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***Abstract*—Within the framework of 5G networks, Network Function Virtualization (NFV) occupies a central position. It offers dynamic provisioning of resources that can flexibly adjust in response to overarching network needs. Service Function Chain (SFC) stands out as a notable application of NFV, as it sequences Virtual Network Functions (VNFs) systematically to yield a specific service. Yet, ensuring resilience in the face of disasters remains a formidable challenge in NFV and SFC deployments. Such disasters, be they natural or due to hardware malfunctions, can throw a wrench in the network's operations, causing service disruptions or diminished performance across disaster zones (DZ). This research introduces an innovative approach to safeguard SFCs through multi-path routing. This strategy divides an SFC across multiple DZ-disjoit working paths, while also utilizing a communal backup path. The Multi-path Protection (MP) technique aims to reduce the drain on network resources, taking into account both the bandwidth needed for directing requests and the computing resources required for executing VNFs. To find the optimal SFC MP solution, we develop an adaptive integer linear program (ILP). Through simulations, it is evident that the introduced MP approach surpasses the conventional Dedicated Protection (DP), showcasing up to a 20% advantage in terms of resource efficiency.**

***Index Terms*—Network Function Virtualization (NFV), Service Function Chain (SFC), Disaster Resiliency, Multi-path Routing, Integer Linear Programming (ILP), Heuristic**

I. Introduction

As the demand for network services escalates, technologies such as cloud and edge computing have progressed, entailing greater network resources and heightened reliability. Conventional network services utilize multiple Network Functions (NFs) on specialized hardware, which inflates both operational (OPEX) and capital (CAPEX) expenditures. Network Function Virtualization (NFV) presents a remedy, allowing for the deployment of NFs on Virtual Machines (VMs) located within data centers. This strategy amplifies flexibility, cost efficiency, and scalability, ultimately trimming expenses and bolstering network reliability. Furthermore, it caters to dynamic scaling, synchronizing with fluctuating service demands. To satisfy network prerequisites, these Virtual Network Functions (VNFs) are sequenced meticulously to craft a Service Function Chain (SFC). The orchestration and organization of this process fall under the purview of the Management and Orchestration (MANO) system. Many studies primarily investigate individual link or node failures in SFC mapping [1]. However, in real-world scenarios, there can be extensive failures known as Disaster Zones (DZ) [2] [3].

The SFC Embedding (SFCE) [4] problem is a sub-problem of Network Embedding (NE) that is NP-hard and has been extensively studied with various approaches and criteria. The landscape of solutions proposed is vast, comprising both MILP/ILP models [5] [6] and Column Generation (CG) techniques [3], all geared towards unearthing optimal solutions. For those inclined towards deriving efficient approximate outcomes, heuristics [1] [7] and meta-heuristics [8] have also been presented. Research revolving around SFC Embedding tends to zone in on refining specific objectives. To name a few, there's an inclination towards minimizing network costs [1] [9] [7], ensuring service availability [8], and optimizing latency parameters [1]. The quest to formulate protective measures against potential failures has ushered in varied strategies. Heuristic algorithms [5], have been a popular choice. Additionally, Integer Linear Programming (ILP) derivations have gained traction, with works such as [1] shedding light on protective measures against individual node, arc, and node/link disruptions.

While a burgeoning interest in disaster-resilient networking is evident in recent literature, as highlighted in [2] [3] [10], there's a notable paucity of research focusing on disaster-resilient SFC embedding [11]. The challenge of maintaining SFC availability during natural calamities, such as earthquakes or wildfires, arises due to the inherent risks these pose to network reliability. Historical solutions span an array of methods. The RA-GEN [8] scheme, for instance, utilizes a heuristic algorithm aiming to curtail deployment and routing costs along with link usage. Another notable approach is multi-path link embedding [12], which is designed to bolster virtual network resilience. A recurring limitation, however, is that most of these strategies allocate identical bandwidth to backup paths, which inadvertently leads to bandwidth wastage. Some researchers have also delved into the reliability aspects of 5G transport-network slices, adopting strategies like bandwidth squeezing and survivable multi-path provisioning [13]. A groundbreaking multi-path strategy for SFC safeguarding emerged in [14], championing the idea of leveraging DZ-disjoint working paths and one shared backup path. This approach aimed to distribute the SFC traffic load evenly, subsequently reducing the bandwidth set aside for backup paths by a minimum of 50%. While an Integer Linear Programming (ILP) model was floated for this endeavor, its pitfall was its reliance on a preordained path count, devoid of real-time network condition considerations. As a consequence, this model might not resonate with genuine operational scenarios, potentially culminating in unworkable solutions. Heuristics were proposed in [15] with an adapted number of paths, but this proposal needed to be supported by a valid formulation and modeling.

This paper aims to enhance disaster protection for SFC through the introduction of adaptive multi-path routing, setting it apart from conventional single-path methods. The primary objective is to minimize network resources while effectively provisioning and safeguarding SFCs. The devised strategy encompasses pivotal network planning optimization facets, namely VNF placement, SFC routing, and protection, culminating in a multifaceted, complex optimization challenge. To address this, we employ flow-based ILP for the optimal solution. Our contributions can be summarized as follows: 1) We propose an adaptive multi-path disaster protection mechanism tailored for SFC provisioning. This incorporates multiple DZ-disjoint working paths coupled with a backup route. Such a setup not only ensures a balanced traffic load but also guarantees a minimum of 50% reduction in the bandwidth allocated for backup paths. 2) The SFC disaster protection problem we studied is NP-hard. We propose a new ILP model that is more adaptable to actual needs. It uses an adaptive, optimized number of paths for SFC provisioning based on network capacity and connectivity, which is unlike existing models that use fixed, predefined paths without considering network conditions. 3) The ILP results were evaluated and compared to those obtained from existing heuristics [15], demonstrating a cost reduction improvement of up to 20% for Multi-path Protection (MP) over conventional methods.

The paper is organized as follows: Section II explores the Disaster-Resilient SFC with Multi-Path Routing strategy. The ILP model is presented as a solution in Section II. The effectiveness of the ILP model and heuristics is evaluated through numerical simulations in Section IV. Finally, we conclude this paper in Section IV-C.

II. Disaster-Resilient Service Function Chains with Adaptive Multi-Path Routing

The provision of dependable and efficient SFC is pivotal to the seamless operation of contemporary networks. Natural disasters, however, pose significant risks to network reliability, making it imperative to ensure the continuous availability of SFCs during such events. As such, there is an urgent need for an optimized disaster protection strategy for SFC provisioning that conserves resources. So, we define the general network structure, serving as the foundation for our disaster protection scheme. This structure includes the physical nodes and edges, as well as the VNFs and virtual links that are exploited to handle SFC requests. Then we introduce our SFC disaster protection strategy, which is based on multi-path routing. In the next sections, we detail our proposed strategy and its practical implementation.

A. Network Structure

In our study, networks are represented as a connected directed graph $G = (V, A)$, where V is a set of N physical nodes $\{v_1, v_2, \cdots, v_N\}$, A is a set of physical arcs, and $uv \in A$ represents one specific arc from node u to node v. The set of disaster zones (DZs) is denoted by $Z = \{z_1, z_2, \cdots\}$. Each DZ contains the set of nodes and arcs that are potentially affected by a single disaster. For each node $v_i \in V$, $c(v_i)$ is the total processing capacity, and $z(v_i)$ is the associated DZ. For each arc $uv \in A$, $b(uv)$ is the total bandwidth capacity and $z(uv)$ is the associated DZ. The set of processed SFC requests is $R = \{r_1, r_2, \cdots, r_l\}$. An SFC request $r \in R$ with a single replica of each VNF and a single virtual link between consecutive VNFs is typically represented as $r = \{s_r, f_1^r, f_2^r, \cdots, f_t^r, d_r\}$, with $F^r = \{f_1^r, f_2^r, \cdots, f_t^r\}$ as the set of t required VNFs, s_r as the source node, and d_r as the destination node of the request. The virtual links are represented as $\{e_1^r, e_2^r, \cdots, e_{t+1}^r\}$, where $e_i^r = (f_{i-1}^r, f_i^r)$ connects two consecutive VNFs, $e_1^r = (s_r, f_1^r)$ and $e_{t+1}^r = (f_t^r, d_r)$ connect the source and destination nodes, respectively. A virtual link can belong to a single physical node or span across multiple nodes to connect the VNFs.

TABLE I
Network Sets and Parameters

$G(V, A)$	Network G is a graph defined by its node set V and arc set A
R	Set of requests $r(s_r, z_r^s, d_r, z_r^d, k_r, F^r)$, where s_r, z_r^s, d_r, z_r^d, k_r and F^r are source node and its DZ, destination node and its DZ, maximum predefined number of DZ-disjoint paths, and the required VNF set.
B_{s_r}	Initial traffic data rate for request r from s_r.
T^r	$T^r = \{1, 2, 3, \cdots, k_r\}$, index set of paths and VNF replicas for request r.
p_t^r	t-th path of request r, and $t \in T^r$.
f_i^r	i-th VNF required by SFC request r.
f_{it}^r	t-th replica of VNF f_i^r, and $t \in T^r$.
$Q_{f_i^r}$	Maximum number of replicas for VNF f_i^r in G.
S	Set of incompatible VNF pairs associated with request r.
e_i^r	Virtual link from f_i^r to f_{i+1}^r.
N_v^- / N_v^+	Set of incoming/outgoing arcs from node $v \in V$.
$z \in Z$	DZ/set of DZs. Each z contains a set of arcs and nodes.
z_r^s	Disaster zone for source node s_r. Note that z_r^s is 0 if source node is outside of any DZ.
z_r^d	Disaster zone where destination node d_r is located at. Note that z_r^d is 0 if destination node is outside any DZ.
$\sigma_{f_i^r}$	Coefficient related to processing capacity per bandwidth unit for VNF replica f_i^r.
θ	Weighting parameter to adjust cost combination.
w_v	Maximum VNF installation limit on node v.
c_v	Maximum available processing capacity for node v.
c_{uv}	Maximum available bandwidth for arc uv.

B. Problem Statement

The necessity to protect network infrastructures and services from potential disaster impacts prompts us to aim for a twofold goal: decreasing the bandwidth consumption and processing overheads of VNFs while ensuring full protection for all SFC requests. The commonly adopted Dedicated Protection (DP) strategy is geared towards mitigating the repercussions of link or path failures within network services and infrastructures. DP's essence lies in establishing two DZ-disjoint paths for

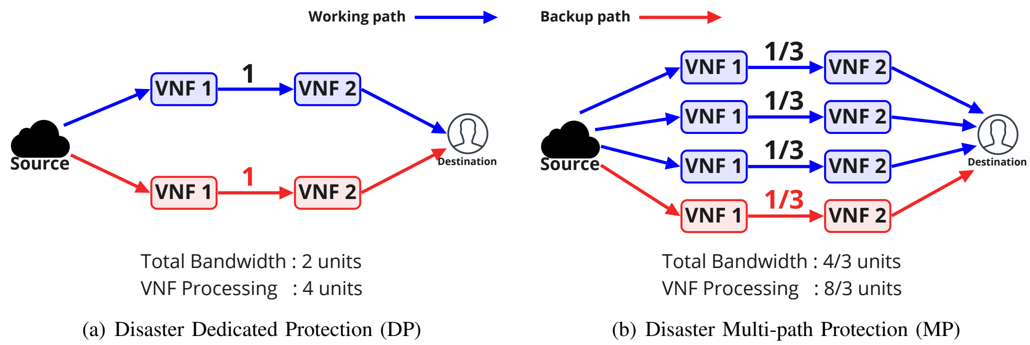

Fig. 1. SFC Disaster Protection Resource Consumption

every SFC request: a primary working path and a backup protection path. These paths traverse all required VNFs in a predetermined order. Ordinarily, the SFC request navigates exclusively via the primary path, necessitating a similar bandwidth reservation on the backup route. To effectively guard against disaster-triggered failures, it's imperative that both paths are DZ-disjoint. This ensures a swift transition of the SFC request to the backup path upon the primary's failure, guaranteeing the availability of at least one functional path during a singular DZ failure. Nevertheless, the DP approach is notably resource-intensive. Resources equivalent to the SFC request are earmarked for utilization only during disaster disruptions, highlighting the need to explore alternative strategies that bolster protection but curtail resource redundancy. Our study intentionally omits certain peripheral cases like the presence of the SFC's origin or endpoint within a failed DZ, or when the primary route bypasses any DZ. Such scenarios, being inconsequential to disaster protection, were deemed outside the scope of our analysis.

The multi-path routing strategy offers a compelling solution, enabling equitable distribution of network traffic across several operational paths. Inspired by this, we introduce a multi-path based disaster protection method (MP). This method equips an SFC request with multiple DZ-disjoint working paths, supplemented by a single shared backup path, thus ensuring resilience against DZ failures. Given that the working paths for a single request are DZ-disjoint, they do not share any common DZ. In the event of a DZ failure, only one operational route is impacted, facilitating a swift transition to the backup path. By implementing the MP method, protection becomes more bandwidth-efficient for the backup path, slashing the typical bandwidth reservation by at least 50% compared to the conventional DP approach. Concurrently, this translates to an equal reduction in the VNF processing expenses for backup path nodes. Figure 1 illustrates an SFC request traveling from a source to a destination, involving 2 VNFs. In the MP scenario, the request is routed through 4 distinct paths, whereas in the DP scenario, only 2 paths are utilized. Notably, all paths are DZ-disjoint and intersect both replicas of VNFs 1 and 2. As depicted, the bandwidth consumption is reduced from 2 in DP to $4/3$ in MP. Likewise, there's a decrease in VNF execution processing from 4 DP to $8/3$ MP.

Expanding the number of paths, however, brings additional implications in terms of costs due to the requirements for extra VNF replicas, physical nodes, and arcs. There exists a balancing act between the number of paths utilized and the encompassing costs associated with VNF storage, instantiation, data fragmentation, and more. The ideal number of paths is intrinsically tied to the specifics of the network topology and the nature of the SFC requests. It's also worth noting that in certain scenarios, creating multiple DZ-disjoint routing paths for every source-destination combination might be unfeasible. Additionally, the count of paths fluctuates depending on the network settings and the type of requests. This necessitates the stipulation of an upper threshold for the number of paths pertaining to each request. Therefore, it becomes paramount to determine the optimum number of paths (beginning with a baseline of two) without surpassing the predetermined maximum represented as k_r. This ensures the streamlined provisioning, safeguarding, and optimization of resources.

In essence, the Disaster-Resilient SFC Multi-Path problem revolves around optimally placing VNFs on physical nodes, executing efficient multi-path routing, and guaranteeing that paths are DZ-disjoint for robust protection.

The Disaster-Resilient SFC MP problem is a variant of the SFC Embedding (SFCE) problem [4], with the integration of supplementary constraints including multipath and DZ-disjoint constraints. Our problem can thus be reduced to the SFCE problem, which is NP-hard [16]. Since the execution of VNFs in SFC follows a specific order, the SFCE problem is equivalent to the traditional Virtual Network Embedding (VNE) problem, which is proved NP-hard [17].

III. Solutions

We present practical solutions that are applicable in real-world scenarios compared to the existing ones. To validate our problem modeling, we propose a novel and adaptive ILP model that provides the optimal solutions.

A. Optimal Solution: Adaptive ILP

In this section, we present an exact method for addressing the multi-faceted optimization problem for the disaster protection of SFC, combining the VNFs placement, SFC routing, and protection. This problem is known to be NP-hard, and becomes even more complex when multiple paths are introduced. In [14] an ILP formulation was proposed, nevertheless, it requires a predefined and fixed number of paths for each request (which is hard in real-world dynamic scenarios). However, we develop a new formulation that addresses this issue and enhances the model's flexibility. In our adaptive ILP, we define only an upper limit for the number of paths that can be used, rather than a fixed number. This requires to introduce new constraints with linearizations. Tables I & II contain the network parameters and ILP variables.

TABLE II
VARIABLES IN ILP FORMULATIONS

$\alpha_z^{p_t^r} \in \{0,1\}$	Equals 1 if path p_t^r of request r crosses DZ z, otherwise 0.
$\beta_{f_{it}^r v}^{p_t^r} \in \{0,1\}$	Equals 1 if the t-th replica of f_i^r on node v is used on the working/backup path p_t^r , otherwise 0.
$\gamma_v^{f_{it}^r} \in \{0,1\}$	Equals 1 if the t-th replica of f_i^r exists on node v, otherwise 0.
$\xi_{uv}^{p_t^r f_i^r} \in \{0,1\}$	Equals 1 if arc (u,v) is used on the working/backup path p_t^r from s_r to the node storing f_i^r, otherwise 0.
$\xi_{uv}^{p_t^r} \in \{0,1\}$	Equals 1 if arc (u,v) is used on the working/backup path p_t^r, otherwise 0.
$m_h^r \in \{0,1\}$	Equals 1 if the number of paths is h $(2 \leq h \leq k_r)$ for request r, otherwise 0.
$\lambda_t^r \in \{0,1\}$	Equals 1 if path t is used for request r, otherwise 0.
$W_{uv}^{p_t^r h} \in \{0,1\}$	Auxiliary variables: $W_{uv}^{p_t^r h} := \xi_{uv}^{p_t^r} \cdot m_h^r$
$Z_{f_{it}^r v}^{p_t^r h} \in \{0,1\}$	Auxiliary variables: $Z_{f_{it}^r v}^{p_t^r h} := \beta_{f_{it}^r v}^{p_t^r} \cdot m_h^r$

1) Objective Function: The goal of introducing multi-path routing for SFC disaster protection is to reduce the total bandwidth and processing cost. We define θ as an adjustable weighting parameter that can be determined by network operators. Therefore, the objective function for our multi-path disaster protection problem can be expressed as follows:

$$\min \quad \sum_{r \in R} \left[B(e_i^r) + \theta \cdot C(f_{it}^r) \right] \tag{1}$$

The first term in (1) represents the total bandwidth usage of all arcs for all SFC requests

$$B(e_i^r) = \sum_{t \in T^r} \sum_{uv \in A} \sum_{h=2}^{k_r} W_{uv}^{p_t^r h} \frac{B_{s_r}}{h-1} \tag{2}$$

The second term in (1) represents the total processing cost for VNF executions, and it is expressed as follows

$$C(f_{it}^r) = \sum_{v \in V} \sum_{f_i^r \in F^r} \sum_{t \in T^r} \sum_{h=2}^{k_r} Z_{f_{it}^r v}^{p_t^r h} \frac{\sigma_{f_i^r} B_{s_r}}{h-1} \tag{3}$$

In order to fully provision and protect SFCs, our ILP model must satisfy constraints (4)-(25)

2) Constraints:

$$\sum_{h=2}^{k_r} m_h^r \cdot h = \sum_{t \in T^r} \lambda_t^r, \qquad \forall r \in R \tag{4}$$

$$\sum_{h=2}^{k_r} m_h^r = 1 \qquad \forall r \in R \tag{5}$$

$$\lambda_t^r \geq \lambda_{t+1}^r \qquad \forall r \in R, \forall t \in [1, k_r - 1] \tag{6}$$

Constraint (4) guarantees that the total number of used paths equals the number of selected paths. (5) ensures that only one specific number of paths is selected from the range between 2 and the maximum number of paths k_r. Constraint (6) ensures that the paths are explored in a sequential order.

$$\sum_{t \in T^r} \lambda_t^r \leq \sum_{v \in V} \sum_{t \in T^r} \gamma_v^{f_{it}^r} \leq Q_{f_i^r}, \quad \forall r \in R, \forall f_i^r \in F^r \tag{7}$$

Constraint (7) sets the lower and upper bounds for the number of VNF replicas f_{it}^r. The number of replicas must be at least as large as the total number of used paths to ensure that each path can be routed through at least one replica of VNF f_i^r. However, the number of replicas should not exceed capacity.

$$\beta_{f_{it}^r v}^{p_t^r} \geq \gamma_v^{f_{it}^r} + \sum_{u \in N_v^-} \xi_{uv}^{p_t^r} - 1, \qquad \forall r \in R, \forall v \notin s_r, \quad \forall t \in T^r, \forall f_i^r \in F^r \tag{8}$$

$$\beta_{f_{it}^r v}^{p_t^r} \leq \gamma_v^{f_{it}^r}, \quad \forall r \in R, \forall v \in V, \forall t \in T^r, \forall f_i^r \in F^r \tag{9}$$

$$\sum_{v \in V} \gamma_v^{f_{it}^r} \leq \lambda_t^r, \qquad \forall r \in R, \forall f_i^r \in F^r, \forall t \in T^r \tag{10}$$

Constraints (8)-(9) determine the location of the i-th required VNF replica f_{it}^r on the working/backup path. Constraint (10) ensures that for a required i-th VNF, the number of allocated replicas f_{it}^r does not exceed the number of used paths.

$$\gamma_v^{f_{it}^r} + \gamma_v^{f_{i't'}^{r'}} \leq 1, \qquad \forall v \in V, \forall t \in T^r, \quad \forall t' \in T^{r'} | (f_{it}^r, f_{i't'}^{r'}) \in S \tag{11}$$

Constraint (11) ensures that two VNFs, f_{it}^r and $f_{i't'}^{r'}$, are not compatible, and cannot be instantiated on the same node.

$$\sum_{u \in N_v^+} \xi_{vu}^{p_t^r f_i^r} - \sum_{u \in N_v^-} \xi_{uv}^{p_t^r f_i^r} = \begin{cases} \lambda_t^r, & v = s_r \\ -\beta_{f_{it}^r v}^{p_t^r}, & v \neq s_r, \forall r \in R, \\ & \forall t \in T^t, \\ & \forall f_i^r \in F^r, \forall uv \end{cases} \tag{12}$$

$$\sum_{u \in N_v^+} \xi_{vu}^{p_t^r} - \sum_{u \in N_v^-} \xi_{uv}^{p_t^r} = \begin{cases} \lambda_t^r, & v = s_r \\ -\lambda_t^r, & v = d_r \quad \forall r \in R, \forall t \in T^r, \forall uv \\ 0, & \text{otherwise} \end{cases} \tag{13}$$

$$\xi_{uv}^{p_t^r f_i^r} \leq \xi_{uv}^{p_t^r f_{(i+1)}^r} \leq \xi_{uv}^{p_t^r}, \qquad \forall r \in R, \forall t \in T^r, \forall uv, \quad \forall f_{(i+1)}^r \in F^r, |F^r| \geq 2 \tag{14}$$

$$\xi_{uv}^{p_t^r f_1^r} \leq \xi_{uv}^{p_t^r}, \qquad \forall r, \forall t \in T^r, \forall uv, \forall f_1^r \in F^r, \ |F^r| = 1 \tag{15}$$

Constraint (12) generates working/backup paths from the source node s_r to the node hosting the VNF replica f^r_{it}. Note that the t-th VNF replica corresponds to the path p^r_t to avoid mixing different paths and replicas. Constraint (13) generates working/backup paths from the source node s_r to the destination node d_r. Constraint (14) specifies the sequence order of VNFs if the number of required VNFs is $|F^r| \geq 2$. If $|F^r| = 1$, constraint (15) ensures that the path from s_r to VNF f^r_1 is included in the working/backup path.

$$\sum_{r\in R}\sum_{f^r_i\in F^r}\sum_{t\in T^r}\beta^{p^r_t}_{f^r_{it}v} \leq w_v, \qquad \forall v \in V \tag{16}$$

$$\sum_{r\in R}\sum_{f^r_i\in F^r}\sum_{t\in T^r}\sum_{h=2}^{k_r} Z^{p^r_t h}_{f^r_{it}v}\frac{\sigma_{f^r_i}B_{s_r}}{h-1} \leq c_v, \qquad \forall v \in V \tag{17}$$

$$Z^{p^r_t h}_{f^r_{it}v} \geq \beta^{p^r_t}_{f^r_{it}v} + m^r_h - 1 \quad \forall r \in R, \forall f^r_i \in F^r, \forall t \in T^r, \forall h \in [2, k_r] \tag{18}$$

$$Z^{p^r_t h}_{f^r_{it}v} \leq \frac{1}{2}(\beta^{p^r_t}_{f^r_{it}v} + m^r_h) \quad \forall r \in R, \forall f^r_i \in F^r, \forall t \in T^r, \forall h \in [2, k_r] \tag{19}$$

$$\sum_{r\in R}\sum_{t\in T^r}\sum_{h=2}^{k_r}\frac{B_{s_r}}{h-1}W^{p^r_t h}_{uv} \leq c_{uv}, \qquad \forall uv \in A \tag{20}$$

$$W^{p^r_t h}_{uv} \geq \xi^{p^r_t}_{uv} + m^r_h - 1 \qquad \forall r \in R, \forall t \in T^r, \forall h \in [2, k_r], \forall uv \in A \tag{21}$$

$$W^{p^r_t h}_{uv} \leq \frac{1}{2}(\xi^{p^r_t}_{uv} + m^r_h) \quad \forall r, \forall t \in T^r, \forall h \in [2, k_r], \forall uv \tag{22}$$

(16) represents the maximum capacity for VNF replicas on the node v. (17) ensures that the node's processing capacity is compliant with all instantiated VNFs. (18) and (19) are linearization constraints. The former ensures that $Z^{p^r_t h}_{f^r_{it}v}$ equals zero if either $\beta^{p^r_t}_{f^r_{it}v}$ or m^r_h is zero. The latter will verify that $Z^{p^r_t h}_{f^r_{it}v}$ equals 1 if both binary variables are set to 1. Constraint (20) ensures that the bandwidth requirement for an arc remains under the physical bandwidth capacity of the arc. (21) and (22) also represent linearization constraints.

$$\alpha^{p^r_t}_z \leq \sum_{uv\in z}\xi^{p^r_t}_{uv}, \quad \forall r \in R, \forall z \in Z, \forall t \in T^r \tag{23}$$

$$\alpha^{p^r_t}_z \geq \xi^{p^r_t}_{uv}, \qquad \forall r \in R, \forall z \in Z, \forall uv \in z, \forall t \in T^r \tag{24}$$

$$\sum_{t\in T^r}\alpha^{p^r_t}_z \leq 1, \qquad \forall r \in R, \forall z \in Z\backslash\{z^s_r, z^d_r\} \tag{25}$$

Constraints (23)-(24) are used to define the Disaster Zone for the working or backup path. Constraint (25) ensures that paths are DZ-disjoint (each DZ affects only one path of the same SFC request r).

Let $K = max\{k_r\}$ denote the maximum number of paths for all requests, and $F = max\{|F^r|\}$ represent the largest size of an SFC for all requests. The computational complexity of the problem is related to the number of dominant variables and constraints in ILP: $\max\{O(|R|\cdot K\cdot F\cdot|A|, |R|\cdot K\cdot|Z|, |R|\cdot K\cdot(K-1)\cdot|A|, |R|\cdot K\cdot(K-1)\cdot F\cdot|V|)\}$ and $\max\{O(|R|\cdot K\cdot F\cdot|A|\cdot|V|, |R|\cdot K\cdot(K-1)\cdot F, |R|\cdot K\cdot(K-1)\cdot|A|, |R|\cdot|Z|\cdot|A|\cdot K)\}$, respectively.

B. Time-efficient Solutions : Heuristics

The problem we address is considered a complex NP-hard problem. While the proposed ILP model is able to provide the optimal solution, it can not be applied for real-world scenarios where a large number of requests need to be processed in large networks within limited time. Therefore, heuristics are proposed in [15] that provide practical solutions close to the optimal solution with high scalability.

1) ***Divide-&-Conquer Based Joint Optimization Heuristic (DCBJOH)*** *[15]:* The algorithm processes SFC requests in two primary steps. Firstly, it identifies multiple paths for each SFC request, ensuring they are DZ-disjoint; specifically, no two paths should cross the same DZ, ensuring resiliency against disasters. Secondly, after determining these paths, the algorithm places VNFs on specific nodes along these routes. The placement adheres to a predefined sequence of VNFs unique to each SFC request, ensuring proper service functionality.

2) ***Two-Stage Optimization Heuristic (TSOH)*** *[15]:* The TSOH algorithm first determines the placement of VNFs on nodes by estimating the required number of replicas. Then it routes SFCs using DZ-disjoint paths, unlike the DCBJOH method, which handles routing before placement.

IV. Numerical Results

We conducted comprehensive simulations to assess the performance and efficacy of the MP strategy. In this evaluation, both the ILP model and heuristic methods were examined. Initially, we compared the efficiency of MP with DP using the ILP model. Subsequently, we compare the effectiveness and time-efficiency of heuristics by contrasting them with the ILP model.

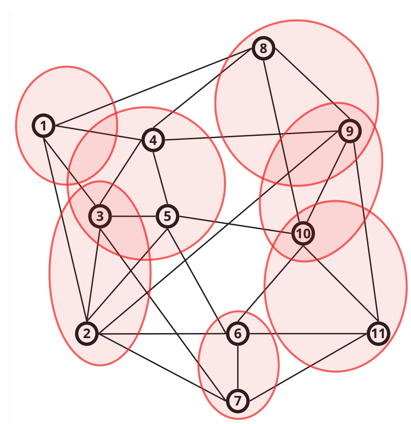

Fig. 2. Cost-239 Network Topology for Simulations [14]

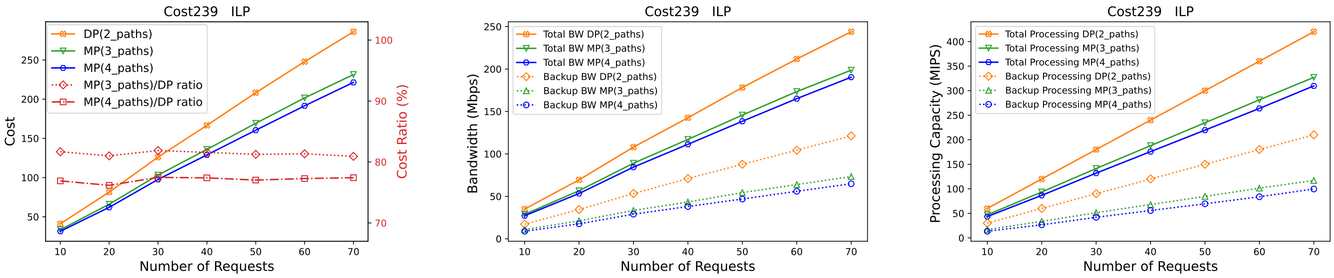

Fig. 3. DP vs. MP using ILP model (Cost239 network)

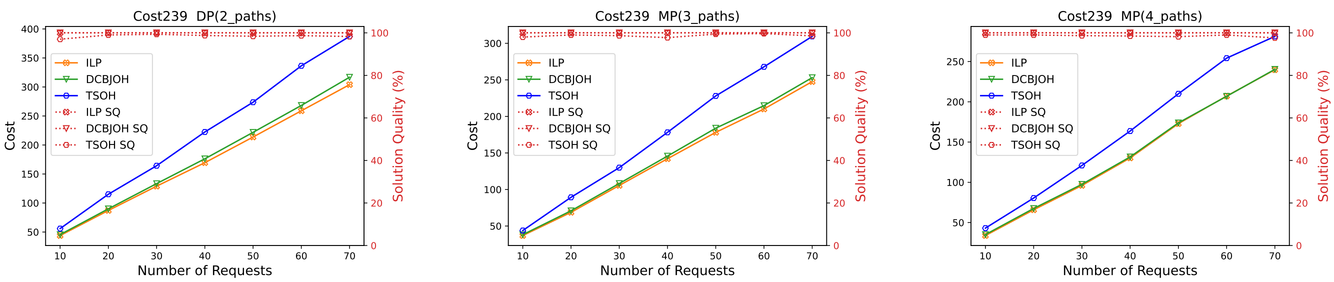

Fig. 4. DCBJOH, TSOH and ILP model for DP & MP (Cost239 network)

A. Simulation Settings

The ILP model was developed in C++ utilizing CPLEX 22.01, while heuristics were coded in Python. We executed the simulation on a computer equipped with an AMD Ryzen 9 16-Core Processor, 3.4 GHz CPU and 128GB of RAM. Cost-239 network topology used for the simulation, depicted in Fig. 2, with characteristics of 11 nodes, 52 connections, 7 DZs, and an average nodal degree of 4.72 [14].

Each request's content and source/destination nodes are randomized, as is the number of necessary network functions. The network administrator sets the weight, θ, in the objective function. We used $\theta = 0.1$ to focus on bandwidth optimization. All arcs have a 1000 Mbps bandwidth, and nodes have a 1000 MIPS processing capacity (typical values [18]). Initial bandwidth for a request starts at 1 Mbps but can change based on service, e.g., 20 Mbps for video streaming. The maximum VNF replicas for an SFC matches the max path splitting, set at 4, with a $\sigma_{f_i^r} = 1$ coefficient for every VNF instance. Nodes can host up to 1000 VNF installations. Backup paths are randomly chosen. Simulation parameters align with existing studies [18] [14].

B. MP compared with DP (using ILP)

In order to compare the performance of the two protection strategies, we conduct simulations in the Cost239 network, with a number of requests ranging from 10 to 70, by solving the ILP model using CPLEX. We assume a scenario with 3 VNFs and an initial traffic data rate of $B_{s_r} = 1$ Mbps. As the number of requests and paths increases, the difficulty in finding the optimal solution also increases, because the ILP model becomes pretty hard and more complex to solve. For example, in case of 4 paths and 70 requests, using the ILP model to find the optimal solution takes 14000 seconds for the Cost239 topology (Table III). Fig. 3 compares the total cost of the DP and MP strategies using ILP for Cost239 topologies. Besides, when the number of SFC requests increases, the results highlight the benefits of the MP strategy, leading to at least 20% resource savings. When transitioning from DP (i.e. 2 paths) to MP with 3 paths, an important gain is observed, with 20% reduction for the total bandwidth and 19% reduction for the total processing. The backup path shows 50% savings for bandwidth and 47% for processing. The implementation of MP with 4 paths provides an additional 2% average improvement compared to MP with 3 paths. The use of multiple paths results in an optimization of resources usage in terms of bandwidth and processing capacity.

C. Validation of Heuristics Efficiency Compared With ILP

We investigate the heuristic's performance compared with ILP for small-scale instances (number of requests varies from 10 to 70) for Cost239 topology. Fig. 4 gives a comparison between DCBJOH, TSOH, and the ILP solution using Cplex for the Cost239 topology under different scenarios: DP, MP with 3 paths, and MP with 4 paths. We evaluate two metrics: Quality of the solution and the Cost, while varying the number of SFC requests. The solution quality is measured as the proportion of protected requests over the total number of requests. For all three scenarios, both heuristics provide high-quality solutions with 100% of requests being protected. For the Cost metric, DCBJOH provides solutions that are very close to the optimal solution (ILP), with a gap that does not exceed 4% even in the worst cases. However, even with good solution quality, TSOH shows a larger gap from 19% to 25% compared to the optimal solution. The execution time results are summarised in Table III.

TABLE III
EXECUTION TIME IN ILP, TSOH AND DSBJOH (COST239 NETWORK)

Number of Requests		10	20	30	70	80	90	100
Scheme	**Method**							
DP (2 paths)	TSOH	0.17	1.21	3.49	26.98	31.71	38.90	40.66
	DCBJOH	1.43	2.92	4.30	9.31	10.37	11.80	12.97
	ILP	0.46	1.63	2.59	1137	1374	1811	2117
MP (3 paths)	TSOH	0.25	2.26	7.74	110	92	128	136
	DCBJOH	2.04	4.34	6.33	210	232	239	177
	ILP	284	910	1020	4365	5589	-	-
MP (4 paths)	TSOH	0.34	3.26	18.48	31.97	97.81	54.50	35.80
	DCBJOH	2.46	30.05	68.25	16.63	17.69	35.36	21.88
	ILP	946	5582	11459	13255	-	-	-

Time unit : second (**s**)

- No feasible ILP solution after 4 hours or exhausting all the memory

CONCLUSIONS

In this study, we introduced an innovative multi-path disaster protection approach for SFC provisioning. Central to our proposition is an adaptive layered-flow based ILP model, which offers a more tailored solution compared to existing methods. Unlike traditional models that rely on a fixed predetermined value, our model flexibly adjusts and optimizes the number of SFC routing paths based on specific requests. We compare our ILP model with existing heuristics. Numerical simulations further highlight the effectiveness of our proposed algorithms, revealing a resource gain of up to 20% compared to traditional disaster protection methods.

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