, or by the failure of the physical machine hosting a VM. In [12], a redundancy series-parallel model was introduced to improve the reliability of LTE Evolved Multimedia Broadcast Multicast Services (eMBMS) services. In [13], the authors have considered a workload assignment problem based on latency and reliability requirements to decide to which MEC node a workload should be assigned. However, their method does not consider that MECs and slices to be selected can be prone to failure. The authors of [14] investigated the trade-off between reliability and cost for resource provisioning in fog-aided IoT networks. However, the work in [14] does not explicitly explain the means of preventing VM failures, nor does it consider the existing traditional protection schemes to provide redundancy, nor the levels of redundancy taken into consideration on the fog resource provisioning problem. The authors of [15] have proposed a non-convex mixed-integer nonlinear model to maximize the number of tasks offloaded to a UAV-mounted cloudlet, subject to application latency and reliability requirements.

The authors in [16] have proposed an integer linear programming model to furnish primary and secondary VNF instances for reliable service provisioning when users request different network services with different reliability requirements. However, the mentioned work did not consider latency requirements, nor did it investigated the impact of secondary VNF instances on the cost of providing reliability to furnish the stringent services requirements of 5G services. Our work differs from the mentioned work since we formulate the MEC placement problem considering a dedicated protection scheme in which the secondary slice is exclusively allocated to one demand point, and a shared protection in which the secondary slice is shared by several demand points. In [17], the authors formulated a MIP to address virtual network embedding under the Constraints of reliability requirements for the physical substrate. In [18], a reliability-aware joint VNF placement is proposed in the context of NFV-enabled data-center networks. The delay Constraints is considered in the placement decision to maximize reliability and minimize the end-to-end delay network services. A MILP and a heuristic algorithm were proposed to solve the problem. However, the work in [18, 17, 12] did not consider simultaneously the reliability and latency requirements, which is important for the 5G use cases. Our MEC placement approach is able to provide simultaneously the reliability and latency Constraints of the 5G services and yet minimize the costs for the InP.

The work in the thesis differs from those in the literature since it formulated the MEC node placement problem considering the stringent reliability requirements and latency simultaneously. Besides, the work in the thesis also investigated the impact of the dedicated and shared protection scheme in providing a reliable MEC node placement problem. The thesis investigated the impact of the cost of providing reliability for different SFC distributions for the MEC placement problem. To the best of our knowledge, none of the existing work investigates the impact of the distribution of the VNFs forming the SFC requests on the cost of providing reliability in 5G networks. Therefore, the presented thesis expands the state-of-the-art in different manners.

3 MEC placement problem in protected 5G networks with SFCs hosted in one MEC

This section considered a scenario of a centralized placement where a single MEC node fully hosts the VNFs forming an SFC request. The impact of hosting VNFs composing an SFC in a single MEC and the cost of providing a reliable 5G network is investigated. The provisioning of reliability in an NFV-based MEC deployment is critical, since a failure of a slice or an MEC can cause a service outage, breaking the continuity of the hosted SFC. To protect the SFCs against failure and ensure the stringent reliability required by the 5G use cases, different protection schemes are investigated. The effectiveness of the traditional dedicated protection, the shared protection schemes, and the new enhanced shared protection scheme proposed by the authors is evaluated to provide reliability in 5G networks with SFC hosted in one MEC. We aim to evaluate the cost of provisioning 5G services requirements that the centralized SFC incurs in 5G networks in terms of the number of MECs deployed. The impact that each protection scheme employed in the centralized SFC model is also of paramount importance do devising the number of MECs and slices demanded for furnishing the low latency and reliability requirements of 5G services.

We formulated the optimization problem as a bi-objective non-linear. To solve the bi-objective formulation, we first minimize the number of slices and then the number of deployed MECs. The goal of minimizing the number of slices is to assign as many demand points as possible to a single slice. To achieve this, these slices need to be packed into the minimum number of active MEC nodes, while avoiding spreading them across multiple MECs.

The notation used in the formulation introduced in this section is summarized in Table 1.

The solution for the centralized MEC placement problem in protected 5G networks where a single MEC fully hosts the SFC request is given by a bi-objective criteria formulation that employs the following decision variables:

- $y_u \in \{0, 1\}$ - with the value 1 designating the MEC u as deployed.
- $w_{uik} \in \{0, 1\}$- with the value 1 indicating that the MEC u hosts slice i employed as the k-th assignment ($k = 0$ means primary, $k = 1$ secondary).
- $x_{uvik} \in \{0, 1\}$ - with the value 1 meaning that slice i in the MEC u is employed as the k-th assignment for a demand point v.

To solve this problem, bi-objective non-linear constrained mathematical formulations were proposed and exactly solved, and solutions were also derived by employing the non-dominated sorting genetic algorithm for large networks.

To minimize the number of slices and MECs demanded, a bi-objective formulation of SFCs hosted by single MEC in protected 5G network with enhanced shared protection is expressed by the Objective Functions 1 and 2:

$$Min \sum_{u\in U} \sum_{i=1}^{C_u} \sum_{k=0}^{K-1} w_{uik} \tag{1}$$

$$Min \sum_{u\in U} y_u \tag{2}$$

subjecto to,

$$\sum_{v\in V} x_{uvi0} \leq 1 \quad \forall u \in U, 1 \leq i \leq C_u \tag{3}$$

$$\sum_{i=1}^{C_u} \sum_{k=0}^{K-1} x_{uvik} = 1 \quad \forall v \in V, u \in U \tag{4}$$

Table 1: Notations used in the formulation of MEC location problem with SFC fully hosted in one MEC

Symbol	Description
Parameters	
U	Set of MECs
V	Set of demand points
E	Set of links
N	Number of demand points that share a secondary slice
K	Protection levels
B_u	Total MEC bandwidth capacity in Mbps
b_v	Bandwidth consumed by the demand point v in Mbps
Ψ_u	MEC CPU capacity in MIPS
Φ_u	MEC RAM capacity in GB
τ_v	Processing demands of the demand point v in MIPS
σ_v	Memory demand of the demand point v in GB
L_v	Bound of the latency requirement of the demand point v in ms
r_u	Failure probability of the MEC $u \in U$
R_v	Required reliability level of the demand point v
ψ_{ui}^U	Upper bound of the CPU capacity allocated to the slice i in the MEC u.
ψ_{ui}^L	Lower bound of CPU capacity allocated to the slice i in the MEC u.
C_u	Maximum possible number of slices in the MEC u
ψ_{ui}	CPU capacity allocated to the slice i in the MEC u in MIPS
ϕ_{ui}	RAM space allocated to the slice i of the MEC u in GB
l_{uvi}	Latency experienced by demand v when using the slice i of MEC u in ms
Variables	
y_u	The decision variable indicates whether a MEC u is deployed
w_{uik}	The decision variable indicating whether a MEC u hosts slice i employed as the k-th assignment
x_{uvik}	The decision variable means whether a slice i in the MEC u is employed as the k-th assignment for the demand point v.
Z_{uvik}	Auxiliary continuous decision variable.
ψ_{ui}^*	Auxiliary continuous decision variable.

$$\sum_{v\in V} x_{uvi1} \leq N \quad \forall u \in U, 1 \leq i \leq C_u \tag{5}$$

$$\sum_{u\in U}\sum_{i=1}^{C_u} x_{uvi0} \leq 1 \quad \forall v \in V \tag{6}$$

$$\sum_{k=0}^{K-1} x_{uvik} \leq 1 \quad \forall u \in U, v \in V, 1 \leq i \leq C_u \tag{7}$$

$$\sum_{v\in V} x_{uvik} \leq |V| \quad \forall u \in U, 1 \leq i \leq C_u, 2 \leq k \leq K-1 \tag{8}$$

$$\sum_{u\in U}\sum_{i=1}^{C_u}\sum_{k=1}^{K-1} x_{uvik} = K \quad \forall v \in V \tag{9}$$

$$x_{uvik} \leq w_{uik} \quad \forall u \in U, v \in V, 1 \leq i \leq C_u, 0 \leq k \leq K-1 \tag{10}$$

$$w_{uik} \leq y_u \quad \forall u \in U, 1 \leq i \leq C_u, 0 \leq k \leq K-1 \tag{11}$$

$$\psi_{ui} = \max_{v\in V, 1\leq k\leq K-1} \{\tau_v x_{uvik}\} \quad \forall u \in U, 1 \leq i \leq C_u \tag{12}$$

$$\phi_{ui} = \max_{v\in V, 1\leq k\leq K-1} \{\sigma_v x_{uvik}\} \quad \forall u \in U, 1 \leq i \leq C_u \tag{13}$$

$$\psi_{ui} \geq \tau_v x_{uvi0} \quad \forall u \in U, v \in V, 0 \leq k \leq K-1, 1 \leq i \leq C_u \tag{14}$$

$$\phi_{ui} \geq \sigma_v x_{uvi0} \quad \forall u \in U, v \in V, 0 \leq k \leq K-1, 1 \leq i \leq C_u \tag{15}$$

$$\sum_{i=1}^{C_u} \psi_{ui} \le \Psi_u \quad \forall u \in U \tag{16}$$

$$\sum_{i=1}^{C_u} \phi_{ui} \le \Phi_u \quad \forall u \in U \tag{17}$$

$$\sum_{v \in V} \sum_{i=1}^{C_u} \sum_{k=0}^{K-1} b_v x_{uvik} \le B_u \quad \forall u \in U \tag{18}$$

$$1 - \prod_{u \in U} [(1-r_u)^{x_{uvi0}}] \prod_{m \in U \setminus \{u\}} [\prod_{k=1}^{K-1} (1-r_m)^{x_{mvik}}] \ge R_v \quad \forall v \in V, u \in U, 1 \le i \le C_u \tag{19}$$

$$\sum_{u \in U} \sum_{k=0}^{K-1} \sum_{i=1}^{C_u} \frac{\tau_v}{\psi_{ui}} x_{uvik} \le L_v \quad \forall v \in V \tag{20}$$

$$y_u, x_{uvik}, w_{uik} \in \{0,1\}, 0 \le \phi_{ui} \le \Phi_u, 0 \le \psi_{ui} \le \Psi_u \quad \forall u \in U, v \in V, 0 \le k \le K-1, 1 \le i \le C_u \tag{21}$$

The objective functions described by Equations (1) and (2) have two aims: to minimize the total number of slices, and minimize the number of deployed MECs. The goal of minimizing the number of slices is to assign as many demand points as possible to a single slice. To achieve this, these slices need to be packed into the minimum number of active MEC nodes, while avoiding spreading them across multiple MECs. Constraints (3) indicate that a primary slice is allocated to at most one demand point. Constraints (4) indicate that the primary slice of a demand point $v \in V$ should not be hosted in the same MEC hosting any other backup slice for this demand point. Constraints (5) indicate that a secondary slice is shared by at most $N < |V|$ demand points. Constraints (6) indicate that a given demand point $v \in V$ is assigned to exactly one primary slice. Constraints (7) indicate that a slice cannot be assigned in more than one level.
Constraints (8) indicate that the MECs used as $K-2$ redundant for a secondary slice can be shared by all the demand points. Constraints (9) establishe the fact that a given demand point must be protected by $K-1$ redundant slices. Constraints (10) indicate that an unassigned slice cannot be allocated to a demand point. Constraints (11) indicate that a slice cannot be hosted in an inactive MEC. Constraints (12) and (13) indicate, respectively, that the capacity in terms of the CPU and RAM of a k-th slice is the maximum capacity value of the N demand points that share that slice. Constraints (14) and (15) state, respectively, that the capacity in terms of CPU and RAM of a primary slice should be greater than or equal to the capacity of the demand point assigned to it. Constraints (16) and (17) ensure, respectively, that the sum of the capacities in terms of CPU and RAM of the slices hosted in a MEC $u \in U$ cannot exceed the capacity of the hosting MEC. Constraints (18) limit the total traffic a MEC u can support.
The reliability Constraints (19) assure that the reliability level achieved should be equal to or greater than R_v, the expected reliability level of a demand point $v \in V$. The left-hand side of the expression (19) is the probability of either the primary slice or a redundant slice hosted on a different MEC being available.
Constraints (20) indicate that the total latency should be less than or equal to the maximum latency allowed for a demand point. L_v represents the maximum latency of a demand $v \in V$. The latency value is the time a demand point incurs for processing the i-th assigned slice hosted on MEC u (l_{uvi}), which is the ratio between the CPU demand τ_v and the CPU capacity allocated to the slice in use, $l_{uvi} = \frac{\tau_v}{\psi_{ui}}$. We assume that in case of a failure, the SFC execution is restarted in the MEC where it was transferred without any context transfer. The left-hand side of Constraints (20) consider all MEC to have failed except for the last one $(K-1)$ protecting the demand point. Therefore, it is necessary to ensure that the latency is even lower or at most equal to that which is required in this worst-case scenario of multiple $(K-1)$ failures. Constraints (21) define binary decision variables.

Constraints (19) are non-linear, thus it can be linearized by using an exponential function, which yields the following linear constraints.

$$\sum_{u \in U} x_{uvi0} \ln(1-r_u) + \sum_{m \in U \setminus \{u\}} \sum_{k=1}^{K-1} x_{mvik} \ln(1-r_m) \le \ln(1-R_v) \quad \forall v \in V, 1 \le i \le C_u \tag{22}$$

Since the Constraints (20) contain the ratio of a binary decision variable x_{uvik} with a continuous decision variable ψ_{ui}, it is non-linear. The expression $\frac{1}{\psi_{ui}}$, $\psi_{ui} \in R^+$ can be modeled, introducing a continuous decision variable ψ^*_{ui} and adding the equation $\psi_{ui}\psi^*_{ui} = 1$. The constant ψ^U_{ui} represents the upper bound of the CPU capacity allocated to the slice i in the MEC u. The constant ψ^L_{ui} represents the lower bound of CPU capacity allocated to the slice i in the MEC u. We introduce an auxiliary continuous decision variable $Z_{uvik} \in^+$, such that $Z_{uvik} = \psi^*_{ui}x_{uvik}$.

$$\sum_{u\in U}\sum_{k=0}^{K-1}\sum_{i=1}^{C_u} \tau_v z_{uvik} \leq L_v \quad \forall v \in V$$

$$z_{uvik} \leq \frac{1}{\psi^L_{ui}} x_{uvik}$$
$$z_{uvik} \geq \frac{1}{\psi^U_{ui}} x_{uvik}$$
$$z_{uvik} \leq \psi^*_{ui} + \frac{1}{\psi^U_{ui}}(1 - x_{uvik})$$
$$z_{uvik} \geq \psi^*_{ui} - \frac{1}{\psi^L_{ui}}(1 - x_{uvik})$$
$$\psi_{ui} \in [\psi^L_{ui}, \psi^U_{ui}]$$
$$\psi^*_{ui} \in [\frac{1}{\psi^U_{ui}}, \frac{1}{\psi^L_{ui}}] (23)$$

By replacing Constraints (19) and (20) with Constraints (22) and (23), respectively, the SFC for the MEC placement problem fully hosted on an MEC in a 5G network protected with a formulation of a shared $1 : N : K$ non-linear protection scheme has been transformed into a linear one.

4 MEC placement problem in protected 5G networks with SFCs hosted on distributed MECs

This problem addressed in the thesis aims at evaluating the impact of VNF distribution on the cost of providing reliability in the design of 5G networks. Distributed SFC (DSFC) consists of the multiple VNFs that form an SFC request that are hosted in a different number of MECs geographically distributed in different locations. The thesis first evaluated the impact of VNF distribution on the cost of providing reliability in the design of 5G networks by placing a VNF (i.e., the last VNF) of an SFC in a separate MEC. This approach was referred to as the partial placement of VNFs forming a SFC. Then the impact of the cost of VNF distribution by placing all VNFs forming an SFC in separate MECs referred to as a fully distributed placement was evaluated.

The thesis proposed the formulation of the MEC placement problem assuming that the VNFs forming SFCs are distributed on different MECs in a 5G protected network.

We model the InP network as an undirected graph $G = (U, E)$, where the vertices U represents the set of MEC nodes and the edges E represents the set of shortest paths between the MEC nodes. Let $u \in U = \{1, 2, ..., |U|\}$ be the set of index associated to each MEC node. Let $v \in V = \{1, 2, ..., |V|\}$ be the set of index associated to the demand points. Let $j \in F = \{1, 2, ..., |F|\}$ denote the index associated to the VNFs. Let $t \in T = \{1, 2, ..., |T|\}$ be the index associated with the types of VNFs. Let $|F|$, $|T|$, $|V|$ denote the total number of VNFs, types of VNF, the demand points, respectively. Let $jvts$ be the j-th VNF of type t in a SFC request of type s associated with the demand point v. Each demand point request one distinctive set of VNFs in a predetermined order. An ordered set of VNFs is called a service function chain (SFC). Each demand point $v \in V$ is associated with one specific SFC of certain type. Let $s \in S = \{1, 2, ..., |S|\}$ to denote the set of index associated with the types of SFCs. We suppose that there are $|S|$ SFC types. Each SFC s consists of a set of ordered VNFs. Let $s = \{1vts, 2vts, ..., M_s vts\}$ indicates the SFC of type s which consist of an ordered set of VNF, each with a given type t. A demand point $v \in V$ solicit the execution of a SFC of a given type s, which is formed by a specific sequence of ordered VNFs. Let M_s denote the total number of VNFs in the SFC request of type s. Let $jvts$ be the j-th VNF of type t in a SFC request of type s associated with the demand point v. The notation used in the formulation introduced in this section is summarized in Table 2.

Each demand point $v \in V$ expects a stringent reliability, and latency requirement of R_v and L_v respectively.

For the problem formulation we defined the following decision variables:

- $y_u \in \{0, 1\}$ - with the value 1 designating the MEC u is selected as NFV node to deploy the VNF instances.
- $w_{uik} \in \{0, 1\}$ - with the value 1 indicating that the MEC u hosts slice i employed as the k-th assignment ($k = 0$ means primary and $k = 1$ secondary).

Table 2: Notations used in the formulation of MEC placement problem with the SFCs hosted on distributed MECs.

Symbol	Description
Parameters	
U	Set of MEC nodes
V	Set of demand point
F	Set of VNFs
T	Set of types of VNFs
S	Set of SFC types.
M_s	The maximum number of VNF in a SFC of type s
K	Protection level assignment of a slice
B_u	Total MEC node bandwidth capacity in Mbps
b_{jvts}	Bandwidth required by j-th VFN of type t in a SFC of type s in Mbps
Ψ_u	MEC node CPU capacity in MIPS
Φ_u	MEC node RAM capacity in GB
τ_{jvts}	Processing required by j-th VFN of type t in a SFC of type s in MIPS
σ_{jvts}	Memory required required by j-th VFN of type t in a SFC of type s in GB
L_v	Bound on the latency requirement of the SFC request v in ms
r_u	Reliability of the MEC node $u \in U$
r_{jvts}	Reliability of the j-th VFN of type t in a SFC of type s
R_v	Required reliability level of the SFC request v
Variables	
C_u	Maximum possible number of slices in the MEC node $u \in U$
ψ_{ui}	CPU capacity allocated to the slice $i \in C_u$ in the MEC u in MIPS
ϕ_{ui}	RAM space allocated to the slice $i \in C_u$ in MEC node u in GB
l_{uvi}	Latency experienced by SFC request v when using the slice i of MEC u in ms
y_u	The decision variable indicates whether a MEC u is deployed
w_{uik}	The decision variable indicating whether a MEC u hosts slice i employed as the $k-th$ assignment
$x_{uivkjts}$	with the value 1 meaning that the j-th VNF of type t in a SFC of type s associated with demand point v is deployed on slice i as its k-th assignment and hosted in MEC u.
$z_{uivkjts}$	Auxiliary continuous decision variable
ψ^*_{ui}	Auxiliary continuous decision variable
ψ^L_{ui}	Lower bound of CPU capacity allocated to the slice i in the MEC u
ψ^U_{ui}	Upper bound of the CPU capacity allocated to the slice i in the MEC u

- $x_{uivkjts} \in \{0, 1\}$ - with the value 1 meaning that the j-th VNF of type t in a SFC of type s associated with demand point v is deployed on slice i as its k-th assignment and hosted in MEC u.

The effectiveness of the traditional dedicated protection, the shared protection schemes, and the newly proposed enhanced shared protection scheme to provide reliability requirements of 5G networks with SFC hosted on distributed MECs were evaluated. In the evaluation of the impact of VNF distribution hosted on different MECs is paramount to consider the types of SFC requests, and the types of VNFs. For each protection scheme, we evaluated the number of distributed MECs that lead to a higher cost compared to when the VNFs of an SFC are hosted in one single MEC.

The goal is to find the optimal locations for a minimal number of MECs, i.e., to find the minimum number of MECs, that can serve all the demand points and position them appropriately to achieve the goal. Moreover, the number of slices must be minimized. The objective was to assess the cost impact of distributing virtual network functions (VNFs) on an InP while provisioning a reliable 5G network that is enabled with Mobile Edge Computing (MEC) nodes. The aim is to minimize the number of slices and MECs required for a 5G network design with minimum cost while meeting the stringent requirements of latency and high-reliability level. The MEC placement problem is formulated as a bi-objective nonlinear mathematical problem. A linearization of the non-linear formulation of the MEC placement problem is proposed to evaluate the precision of the proposed meta-heuristic.

The mathematical formulation for the MEC placement problem while taking into account the distribution of Virtual Network Functions (VNFs) of SFCs with the enhanced shared protection scheme $1 : N : K$ is formulated as follow:

$$Min \sum_{u \in U} \sum_{i=1}^{C_u} \sum_{k=0}^{K-1} w_{uik} \tag{24}$$

$$Min \sum_{u \in U} y_u \tag{25}$$

Subject to,

$$\sum_{v \in V} \sum_{s \in S} \sum_{t \in T} \sum_{j=1}^{M_s} x_{ui0jvts} \leq 1 \quad \forall u \in U, 1 \leq i \leq C_u \tag{26}$$

$$\sum_{i=1}^{C_u}\sum_{k=0}^{K-1} x_{uikjvts} = 1 \quad \forall u \in U, v \in V, s \in S, t \in T, 1 \le j \le M_s \tag{27}$$

$$\sum_{v\in V}\sum_{s\in S}\sum_{t\in T}\sum_{j=1}^{M_s} x_{ui1jvts} \le N \quad \forall u \in U, 1 \le i \le C_u \tag{28}$$

$$\sum_{u\in U}\sum_{i=1}^{C_u} x_{ui0jvts} \le 1 \quad \forall v \in V, s \in S, t \in T, 1 \le j \le M_s \tag{29}$$

$$\sum_{k=0}^{K-1} x_{uikjvts} \le 1 \quad \forall u \in U, 1 \le i \le C_u, v \in V, s \in S, t \in T, 1 \le j \le M_s \tag{30}$$

$$\sum_{v\in V}\sum_{s\in S}\sum_{t\in T}\sum_{j=1}^{M_s} x_{uikjvts} \le |V| \quad \forall u \in U, 1 \le i \le C_u, 2 \le k \le K-1 \tag{31}$$

$$\sum_{u\in U}\sum_{i=1}^{C_u}\sum_{k=1}^{K-1} x_{uikjvts} \le K \quad \forall v \in V, s \in S, t \in T, 1 \le j \le M_s \tag{32}$$

$$\sum_{j=1}^{M_s} x_{uivkjts} = 1 \quad \forall u \in U, v \in V, s \in S, t \in T, 1 \le i \le C_u, 0 \le k \le K-1 \tag{33}$$

$$w_{uik} \le y_u \quad \forall u \in U, 1 \le i \le C_u, 0 \le k \le K-1 \tag{34}$$

$$x_{uivkjts} \le w_{uik} \quad \forall u \in U, v \in V, s \in S, t \in T, 1 \le i \le C_u, 0 \le k \le K-1 \tag{35}$$

$$\psi_{ui} = \max_{v\in V, t\in T, s\in S, 1\le j\le M_s} \{\tau_{jvts} x_{uivkjts}\} \quad \forall u \in U, 1 \le i \le C_u, 0 \le k \le K-1 \tag{36}$$

$$\phi_{ui} = \max_{v\in V, t\in T, s\in S, 1\le j\le M_s} \{\sigma_{jvts} x_{uivkjts}\} \quad \forall u \in U, 1 \le i \le C_u, 0 \le k \le K-1 \tag{37}$$

$$\sum_{i=1}^{C_u} \psi_{ui} \le \Psi_u \quad \forall u \in U \tag{38}$$

$$\sum_{i=1}^{C_u} \phi_{ui} \le \Phi_u \quad \forall u \in U \tag{39}$$

$$\sum_{v\in V}\sum_{t\in T}\sum_{s\in S}\sum_{i=1}^{C_u}\sum_{k=0}^{K-1}\sum_{j=1}^{M_s} b_{jvts} x_{uivkjts} \le B_u \quad \forall u \in U \tag{40}$$

$$1 - \prod_{u\in U}[\prod_{j=1}^{M_s}(1 - r_u * r_{jvts})^{x_{uiv0jts}}] \prod_{m\in U\setminus\{u\}} [\prod_{j=1}^{M_s}\prod_{k=1}^{K-1}(1 - r_m * r_{jvts})^{x_{uivkjts}}] \ge R_v$$

$$\forall v \in V, t \in T, s \in S, 1 \le i \le C_u$$

(41)

$$\sum_{u\in U}\sum_{k=0}^{K-1}\sum_{i=1}^{C_u}\sum_{j=1}^{M_s} \frac{\tau_{jvts}}{\psi_{ui}} x_{uivkjts} \le L_v \quad \forall v \in V, t \in T, s \in S \tag{42}$$

$$y_u, x_{uivkjts}, w_{uik} \in \{0,1\}, 0 \le \phi_{ui} \le \Phi_u, 0 \le \psi_{ui} \le \Psi_u$$

$$\forall u \in U, v \in V, t \in T, s \in S, 1 \le i \le C_u, 1 \le j \le M_s, 0 \le k \le K-1$$

(43)

Constraints (26) indicate that a primary slice is allocated to exactly one demand point. Constraints (27) state that the primary slice of a demand point $v \in V$ should not be hosted on the same MEC hosting any other backup slice for this demand point. Constraints (28) establish that a secondary slice is shared by $N < |V|$ demand points. Constraints (29) indicate that a given demand point $v \in V$ is assigned to one primary slice. Constraints (30) establish that a slice cannot be assigned at multiple levels. The Constraints (31) states that all the demand points can share the slices used as $K-2$ redundant slices for a secondary

slice. Constraints (32) establish that $K-1$ redundant slices must protect a given demand point. Constraints (33) indicate that the VNFs that form an SFC request should not be deployed in the same slice and MEC. Constraints (34) establishe that an unassigned slice cannot be allocated to a demand point. The Constraints (35) states that a slice cannot be hosted in an inactive MEC. Constraints (36) and (37) indicate, respectively, that the capacity in terms of CPU and RAM of a k-th slice is the maximum capacity value of the N demand points that share that slice. Constraints (38) and constraints (39) ensure, respectively, that the sum of the capacities in terms of CPU and RAM of the slices hosted in an MEC $u \in U$ cannot exceed the capacity of the hosting MEC. Constraints (40) sets a bound on the total traffic an MEC u can support.
The reliability Constraints (41) ensures that the achieved reliability level must be equal to or greater than R_v, the expected reliability level of a demand point $v \in V$. The left-hand side of Constraints (41) is the probability of having either the primary slice or a redundant slice hosted on a different MEC available. The Constraints (42) indicate that the total latency should be less than or equal to the maximum latency allowed for a demand point. L_v represents the maximum latency of a demand $v \in V$. The latency value is the time that a demand point incurs to process the i-th assigned slice hosted on MEC u (l_{uvi}), which is the ratio between CPU demand τ_v and CPU capacity allocated to the slice used, $l_{uvi} = \frac{\tau_v}{\psi_{ui}}$. We assume that in the case of a failure, the SFC execution is restarted in the MEC where it was transferred without any context transfer. The left-hand side of the Constraints (42) considers all MECs to have failed except the last one $(K-1)$ protecting the demand point. Therefore, ensuring that the latency is even lower than or equal to that required in this worst-case scenario of multiple $(K-1)$ failures is necessary. Constraints (43) define binary decision variables.

Formulation in Section 4 are linearized using the same rules applied in Section 3. By replacing Constraints (41) and (41) with Constraints (44) and (45), the non-linear formulation presented in Section 4 is then transformed into a linear one, which can now be solved with an optimization solver.

$$\sum_{u \in U} \sum_{j=1}^{M_s} x_{uiv0jts} \ln(1 - r_u * r_{jvts}) +$$

$$+ \sum_{m \in U \setminus \{u\}} \sum_{j=1}^{M_s} x_{uiv1jts} \ln(1 - r_m * r_{jvts}) \leq \ln(1 - R_v)$$

$$\forall v \in V, t \in T, s \in S, 1 \leq i \leq C_u$$

(44)

$$\sum_{u \in U} \sum_{k=0}^{K-1} \sum_{i=1}^{C_u} \tau_{jvts} z_{uivkjts} \leq L_v \quad \forall v \in V$$

$$z_{uivkjts} \leq \frac{1}{\psi_{ui}^L} x_{uivkjts}$$

$$z_{uivkjts} \geq \frac{1}{\psi_{ui}^U} x_{uivkjts}$$

$$z_{uivkjts} \leq \psi_{ui}^* + \frac{1}{\psi_{ui}^U}(1 - x_{uivkjts})$$

$$z_{uivkjts} \geq \psi_{ui}^* - \frac{1}{\psi_{ui}^L}(1 - x_{uivkjts})$$

$$\psi_{ui} \in [\psi_{ui}^L, \psi_{ui}^U]$$

$$\psi_{ui}^* \in [\frac{1}{\psi_{ui}^U}, \frac{1}{\psi_{ui}^L}]$$

(45)

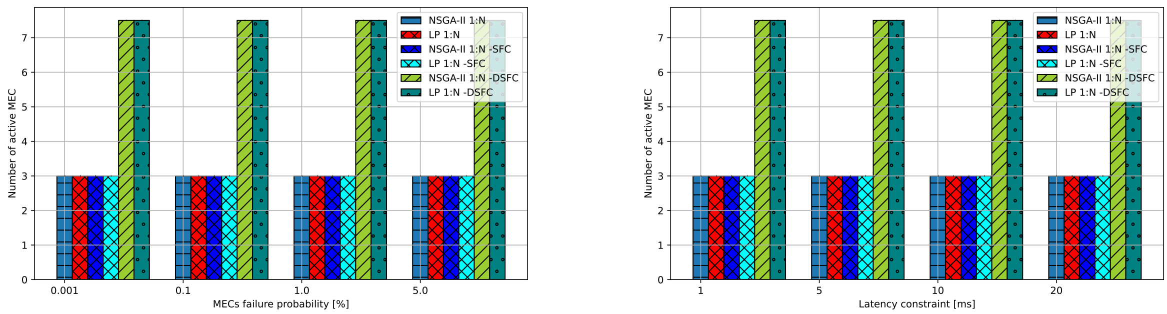
5 Results

In this section, the main results obtained in the thesis are presented. Detailed analyses can be seen in the thesis [2]. The scenario for the MEC placement problem is composed of MEC nodes, distributed in a grid topology over an area of 1000 x 1000 meters. The non-dominated sorting genetic algorithm tailored to solve the MEC Location Problem was solved on a JMetalPy version 5.3. The linearized integer formulation of the MEC placement problem was solved and implemented in the Gurobi Optimizer solver.

For each of the protection schemes, dedicated $(1:1)$, shared $(1:N)$ and enhanced shared $(1:N:K)$ a comparison of the cost for the proposed SFC distribution in the MECs placement problem were evaluated.

The non-linear bi-objective formulation with SFCs fully deployed in one MEC is labeled in the figures as $(NSGA-II)$, the partial distribution of SFC is labeled as $(NSGA-II\ SFC)$, and the fully distribution of SFC is labeled then as $(NSGA-II\ DSFC)$. The linearized bi-objective formulation of MEC placement problem is then labeled as follow (LP) for SFCs fully deployed in one MEC, $(LP\ SFC)$ for SFC partial distributed and $(LP\ DSFC)$ for the formulation that the SFCs are fully distributed across different MECs. A mono-objective formulation with $K = 3$ level of redundancy is labeled as follow $(Min.\#Slice\ K = 3)$ for the SFC fully deployed in one MEC, $(Min.\#Slice\ K = 3\ SFC)$ for SFC partially distributed, and $(Min.\#Slice\ K = 3\ DFC)$ for SFC fully distributed.

Due to computational complexity, we use a small $(|U| = 5, N = 5, |V| = 9)$ configuration to assess the precision of the proposed nonlinear bi-objective. Figures 1a and 1b compare the number of MECs needed with the bi-objective linearized problem formulation. The results in Figure 1 confirm the high precision of the metaheuristic $(NSGA-II)$. Figures 1a and 1b show that the number of MECs demanded remains the same for the metaheuristic and linearized formulations, and evinces that the metaheuristic has high precision. With this confirmation, the system model was then evaluated for larger scenarios.

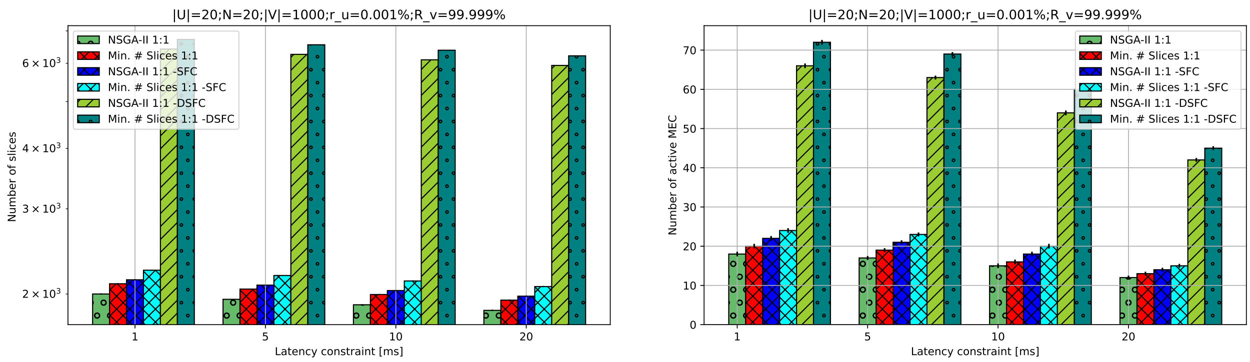


(a) Number of MECs demanded for U=5 as a function of MEC failure probability.

(b) Number of MECs demanded for U=5 as a function of latency Constraints.

Figure 1: Number of MEC demanded for different scenarios for a fully distributed SFC with $1 : N$.

In Figures 2a and 2b, the number of demanded slices and MECs are evaluated as function of latency Constraints respectively. From the definition of the 1 : 1 protection schemes, every demand point has a dedicated secondary backup node reserved in case of failure. Thus, in a full distributed VNF location where each single VNF forming an SFC request is placed on separated MEC, the dedicated protection scheme employed triple the number of demanded slices and MECs respectively. The impact of distributing the VNFs in MEC placement problem with a dedicated protection scheme is very high in the order of 68 MECs compared to the 24 MECs in the partial distribution and the 18 MECs in the SFC fully deployed in a single MEC.

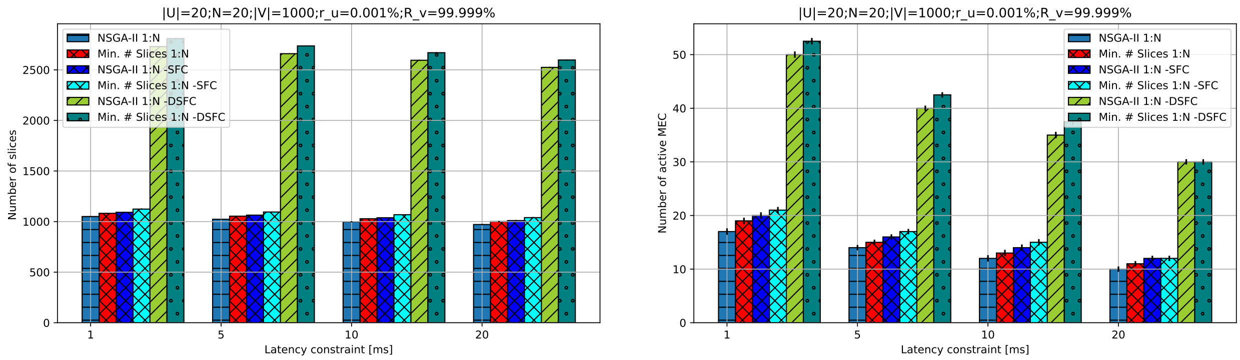


(a) Number of Slices demanded as a function of latency Constraints.

(b) Number of MECs demanded as a function of latency Constraints.

Figure 2: Number of Slices and MEC demanded for a full distributed SFC with $1 : 1$.

Figures 3a and 3b show the number of slices and MECs demanded as function of latency Constraints. Figures 3a and 3b show that the variation in terms of latency Constraints minimize the impact of the number of shared demand point N. The figures also confirm the observation that the full distributed approach may not be preferable to an InP, as the configuration of the 5G MEC based network in the fully distributed (NSGA-II 1:N DSFC) VNF placement demand more MECs, e.g in the order of 50 MECs compared to the 20 MECs in partial distributed VNFs (NSGA-II 1:N SFC).

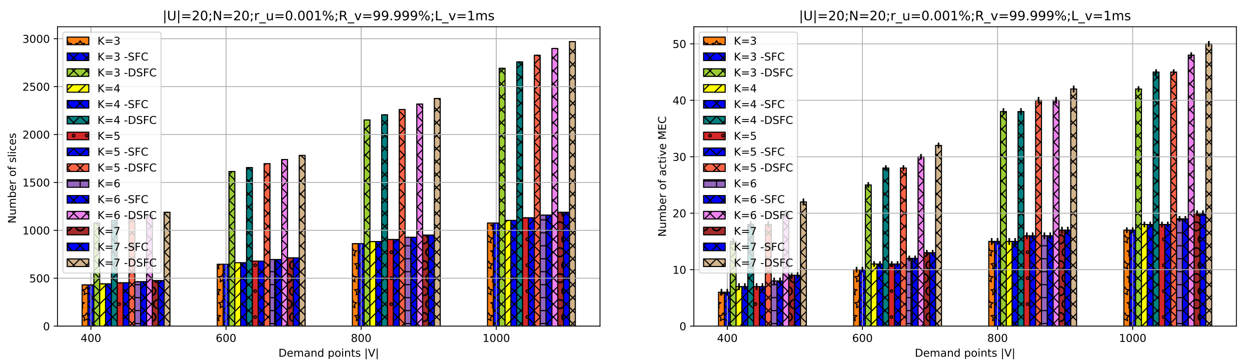


(a) Number of Slices demanded as a function of latency Constraints.

(b) Number of MECs demanded as a function of latency Constraints.

Figure 3: Number of Slices and MEC demanded for a full distributed SFC with $1 : N$.

Figures 4a and 4b show the costs of demanded slices and MECs as a function of demand points $|V|$ from $K = 3$ to $K = 7$ for the VNFs of a SFC placement studied in this thesis work. The results show that the costs increases as the number of demand points increases. We also observe that as we increase the number of K redundant nodes so the costs in terms of demanded slices and MECs increases. Thus, the full distribution of VNFs of a SFC placement in which each VNF belonging a SFC request must be placed on a separated VM results in a significant impact in terms of costs and operation of the network for an InP. Therefore, comparing the full distribution of VNFs placement with the VNFs forming a SFC request placed in one VM and the partial distributed (e.g. the last VNF of an SFC placed on a separated VM), the later approach might be preferable as they provide twice less slices and MECs when comparing with the former.



(a) Number of Slices required.

(b) Number of MECs required.

Figure 4: Number of slices and MECs required as a function of demand points for a full distributed SFC with $1 : N : K$.

Results demonstrated that when end-users demand a higher level of redundancy, more resources are needed, thus increasing the cost linearly with the level of redundancy. For the centralized placement, the configuration with $1 : N : 3$ with two redundant nodes is cost-beneficial for end-users as it provides an extra level of protection with the same cost of the shared $1 : N$ protection scheme. The type of protection used in the placement of Multi-access Edge Computing (MEC) nodes depends on the criticality of the service being provided. For instance, services such as ultra-Reliable Low Latency Communications (uRLLC) that are used for applications such as remote surgery may need dedicated nodes to ensure service continuity in case of failures. In this case, a $1 : 1$ protection scheme may be preferable, despite the high costs. On the other hand, services like autonomous vehicles can benefit from an additional level of redundancy in case of node failure along a route, and the $1 : N : K$ protection scheme may be a better option, as it provides an extra level of redundancy at a lower cost compared to other protection schemes.

6 Conclusions

The thesis reviewed in this paper explored different protection schemes for furnishing reliable services in 5G MEC-based networks. Moreover, we evaluated the impact of the cost of different distribution methods for VNFs of SFC requests in the MEC placement problem with protection schemes. The findings of this thesis suggested that fully distributing VNFs results in a more expensive network design compared to the other methods, regardless of the protection scheme used. Therefore, depending on the requirements of the end users one may prefer the partial or centralized distribution methods with an enhanced protection scheme as they require fewer nodes and slices while providing an additional level of redundancy compared to other protection schemes. This thesis differs from the existing works in the literature given that the majority assumes that the VNFs are distributed and the costs and the impacts of the VNF distribution are neglected. This thesis studied the impact of VNF distribution on the cost of providing reliability in 5G network design. The thesis evaluated the problem of locating MECs and slices in a 5G infrastructure are protected by different protection schemes and yet the thesis proposed a new enhanced scheme $1 : N : K$ to protect 5G networks. Possible future directions of this work can be explored for disaster recovery, and the dynamic VNF placement approaches including multiple self-contained networks over a shared infrastructure, enabled by self-optimization and self-healing functionalities.

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