Survivable Virtual Network Mapping against Double-Link Failures Based on Virtual Network Capacity Sharing

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***Abstract*—Network Slicing is one of the key enabling technologies in 5G networks, as it allows the same network infrastructure to host numerous services, characterized by different Quality of Service (QoS) requirements. Network slicing provides greater flexibility when assigning resources to virtual networks (VNs, or, equivalently, "network slices"), allowing to meet very diverse service requirements. However, network slicing also brings numerous challenges in terms of management of network resources. Among these, service reliability is one of the most important, especially in light of the rising importance of ultra-reliable services in 5G. In this study, we investigate the Survivable Virtual Network Mapping (SVNM) problem focusing on double-link failures. SVNM against double-link failures can be guaranteed enforcing appropriate SVNM constraints, but this approach requires excessive redundant capacity, and induce significant underutilization of network capacity. Capacity sharing represents a more capacity-efficient solution to ensure survivability against double-link failures. Hence, we propose a new SVNM strategy that allows capacity sharing across different virtual networks in case of double-link failure. To evaluate benefits of the proposed technique we categorize six different SVNM scenarios (with and without capacity sharing, jointly applied with SVNM or not) and formalize them through Integer Linear Programming (ILP) models. Results show that the proposed technique for SVNM with capacity sharing enables availability gains (up to about 29%) over traditional SVNM against single-link failures and significant capacity savings (up to about 50%) over SVNM against double-link failures. The advantages are more significant for increasing number of virtual networks.**

***Index Terms*—5G Networks, Network Slicing, Survivability, Survivable Virtual Network Mapping, Capacity Sharing, Double-Link Failures**

I. Introduction

Nowadays, Internet is an essential resource for our lives. Users' demands vary a lot, according to the type of adopted network services, which can be characterized by very different Quality of Service (QoS) requirements. Some applications such as ultra-high definition (UHD) video and augmented reality require high-speed, while others, such as, e.g., mission critical Internet of Things (IoT) and autonomous vehicles, require ultra-low latency and ultra-reliable communications [1]. Fifth Generation (5G) networks are expected to satisfy these requirements and network slicing is a promising 5G technology to provide services tailored to users' specific QoS demands [2]. In a network slicing environment, an Infrastructure Provider (InP) manages physical network resources and several Service Providers (SPs) require the use of these resources to provide their services to end users. SPs (also known as "tenants") generally rely on virtual networks (or logical networks). A virtual network (VN) is made up of virtual nodes representing virtual functions and connections (or requests) between these virtual nodes are virtual links (VLs). In this context, network slicing enables an InP to efficiently utilize network resources by embedding VNs to support services with different requirements from multiple SPs [3], [4]. However, benefits from network slicing come at the cost of additional network-management challenges for an InP. One of the main challenges is to ensure service reliability against failures, which requires to map the VLs of a VN onto physical paths in such a way that the VN can survive failures of the physical network. This problem, known as Survivable Virtual Network Mapping (SVNM) [5], consists in assigning physical network resources to the VLs of a VN, such that the resulting VN mapping is survivable to failures occurring in the physical topology, i.e., the VN does not get partitioned into isolated networks in case of physical link failure. Network survivability is defined as the ability to recover the network traffic in the event of a failure, causing little or no consequences to the users. As networks' size and complexity continue to grow, multiple-link failures become increasing probable and ensuring survivability against multiple failures becomes more important. Figure 1 shows an example of a non-survivable vs. a survivable mapping against single-link failures. More precisely, Fig.1 (a) shows the VN whose VLs must be mapped on physical paths over

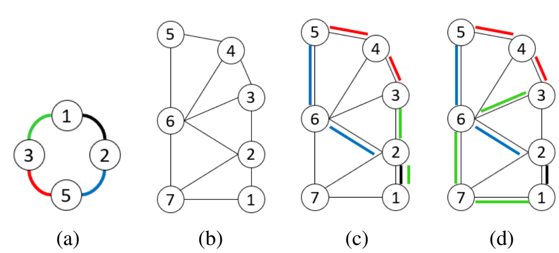


Fig. 1: (a) Requested 4-node VN (b) sample 7-node physical network, (c) non-survivable VN mapping, (d) VN mapping survivable against single-link failures.

the physical network in Fig. 1 (b). Figure 1 (c) shows a non-survivable mapping of this VN, as a failure of physical link (1-2) interrupts two VLs, (1-2), (1-3) and disconnects the VN (node 1 gets isolated). Instead, the mapping in Fig. 1 (d) is survivable as no single-link failure can disconnect the VN. In other words, it must be avoided that all VLs belonging to a VN cut-set[1], are mapped on the same physical link. Network survivability can be guaranteed by SVNM against double-link failures, but such mapping requires to meet two conditions: i) minimum node degree of the physical network is at least equal to three. ii) minimum node degree of each virtual network is at least equal to three. Therefore, providing SVNM against double-link failures is not always possible and in case is possible it may require high cost in terms of wavelength consumption.

In this paper, we focus on the SVNM problem for multiple VNs with inter-VN capacity sharing in order to guarantee network survivability against double-link failures. We refer to this problem as SVNM with capacity sharing. Although the SVNM against double-link failures has been solved in other works, to the best of our knowledge, this is the first study that investigates it using VN capacity sharing and considering multiple VNs.

To solve the SVNM with capacity sharing we propose a technique called *SVNM with inter-VN capacity sharing (SINC)*, which improves the reliability of the VNs and allows to preserve the service reachability in case of a double-link failure by minimizing the amount of physical network resources (i.e., number of wavelengths occupied) with respect to SVNM without VN capacity sharing. Note that, intra-VN survivability against single-link failures is guaranteed by SVNM without capacity sharing, while inter-VN survivability against double-link failures is reached through VN capacity sharing.

The main contributions of this study are as follows: 1) we propose a new technique called SINC for guaranteeing VN survivability against double-link failures based on capacity sharing; 2) we propose new ILP formulations for modeling SINC with the objective to maximize VN availability and minimize total wavelength consumption; 3) we perform a numerical analysis to evaluate the benefits of SINC with respect to SVNM without capacity sharing.

The rest of the paper is organized as follows. Sec. II discusses related work. Sec. III formally states the problem of SVNM with capacity sharing and presents SINC. Sec. IV describes the proposed ILP models. Sec. V discusses some numerical results. Sec. VI concludes the paper.

II. Related Work

The SVNM problem has been modeled and solved in several previous works, under different assumptions and following different methodologies [3], [5] - [10], [17] - [19]. Several papers have addressed SVNM using protection and restoration approaches against a single physical link failure. In Refs. [6], [7], authors propose ILP models and heuristic approaches for SVNM in IP-over-WDM networks. In Ref. [6], authors use SVNM to guarantee VN survivability against single-link failures considering backup capacity sharing between connections at the IP and optical layer, and compare their approach with shared protection at the optical layer. Both [7] and [8] propose approaches based on cut-disjointness to ensure survivability. Ref. [9] presents a two-stage approach to provide a SVNM against single-link failures using the concept of optimal backup topologies. In Ref. [5], authors study how to ensure SVNM wih content connectivity against single-link failures and SVNM with content connectivity against double-link failures. In our work, we focus only on network connectivity. In Ref. [10], authors provide a topology-aware SVNM approach to recover from failures of the critical nodes of the substrate network.

A more generic version of the SVNM problem is the Survivable Virtual Network Embedding (SVNE) problem [11] – [16], where the locations of the virtual nodes are an output of the problem (i.e., not only the mapping of virtual links, but also the mapping of virtual nodes over the physical network must be decided, unlike in SVNM where node mapping is given). In Refs. [11] and [12], authors study how to protect virtual nodes and links with backup resources in the physical network, while Refs. [13] and [14] solve the SVNE problem using recovery methods. In Ref. [15], authors ensure that the unaffected part of a VN remains connected under a single node failure to continue the services provided by the VN. In Ref. [16], authors discuss an availability-aware SVNE in optical inter-DC networks.

Research studies investigating SVNM against multiple-link failures have also appeared. Ref. [17], proposes an ILP model to solve SVNM ensuring the content connectivity against k-link failures, while Ref. [3] investigates a strategy to ensure VN survivability through the recovery of slices in the presence of multiple-link failures. In Ref. [18], author presents a cost effective solution to provide temporary connectivity between network nodes affected by multiple-link failures. In particular, some innovative concepts like the utilization of a third-party network and the identification of gateways to move traffic from one VN to another, have inspired some parts of our work. In Ref. [19], authors propose three algorithms for survivable Service Function Chaining while exploiting unused backup capacity of high priority requests as backup resources for low priority users. In our work, we apply a similar concept to allow the capacity sharing among VNs. Concluding, to the best of our knowledge, no previous work has investigated SVNM of multiple VNs using VN capacity sharing.

III. Survivable Virtual Network Mapping with Capacity Sharing

A. Problem Formulation

The SVNM with capacity sharing problem can be stated as follows. **Given** 1) a physical network modeled by a graph $G(N, E)$, consisting of N nodes and E edges, 2) a set of VNs V, each represented by a graph $G^v(N_L^v, E_L^v)$, where N_L^v

[1]A cut-set is a set of links whose removal disconnects the VN [7].

is the set of virtual (logical) nodes and N_L^v is the set of virtual (logical) links representing bidirectional requests for each pair of nodes in each VN $v \in V$, and 3) the set of all double-link failures in the physical network represented as F (which we refer to as double-failed-link sets), we **decide** the mapping of the VNs (i.e., the routing of all VLs in all VNs) over the physical network considering all failure sets, guaranteeing intra-VN survivability to single-link failures and allowing inter-VN capacity sharing in case of double-link failure, with the **objective** of maximizing the availability (AV) and minimizing the total wavelength consumption[2] (TWC), **constrained by:** i) *SVNM constraints*, i.e., each VN must remain connected in the event of a single-link failure, ii) *Capacity sharing constraints*, i.e., an available path (i.e., a surviving path which connects the endpoints of a disconnected VL) can be found on the combined VN to disconnected VLs, iii) *Capacity sharing limit constraints*, i.e., a limit to capacity sharing to specific cases of failures is imposed. We use *combined virtual network* to denote an overarching VN that is composed by all virtual nodes and all VLs of all VNs, i.e., the union of all VNs. Common virtual nodes are joined into a single node, while equal VLs are represented distinctly, as different VLs in the combined VN. Note that we consider a VN v as disconnected by a double-failed-link set k if v is separated at least in two different components after links in k fail.

B. SVNM with Inter-VN Capacity Sharing (SINC)

SINC performs intra-VN SVNM against single-link failures, but with the possibility of inter-VNs capacity sharing in case of double-link failures. In fact, double-link failures may disconnect many VLs and, in some cases, may cause the disconnection of the entire VN (i.e. when some nodes of the VN are disconnected from the rest of the topology), causing the interruption of a service for the end users. To avoid such undesired scenarios, SINC allows a VN A to share its capacity with a VN B only when the latter is disconnected due to double-link failures. This way, we allow disconnected VNs to be back up and continue functioning despite double-link failures.

We note here that network slice isolation is an important property in network slicing. It can be defined as the property that services in a slice may operate without any direct or indirect influence from activities in other slices, and unsolicited influence of the InP [20]. Although inter-VN capacity sharing does not fully preserve this property, we emphasize here that our approach preserves isolation for single failure, and gives up isolation on double failures.

The details of this procedure will have to be inserted and specified in the Service Level Agreement (SLA) between the InP and its tenants. Some possible guidelines for a SLA with SINC are reported below:

1) It must be specified which VNs can share capacity. In our case we consider all VNs can share their capacity, to show the maximum advantage SINC provides.
2) Different limitations on capacity sharing can be defined, so that it is applied only when really necessary. For example, failure situations in which it can be applied can be pre-defined. In this way, network slices isolation is kept as much as possible. In our study, we apply capacity sharing only when at least one VN is disconnected by a double-link failure.
3) A VN can request a limited amount of sharing capacity and this process can be applied only if it does not interrupt the service of the VN that shares its capacity. For the sake of simplicity, we do not apply a constraint on the amount of shared capacity.

In SINC, traffic can be transferred from one slice to another through common nodes, which we refer to as inter-slice gateways, between two VNs. These gateways allow to reconnect a VL of a VN affected by a failure. Figures 2 and 3 show examples of how inter-VN capacity sharing is applied to provide survivability against double-link failures. Figures 2 (a) and (b) show two different VNs and Fig. 2 (c) shows the union of the two VNs (that is, a VN consisting of all nodes and VLs of the two VNs combined in one VN). Note that common nodes 1 and 6 (i.e., inter-slice gateways) are joined into one single node (highlighted in yellow). Looking at Fig. 2 (c) is possible to notice if traffic belonging to a certain VL can be forwarded or not by sharing the capacity of the other VN. For example, if VLs (1-7) and (1-4) of VN A fail, they can be reconnected sharing the capacity of VN B through paths 1-6-7 and 1-6-4 respectively. In particular, a disconnected VL can be reconnected by SINC only if exists at least an available path in the combined VN that connects its source and its destination.

Figure 3 shows a double-link failure situation and how this affects the VNs introduced in Fig. 2. The same VNs and combined VN of Fig. 2 are depicted respectively in (a), (b), (c) and a physical network is represented in (d), where a survivable mapping of the two networks has been applied. The failure of physical links (1-7) and (2-6) cause the failure of VLs (1-7) of VN A and of (1-6), (2,5) of VN B. Failures are reported also in the combined VN. In this case VN A is not disconnected by double-link failure, since it is not separated in two different parts. On the contrary, VN B is disconnected. With capacity sharing, VLs (1-6) and (2-5) of VN B can be reconnected because an available path in the combined VN that connects their sources and destinations can be found. In particular, VL (1-6) is reconnected through virtual path 1-4-6 and VL (2-5) is reconnected through virtual path 2-1-4-6-5. A

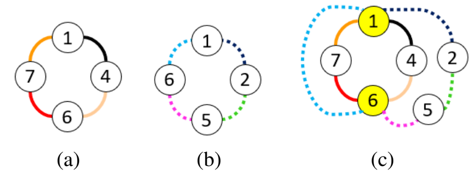


Fig. 2: (a) Virtual network A, (b) virtual network B, (c) combined virtual network A+B with inter-slice gateways highlighted in yellow.

[2]The order of priority of the two objectives is inter-changed from one scenario to another for the aim of presenting a comprehensive analysis.

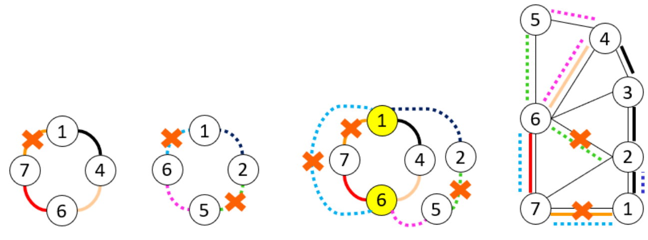


Fig. 3: (a) Virtual network A, (b) virtual network B, (c) combined virtual network A+B with inter-slice gateways highlighted in yellow, (d) physical network with a survivable mapping against single-link failures and a double-link failure. Disconnected VLs can be reconnected through inter-VN capacity sharing.

physical available path corresponds to each logical available path of the combined VN. Therefore, capacity sharing allows both VNs to remain connected despite the failures.

To maintain the isolation between network slices as much as possible, inter-slice gateways must not be used if it is not strictly necessary. So we enforce that a VL can use a gateway only when all these conditions are jointly occurring: i) The failure disconnects the VL. ii) The failure does not affect the path from the source of the VL to the gateway. iii) The failure disconnects the VN (as for this last condition, note that, if no cut-set of a VN is disconnected, for sure the VN remains connected and it does not need capacity sharing). iv) At least an available path connecting source and destination of the disconnected VL in the combined VN exists. As it will be shown in section V, capacity sharing allows to reconnect the vast majority of disconnected VLs. Successful reconnection of all VLs on the combined VN cannot be guaranteed, because some combinations prevent VLs from using of inter-slice gateways. More rigorously, inter-slice gateways cannot be used when: i) A VN has only one node or no nodes in common with other VNs. ii) Failure causes the isolation of at least one node from the rest of the physical topology. iii) Failure disconnects one or more nodes of the VN and those nodes cannot reach a gateway of that VN (i.e., those nodes are not gateways and are isolated from the rest of the VN).

We propose to apply SINC with two different objectives.

One-step SINC max availability (1-SINC-MA): This survivability scenario combines SVNM and inter-VN capacity sharing. Resource allocation is performed in a single step, which allows to reach higher resource efficiency, since mapping can be performed taking count of the consequent reconnection of disconnected VLs for all double-failed-link sets. 1-SINC-MA first maximizes AV and then minimizes TWC.

One-step SINC min wavelengths (1-SINC-MW): This scenario differs from the previous one only for the priority order of the objective functions, as it first minimizes TWC and then maximizes AV.

C. Benchmark Survivability Scenarios

In this section, we present the benchmark survivability scenarios considered in our work.

SVNM against double-link failures (SVNM-DF), i.e., ensuring a virtual network mapping that is survivable to double-link failures. If such mapping exists, VN survivability against double-link failures is guaranteed. SVNM-DF has very high resource consumption, and it is used to evaluate how much wavelength channels can be saved using SINC.

SVNM min wavelengths (SVNM-MW), i.e., ensuring a virtual network mapping that is survivable to single-link failures. Its objectives are, in terms of priority, (1) to minimize TWC and (2) to maximize AV of VNs.

SVNM max availability (SVNM-MA). SVNM-MA differs from SVNM-MW only for the priority order of the objectives: SVNM-MA maximizes first AV, and second it minimizes TWC. Since objectives are different, the mappings performed by these two scenarios may be different. Comparing SVNM-MA with SVNM-MW we can observe the trade-off between AV and wavelength usage.

Two-step SINC min wavelengths (2-SINC-MW), i.e., applying SINC using a two-step approach: 1) A first step provides a SVNM over the physical network. 2) Given the mapping of all VNs, the second step reconnects all disconnected VLs through the combined VN allowing the capacity sharing through inter-slice gateways. 2-SINC-MW first minimizes TWC and then maximizes AV. It allows to understand if we can reach the survivability against double-link failures even if we divide the procedure in two steps.

Two-step SINC max availability (2-SINC-MA): 2-SINC-MA has a different ordering of objectives. It first maximizes AV and then minimizes TWC.

IV. Integer Linear Programming Formulation

In this section we present in details the ILP models proposed to solve the problem. The ILPs will be presented in an incremental manner, going from the basic scenario (classical SVNM) to more complex ones. Note that decision variables and constraints of initial scenarios will be used also for later scenarios.

A. ILP 1: SVNM

ILP 1 provides a survivable mapping of the VNs against single-link failures.

Sets and parameters, and variables are described in Tables I and II, respectively.

Objectives: We consider two possible objective functions, maximize AV 1 and minimize TWC 2:

$$1)\ max\ 1 - \frac{\sum_{k \in F} \sum_{v \in V} \alpha_k^v}{\mid V \mid * \mid F \mid} \tag{1}$$

$$2)\ min \sum_{(v,s,t) \in B_L^T} \sum_{(i,j) \in A} q_{ij}^{vst} \tag{2}$$

In Eqn. 1 AV is defined as the sum over all double-failed-link sets of the number of surviving VNs (i.e., number of VNs not

Tab. I: Parameters and sets description for the ILP models.

Sets	Description
$G(N,E)$	Undirected graph representing the physical network, where N denotes the set of physical nodes and E the set of undirected physical links
A	Set of directed physical links
V	Set of virtual networks
$G^v_L(N^v_L, E^v_L)$	Undirected graph representing the VN $v \in V$, where $N^v_L \subseteq N$ is the set of virtual nodes and E^v_L represents the set of VLs
$G^T_L(N^T_L, E^T_L)$	Undirected graph representing the combination of all VNs, where $N^T_L \subseteq N$ is the set of all virtual nodes and E^T_L represents the set of all VLs
B^T_L	Set of directed VLs of the combined VN
$C^v(S^v, N^v_L - S^v)$	Cut-sets of VN $v \in V$
F	Set of all combinations of double-link failures of the physical network
D_k	VLs of combination $k \in F$ of double failures
$c_{i,j}$	Capacity of physical link $(i,j) \in A$
e	Minimum wavelength consumption value

Tab. II: Description of the variables of the ILP models.

Variable	Description
γ^{vst}_{ij}	Binary, equal to 1 if VL (s,t) belonging to a VN $v \in V$ (also called virtual connection $(v,s,t) \in E^T_L$) is mapped on physical link $(i,j) \in E$
q^{vst}_{ij}	Binary, equal to 1 if virtual connection $(v,s,t) \in B^T_L$ is mapped on physical link $(i,j) \in A$
g^{vst}_k	Binary, equal to 1 if VL $(v,s,t) \in E^T_L$ is disconnected by double-link failure $k \in F$
r^{vh}_k	Binary, equal to 1 if cut-set $h \in S^v$ of VN $v \in V$ is disconnected by double-link failure $k \in F$
α^v_k	Binary, equal to 1 if VN $v \in V$ is disconnected by double link failure $k \in F$
l^{vst}_{ijad}	Binary, equal to 1 if virtual connection $(v,s,t) \in B^T_L$ is mapped on physical link $(i,j) \in A$ or on physical link $(a,d) \in A$
$p^{v_1 st}_{v_2 adk}$	Binary, equal to 1 if virtual connection $(v_1,s,t) \in B^T_L$ is forwarded through VL $(v_2,a,d) \in B^T_L$ for double-failed-link set $k \in F$
$\rho^{v_1 st}_{v_2 adk}$	Binary, equal to 1 if virtual connection $(v_1,s,t) \in E^T_L$ is forwarded through VL $(v_2,a,d) \in E^T_L$ for double-failed-link set $k \in F$
f^{vst}_k	Binary, equal to 1 if virtual connection $(v,s,t) \in E^T_L$ is forwarded through a disconnected link on the combined VN for double-failed-link set $k \in F$
$\sigma^{v_1 st}_{v_2 adk}$	Binary, equal to 1 if virtual connection $(v_1,s,t) \in B^T_L$ is forwarded through a disconnected VL $(v_2,a,d) \in B^T_L$ for double-failed-link set $k \in F$
$m^{v_1 st}_{v_2 adk}$	Binary, equal to 1 if virtual connection $(v_1,s,t) \in E^T_L$ is forwarded through a VL (a,d) of a different VN $(v_2 \neq v_1)$ for double-failed-link set $k \in F$
n^{vst}_k	Binary, equal to 1 if virtual connection $(v,s,t) \in E^T_L$ is forwarded through at least a VL of another VN ($\neq v$) for double-failed-link set $k \in F$
χ^{vh}_k	Binary, equal to 1 if cut-set $h \in S^v$ of VN $v \in V$ is disconnected for double-failed-link set $k \in F$
θ^v_k	Binary, equal to 1 if VN $v \in V$ has at least a cut-set down for double-failed-link set $k \in F$

disconnected by double-failed-link sets), divided by the best possible case, in which all VNs survive to each double-failed-link set (i.e., no VN is disconnected for each double-failed-link set). The two objectives are weighted to give more importance to one or the other.

Subject to:

SVNM Constraints: Constr. 3 is the VL mapping constraint. It ensures that all VLs of a VN are mapped onto one physical path of the physical network. Constr. 4 is the link capacity constraint and ensures that the sum of all VLs mapped over one physical link does not exceed the capacity of that physical link. Constr. 5 is the survivability constraint and guarantees that the mapping of all VLs of a VN is survivable, enforcing that all VLs which belong to a cut-set of the VN cannot be mapped on the same physical link, where $C^v(S^v, N^v_L - S^v)$ represents the set of VLs that belong to a cut of VN $G^v_L(N^v_L, E^v_L)$ where $S^v \subset N^v_L$ represents a subset of logical nodes N^v_L.

$$\sum_{(i,j)\in A} q^{vst}_{ij} - \sum_{(j,i)\in A} q^{vst}_{ij} = \begin{cases} 1 & i = s \\ -1 & i = t \\ 0 & otherwise \end{cases} \qquad \forall i \in N,\ \forall (v,s,t) \in B^T_L \quad (3)$$

$$\sum_{(v,s,t)\in B^T_L} q^{vst}_{ij} \le c_{i,j} \qquad \forall (i,j) \in A \quad (4)$$

$$\sum_{(s,t)\in C^v(S^v, N^v_L - S^v)} \gamma^{vst}_{ij} < |C^v(S^v, N^v_L - S^v)| \qquad \forall (i,j) \in E,\ \forall v \in V,\ \forall S^v \subset N^v_L \quad (5)$$

Availability Computation Constraints: Constr. 6 and 7 allow to identify the disconnected VLs of each VN for each double-failed-link set. Starting from the disconnected VLs, constraints 8 and 9 identify the disconnected cut-sets of each VN for each double-failed-link set. The disconnected cut-sets are used to define if a VN is disconnected or not for each double-failed-link set. Constr. 10 and 11 find if a VN is disconnected or not for each double-failed-link set. A VN is disconnected if at least one of its cut-sets is disconnected from the considered double-failed-link set.

$$g^{vst}_k \ge \gamma^{vst}_{ij} \qquad \forall (v,s,t) \in E^T_L,\ \forall k \in F,\ \forall (i,j) \in D_k \quad (6)$$

$$g^{vst}_k \le \sum_{(i,j)\in D_k} \gamma^{vst}_{ij} \qquad \forall (v,s,t) \in E^T_L,\ \forall k \in F \quad (7)$$

$$r^{vh}_k \le g^{vst}_k \qquad \forall v \in V,\ \forall k \in F,\ \forall (s,t) \in C^v(S^v, N^v_L - S^v),\ \forall S^v \subset N^v_L \quad (8)$$

$$r^{vh}_k \ge \sum_{(s,t)\in C^v(S^v, N^v_L - S^v)} g^{vst}_k - (|C^v(S^v, N^v_L - S^v)| - 1) \qquad \forall v \in V,\ \forall S^v \subset N^v_L,\ \forall k \in F \quad (9)$$

$$\alpha^v_k \ge r^{vh}_k \qquad \forall v \in V,\ \forall S^v \subset N^v_L,\ \forall k \in F \quad (10)$$

$$\alpha^v_k \le \sum_{S^v \subset N^v_L} r^{vh}_k \qquad \forall v \in V,\ \forall k \in F \quad (11)$$

B. ILP 2: SVNM against double-link failures

ILP 2 provides a survivable mapping of the VNs against double-link failures and considers as unique objective to minimize the TWC.

Double-Link Survivability Constraints: Constr. 12 and 13 guarantee that the mapping of all VLs of a VN is survivable against double-link failures.

$$0 \leq 2 * l_{ijad}^{vst} - \gamma_{ij}^{vst} - \gamma_{ad}^{vst} \leq 1$$
$$\forall (i,j) \in E,\ \forall (a,d) \in E,\ \forall (v,s,t) \in E_L^T \quad (12)$$

$$\sum_{(s,t) \in C^v(S^v, N_L^v - S^v)} l_{ijad}^{vst} < |C^v(S^v, N_L^v - S^v)|$$
$$\forall (i,j) \in E,\ \forall (a,d) \in E,\ \forall v \in V,\ \forall S^v \subset N_L^v \quad (13)$$

C. ILP 3: Two-step SINC

If we execute ILP 1 and in a second step, ILP 3, we model the two-step SINC scenarios. ILP 3 takes as input a survivable mapping from ILP 1 and applies the inter-VN capacity sharing.

Capacity Sharing Constraints: Constr. 14 finds a virtual path to VLs on the combined VN for double-failed-link set k. The virtual path of each VL will determine if the VL remains connected for each double-failed-link set and if capacity sharing need to be used or not. Constr. 15 imposes that VLs not affected by the failure remain connected. The latter constraint allows to save computational time because the model has to find a virtual path on the combined VN only to disconnected VLs. Constr. 16 and 17 allow to identify if VLs are satisfied or not by inter-VN capacity sharing, i.e., if each VL finds at least an available path on the combined VN or not for each double-failed-link set k.

$$\sum_{(v_2,a,d) \in B_L^T} p_{v_2adk}^{v_1st} - \sum_{(v_2,d,a) \in B_L^T} p_{v_2dak}^{v_1st} = \begin{cases} 1 & a = s \\ -1 & a = t \\ 0 & other. \end{cases}$$
$$\forall (v_1,s,t) \in B_L^T,\ \forall a \in N_L^{v_1},\ \forall k \in F \quad (14)$$

$$\rho_{v_2adk}^{v_1st} \geq (1 - g_{v_2adk})$$
$$\forall (v_2,a,d) \in E_L^T,\ \forall (v_1,s,t) \in E_L^T : (v_1,s,t) = (v_2,a,d),\ \forall k \in F \quad (15)$$

$$f_k^{v_1st} \geq \rho_{v_2adk}^{v_1st} * g_{v_2adk}$$
$$\forall (v_2,a,d) \in E_L^T,\ \forall (v_1,s,t) \in E_L^T,\ \forall k \in F \quad (16)$$

$$f_k^{v_1st} \leq \sum_{(v_2,a,d) \in E_L^T} \rho_{v_2adk}^{v_1st} * g_{v_2adk}$$
$$\forall (v_1,s,t) \in E_L^T,\ \forall k \in F \quad (17)$$

Availability Computation Constraints: Constr. 18 and 19 find if a VN is available or not for each double-failed-link set. A disconnected VN is unavailable if at least one of its disconnected VLs cannot be reconnected by inter-VN capacity sharing, i.e., the VL cannot be reconnected through an available path on the combined VN.

$$\alpha_k^v \geq f_k^{vst} \qquad \forall (v,s,t) \in E_L^T,\ \forall k \in F \quad (18)$$
$$\alpha_k^v \leq \sum_{(v,s,t) \in E_L^T} f_k^{vst} \qquad \forall v \in V,\ \forall k \in F \quad (19)$$

D. ILP 4: One-step SINC

ILP 4 models one-step SINC scenarios.

Capacity Sharing Constraints: Constr. 20-22 allow to identify disconnected VLs. Constr. 23 and 24 find if each disconnected VL is reconnected through an available path on the combined VN or not.

$$\sigma_{v_2adk}^{v_1st} \leq \rho_{v_2adk}^{v_1st}$$
$$\forall (v_2,a,d) \in E_L^T,\ \forall (v_1,s,t) \in E_L^T,\ \forall k \in F \quad (20)$$

$$\sigma_{v_2adk}^{v_1st} \leq g_{v_2adk}$$
$$\forall (v_2,a,d) \in E_L^T,\ \forall (v_1,s,t) \in E_L^T,\ \forall k \in F \quad (21)$$

$$\sigma_{v_2adk}^{v_1st} \geq \rho_{v_2adk}^{v_1st} + g_{v_2adk} - 1$$
$$\forall (v_2,a,d) \in E_L^T,\ \forall (v_1,s,t) \in E_L^T,\ \forall k \in F \quad (22)$$

$$f_k^{v_1st} \geq \sigma_{v_2adk}^{v_1st}$$
$$\forall (v_2,a,d) \in E_L^T,\ \forall (v_1,s,t) \in E_L^T,\ \forall k \in F \quad (23)$$

$$f_k^{v_1st} \leq \sum_{(v_2,a,d) \in E_L^T} \sigma_{v_2adk}^{v_1st}$$
$$\forall (v_1,s,t) \in E_L^T,\ \forall k \in F \quad (24)$$

Capacity Sharing Limit Constraints: Constr. 25-27 identify which VLs require the inter-VN capacity sharing to be satisfied properly. A disconnected VL uses the capacity sharing if it is reconnected through a path that contains at least a VL of another VN. Constr. 28 and 29 identify the disconnected cut-sets for each double-failed-link set, while constraints 30 and 31 find if at least a cut-set of a VN is down for each double-failed-link set. Constr. 32 limit the inter-VN capacity sharing, imposing that all VLs of a VN must not be forwarded through other VNs if that VN is not disconnected.

$$m_{v_2adk}^{v_1st} = \rho_{v_2adk}^{v_1st}$$
$$\forall v_1, v_2 \in V : (v_1 \neq v_2),\ \forall (s,t) \in E_L^{v_1},\ \forall (a,d) \in E_L^{v_2},\ \forall k \in F \quad (25)$$

$$n_{v_1stk} \geq m_{v_2adk}^{v_1st}$$
$$\forall v_1, v_2 \in V,\ \forall (s,t) \in E_L^{v_1},\ \forall (a,d) \in E_L^{v_2},\ \forall k \in F \quad (26)$$

$$n_{v_1stk} \leq \sum_{v_2 \in V, (a,d) \in E_L^{v_2}} m_{v_2adk}^{v_1st}$$
$$\forall v_1 \in V,\ \forall (s,t) \in E_L^{v_1},\ \forall k \in F \quad (27)$$

$$\chi_k^{vh} \leq g_{vstk}$$
$$\forall v \in V,\ \forall k \in F,\ \forall (s,t) \in C^v(S^v, N_L^v - S^v),\ \forall S^v \subset N_L^v \quad (28)$$

$$\chi_k^{vh} \geq \sum_{(s,t) \in C^v(S^v, N_L^v - S^v)} g_{vstk}$$
$$\forall v \in V,\ \forall S^v \subset N_L^v,\ \forall k \in F \quad (29)$$

Tab. III: Summary of survivability scenarios, ILP models and objective functions.

Survivability Scenarios	ILP Models	Objectives
SVNM-MW	ILP 1	1) min TWC, 2) max AV
SVNM-MA	ILP 1	1) max AV, 2) min TWC
SVNM-DF	ILP 2	min TWC
2-SINC-MW	ILP 1 then ILP 3	ILP 1: 1) min TWC, 2) max AV ILP 3: max AV
2-SINC-MA	ILP 1 then ILP 3	ILP 1: 1) max AV, 2) min TWC ILP 3: max AV
1-SINC-MW	ILP 4	1) min TWC, 2) max AV
1-SINC-MA	ILP 4	1) max AV, 2) min TWC

$$\theta_k^v \geq \chi_k^{vh} \qquad \forall v \in V,\ \forall S^v \subset N_L^v,\ \forall k \in F \quad (30)$$

$$\theta_k^v \leq \sum_{S^v \subset N_L^v} \chi_k^{vh} \qquad \forall v \in V,\ \forall k \in F \quad (31)$$

$$n_{vstk} \leq \theta_k^v \qquad \forall v \in V,\ \forall (s,t) \in E_L^v,\ \forall k \in F \quad (32)$$

Wavelength Consumption Limit Constraint: Constr. 33 limits the TWC to the minimum value e. This constraint is applied only for 1-SINC-MW to save computational time considering as unique objective the maximization of AV.

$$\sum_{(i,j)\in A,\ (v,s,t)\in B_L^T} q_{ij}^{vst} \leq e \quad (33)$$

Survivability scenarios with their objectives and ILP models are summarized in Tab. III.

V. Numerical results

This section presents numerical results obtained by the ILP models considering different physical and virtual networks. We perform two analysis: i) SINC vs SVNM against double-link failures and ii) SINC vs Benchmark scenarios. The first analysis allows to evaluate the wavelength savings when SINC reaches the complete survivability against double-link failures, while the second analysis allows to quantify the AV improvement enabled by SINC compared to SVNM and to understand if survivability against double-link failures can be obtained applying SINC in a separate step from SVNM. We implemented the ILPs using AMPL and we used CPLEX 12.10 to solve all the ILP versions of the optimization problem. All evaluations for ILPs are performed on a computer with Intel(R)Core(TM) i5-1035 CPU (@ 1.00GHz) processor and 8192 MB of memory. Figure 4 shows the physical networks ((a), (b) and (c)) and the VNs (d) considered in our work.

A. SINC vs SVNM Against Double-Link Failures

Before starting commenting results, we note that, to guarantee VN survivability against double-link failures two conditions must be satisfied: i) minimum node degree of the physical network is at least equal to three. ii) minimum node degree of each virtual network is at least equal to three. Hence, we modified the 7-node German network by adding two links to it, in order to have a minimal node degree of 3 (we refer to this modified network topology by *modified 7-node German network* and it is shown in Fig. 4(b)). We consider 4 and 5-node ring or full-mesh VNs and a number of VNs ranging from 2 to 6. We compare the performance of the survivability

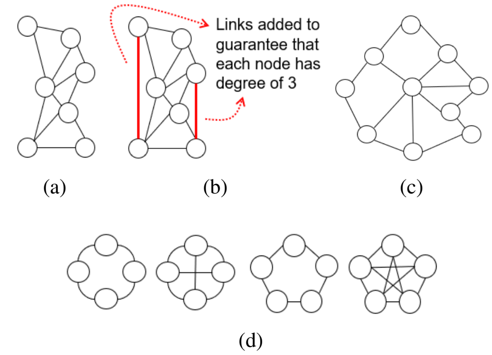


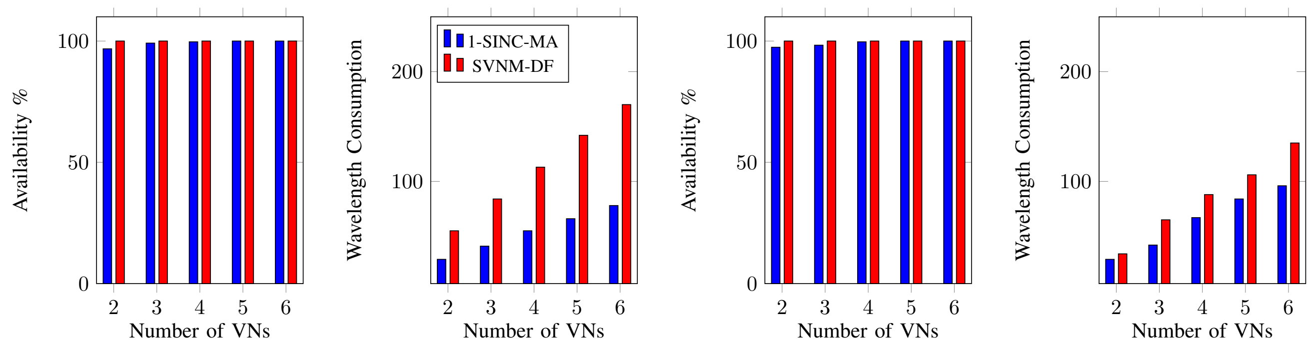
Fig. 4: The (a) 7-node German, (b) 7-node German modified (minimum node degree 3) and (c) 10-node Italian physical networks and the set of VNs (d) considered in the evaluations.

scenarios in terms of i) availability and ii) total wavelength consumption. To increase generality of our numerical results, we average them over ten different instances for every case study and we also vary the node mapping among the different evaluations.

Figure 5 shows the comparison in terms of AV and TWC between 1-SINC-MA and SVNM-DF considering a number of 5-node ring VNs and of 4/5-node mixed (ring or full-mesh) VNs ranging from 2 to 6. Providing a SVNM-DF guarantees the 100% of AV in all cases but it is very costly in terms of TWC. 1-SINC-MA provides AV values close to SVNM-DF with about half of the TWC in the case of ring VNs and, more in general, with a much lower TWC compared to other cases. As the number of VNs increases 1-SINC-MA improves the AV, since the number of nodes that can act as inter-slice gateways grows and the ability to share capacity also grows. In particular, 1-SINC-MA guarantees the complete survivability against double-link failures (Fig. 5 (a) and (c)) with at least 5 VNs in both cases (ring or mixed VNs), while the wavelength savings are on average of 46,67% and of 18,64% respectively with ring VNs (Fig. 5 (b)) and mixed VNs (Fig. 5 (d)). Wavelength savings are more limited with mixed (ring or full-mesh) VNs because full-mesh VNs are highly-connected.

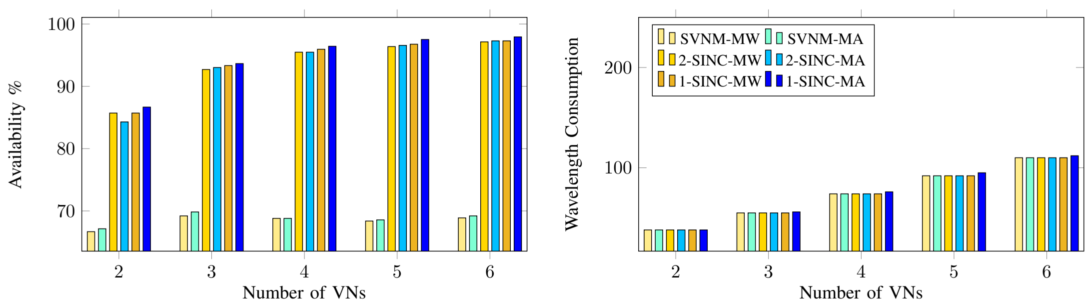
B. SINC vs Benchmark Scenarios

We now compare SINC to other survivability scenarios in terms of AV and TWC to quantify the gains provided by inter-VN capacity sharing and to evaluate the impact of the joint optimization. In this analysis, we do not consider SVNM-DF as the physical topologies considered do not have all nodes with a node degree of 3, and therefore SVNM-DF cannot be applied. We consider the 7-node German network (shown in Fig. 4(a)) and the 10-node Italian network (shown in Fig. 4(c)) as physical networks. We divide the analysis into two sections. In the first, we consider 5-node ring VNs (section referred to as *Ring VNs*) while in the second we consider full-mesh VNs (section referred to as *Mixed VNs*). In all cases, we consider number of VNs ranging from 2 to 6. We average results over ten different instances for every case study varying the node



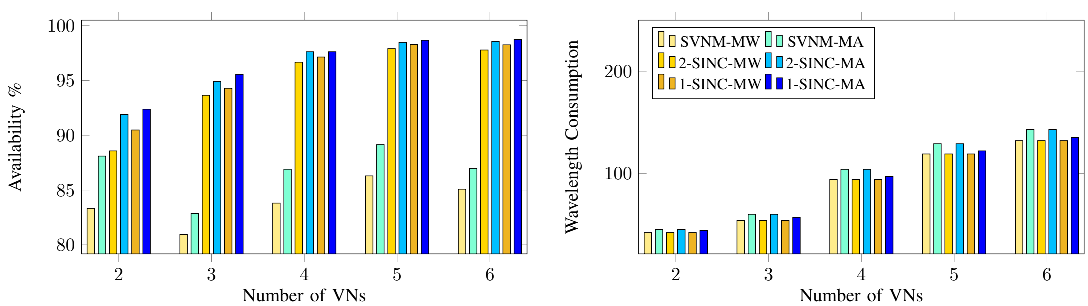
(a) Availability % with ring VNs (b) Wavelength consumption with ring VNs (c) Availability % with mixed VNs (d) Wavelength consumption with mixed VNs

Fig. 5: Availability and wavelength consumption comparison between 1-SINC-MA and SVNM-DF as a function of the number of VNs for the modified 7-node German network as physical network and for the ring ((a) and (b)) or mixed (ring or full-mesh) ((c) and (d)) networks as virtual networks.



(a) Availability % (b) Wavelength consumption

Fig. 6: Availability and wavelength consumption for the different survivability scenarios as a function of the number of VNs for the 10-node Italian network as physical network and for the 5-node ring networks as virtual networks.



(a) Availability % (b) Wavelength consumption

Fig. 7: Availability and wavelength consumption for the different survivability scenarios as a function of the number of VNs for the 10-node Italian network as physical network and for the 4/5-node mixed (ring or full-mesh) networks as virtual networks.

mapping among the different evaluations to increase generality of results.

Ring VNs: Figures 6(a) and 6(b) show the AV and the TWC of all survivability scenarios for a number of VNs ranging from 2 to 6 in the 10-node Italian physical network.

Results show that *1-SINC-MA* has the highest AV among all survivability scenarios showing a constant increase in terms of AV as the number of VNs in the network increases. On average, 1-SINC-MA gets an AV gain of about 25% than SVNM-MW and SVNM-MA, while it provides a little AV improvement than 2-SINC-MW, 2-SINC-MA and 1-SINC-MW (respectively of 0,96%, 1,11% and 0,63%). The AV gain provided by 1-SINC-MA comes on a very slight additional TWC. More in detail, a first increase of AV is provided by inter-VN capacity sharing from SVNM-MW and SVNM-MA to 2-SINC-MW and 2-SINC-MA, requiring the same network cost. The joint optimization applied in 1-SINC-MW and in 1-SINC-MA further increases the AV requiring a slightly higher TWC. The AV of 1-SINC-MW and 1-SINC-MA ranges respectively between 85,71% (with 2 VNs) and 97,30% (with 6 VNs), and between 86,67% (with 2 VNs) and 97,94% (with 6 VNs). As expected, the AV provided by SINC increases with the increase of the number of VNs.

Mixed VNs: Figures 7(a) and 7(b) show the AV and the TWC of all survivability scenarios, for a number of VNs ranging from 2 to 6 in the 10-node Italian physical network. Also with mixed VNs, 1-SINC-MA has the highest AV among all survivability scenarios, but the AV gain is lower than the case with ring VNs. On average, 1-SINC-MA guarantees an AV improvement of 11,80% and of 9,79% than SVNM-MW and SVNM-MA respectively, while it shows a small AV gain compared to the other three scenarios (about 1%). Inter-VN capacity sharing improves the AV of 2-SINC-MW and of 2-SINC-MA compared to SVNM-MW and SVNM-MA respectively, while the joint optimization further increases the AV from 2-SINC-MW and 2-SINC-MA to 1-SINC-MW and 1-SINC-MA. Note that 1-SINC-MA provides higher AV than 2-SINC-MA with lower TWC. As before, if the number of VNs grows, also the AV provided by SINC grows.

VI. Conclusion

We propose and investigates new techniques to solve the problem of Survivable Virtual Network Mapping with capacity sharing with the aim of maximizing the availability and minimizing the total wavelength consumption. We call the proposed strategy *SVNM with inter-VN capacity sharing (SINC)*. SINC permits capacity sharing among VNs only in presence of double-link failures. We identify six survivability scenarios, representing different survivability strategies, with different objectives. We formulated ILP models for all considered scenarios. Numerical results, obtained on a representative network instance, show that the VN availability achieved using SINC is improved significantly (up to 25% with ring VNs and up to 12% with mixed VNs) compared to that of SVNM against single-link failures. In addition, SINC does not require a minimum node degree equal to 3, differently from SVNM against double-link failures. For the considered scenarios, with 5 or 6 VNs SINC achieves the survivability against double-link failures with a much lower wavelength consumption (on average 46,67% and 18,64% of wavelengths savings respectively with ring and mixed VNs) compared to SVNM against double-link failures. As expected, the advantages of SINC are dependent on the number of VNs considered, since as this number grows, the number of common nodes that can act as inter-slice gateways also grows. As future works, we plan to develop efficient heuristic solution applicable to larger network instances, and to extend the analysis to more general problem of Survivable Virtual Network Embedding (SVNE).

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