# VNF Orchestration and Power-disjoint Traffic Flow Routing for Optimal Communication Robustness in Smart Grid with Cyber-Physical Interdependence

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***Abstract*—We explore the use of software-defined networking (SDN) technology in building a communication network for smart grid. With cyber-physical interdependence, such communication network may suffer from cross-network cascading failures. To prevent the failures, we perform virtual network function (VNF) orchestration jointly with power-disjoint routing. Our work is novel in proposing an efficient scheme to find power-disjoint routes at the same time of performing VNF orchestration. We formulate an optimization to maximize the ratio of power-disjoint route count to VNF orchestration cost. The optimization has a non-linear non-convex objective function. We propose a two-level hierarchical solution approach. At higher level, the scheme converts the problem into a fractional maximum flow circulation, which can be solved using simplex method to find the maximum number of power-disjoint routes. Given a higher level solution, the lower level aims to minimize the VNF orchestration cost while satisfying VNF chaining and placement requirements. This lower level hierarchy uses the Dijkstra's algorithm in building a sequence of minimum spanning trees, each roots at the current VNF hosting node in a VNF chain. Extensive simulation results confirm that the proposed scheme can find the maximum number of power-disjoint routes and minimize the cost within a second, for a system with 120 communication nodes. The results show that the number of power-disjoint routes can be increased by increasing either the number of nodes or node degree, but only the node degree can keep the cost flat. Therefore, one should build a robust software-defined smart grid communication network by enhancing node connectivity.**

***Index Terms*—Smart grid, cyber-physical interdependence, power-disjoint route, network function virtualization, software-defined networking.**

## I. Introduction

In our fight against global warming, a smart grid facilitates a large scale integration of renewable energy resources into a power grid. In the presence of time-varying and intermittent renewable power generations, smart grid can dynamically adjust its operation to continuously match electricity supply and demand [1]–[3]. This dynamic control is crucial because an excessive supply-demand gap can lead to a catastrophic failure of the entire power system. For the dynamic control, smart grid requires an advanced communication network to collect data from remote sensors and to disseminate control commands throughout the power grid [4]–[7].

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Building a private communication network to support the dynamic control can incur a large capital expenditure. Therefore, a smart grid operator should lease an existing communication network, instead of building its own one. By avoiding the expensive capital expenditure, the operator can invest the resources in other aspects that cannot be easily outsourced. To capture this business opportunity in a profitable manner, a telecommunication service provider may exploit software-defined networking (SDN) [8]–[10] and network function virtualization (NFV) [11]. Through these technologies, the service provider can rapidly build a smart grid communication network on top of a multi-tenant communication infrastructure which is shared with other non smart grid communication networks.

Strictly, SDN seeks to separate network control functions from packet forwarding functions, while NFV seeks to abstract packet forwarding as well as other networking functions and services from the hardware on which it runs. Specifically, NFV decouples the software of network functions from the physical hardware that runs it on a software-only virtual machine, which is also known as container. Here, the software is called virtual network function (VNF) and the physical hardware is called network function virtualization infrastructure (NFVI) [12]. In this paper, we consider a scenario where SDN requires NFV for the implementation of VNFs on NFVI nodes. Hereafter, we use the term SDN/NFV to refer to this scenario.

Compared to a traditional communication network with specialized hardware, SDN/NFV implements networking middle-boxes in software on cost-efficient generic hardware. Through SDN/NFV, a physical network can be securely sliced into multiple independent virtual networks. In the context of this paper, one of these virtual networks can be our smart grid communication network. Also, networking services, such as network address translator, cache, firewall, gateway, and proxy can be implemented in a quick, flexible and cost-efficient manner. Specifically, VNFs can be dynamically instantiated or terminated, and be scaled up or down to adapt to varying network conditions. Different VNFs can be hosted at different NFVI nodes, and a VNF can be moved from one NFVI node to another node for consolidation.

In a traditional network, a traffic flow travels through different intermediate nodes following a route to reach a destination. In SDN/NFV, there is an additional requirement for the traffic flow to visit some intermediate nodes, which host the VNFs that are necessary in composing a desired networking service. For example, a traffic flow from a sensor must visit a NFVI node that hosts a data encryption function before visiting another node that performs deep-inspection on packet headers, and the encryption VNF must appear immediately after the sensor towards the control center. This additional requirement exists because each networking service is expressed as a graph of VNFs, or more precisely, a sequence of interconnected VNFs with specific functionalities. To meet the requirement, VNF placement and VNF chaining are needed. VNF placement is responsible in making sure that all necessary VNFs are hosted at suitable NFVI nodes. On the other hand, VNF chaining ensures that all necessary VNFs are performed in a prescribed order. Both VNF placement and VNF chaining are two separate processes that are collectively called the VNF orchestration operation.

Existing VNF orchestration schemes have not taken into account the fact that smart grid is a cyber-physical system with interdependence between power grid and its communication network. While the power grid depends on the communication network to transmit data and commands to facilitate dynamic control, the communication network depends on the power grid for its electricity supply [13]. Such cyber-physical interdependence can make smart grid vulnerable to cascading failures [14]. A broken power node can cause a loss of electricity supply to some communication nodes. Without electricity, the affected communication nodes may stop operation [15]. As an example reported in [16], in the 2003 blackout in Italy on September 28th, an unplanned power station shutdown has led to failures of communication network nodes which were responsible for controlling the power grid. This has resulted in a loss of control in a power node, which then cut its electricity supply to some other communication nodes. This process of cascading failures may continue several cycles until the entire system fails [17].

Cascading failures can be prevented by fortifying critical communication nodes so that they will not fail or by providing redundancy to power nodes so that they will not suffer from a loss of control due to a single failure in the communication network. The first approach requires identification of critical nodes, which is a computation intensive process for the need to consider all possible usage and failure scenarios. For the identified critical nodes, fortification will incur a cost for additional resources. As presented in [18], the fortification may appear in the form of providing backup batteries to the communication nodes such that these nodes can continue operation after losing electricity supply from the power grid. However, for this example, there is still no guarantee that the fortified nodes will not fail because the backup battery may run out before the failed power node is restored. This is true because, as highlighted in [19], rapid restoration may be prevented by natural disasters, severe bad weather conditions, etc. Specifically, snowstorms in winter and hurricanes in summer can disrupt power transmission system for an extended period. In summer 2017, a typhoon has brought down a power transmission line tower in Taiwan and has interrupted the power transmission operation for about a week due to the remote location of the collapsed tower.

As shown in the literature, we can provide redundancy to power nodes by establishing multiple power-disjoint communication routes between a power node and the control center [15]. Power-disjointness is a more stringent condition than node-disjointness, where a power-disjoint route must be node-disjoint but not vice versa. Two communication routes are power-disjoint, if routers in one route do not draw electricity supply from a power node that is also an electricity supplier to any router in another route. As such, a failure in a power node may disconnect at most only one of the multiple power-disjoint routes. According to [15], power-disjoint routes can prevent cascading failures without the need of backup batteries for any communication node. In this paper, we develop a method to jointly perform VNF orchestration and power-disjoint traffic flow routing for optimal communication robustness in a smart grid with cyber-physical interdependence. Here, communication robustness is quantified in terms of the number of power-disjoint routes between a power node and the control center. A system is more robust with more power-disjoint routes because a power node will be disconnected from the control center only if all the routes are broken.

The contributions of this papers are summarized as follows:

- Propose to support the communication needs of a smart grid system through SDN/NFV, on top of a multi-tenant communication infrastructure which is shared with other non smart grid communication networks.
- Propose to achieve communication network robustness by establishing multiple power-disjoint communication routes between a power node and the control center.
- Formulate an optimization to maximize the ratio of power-disjoint route count to VNF orchestration cost. This objective function is non-linear non-convex. For the optimization, propose a two-level hierarchical solution approach to jointly maximize the number of power-disjoint routes and minimize the VNF orchestration cost. Perform extensive simulations to evaluate performance of the proposed solution approach.

The rest of this paper is organized as follows. Section II presents a comprehensive survey on related works. The adopted system model is described in Section III. The joint power-disjoint routing and VNF orchestration problem is formulated and solved in Section IV. Section V discusses performance evaluation results, before the paper ends with concluding remarks in Section VI.

## II. Related Work

While there is a rich literature on VNF orchestration, not all existing works have dealt with both VNF placement and VNF chaining [20]–[22]. In [23], an optimization has been formulated to minimize communication latency by controlling VNF placement and computational capacity allocation. Without VNF chaining, [23] has no guarantee in achieving a required VNF sequence order.

The work [24] has dealt with both VNF placement and chaining with consideration on limited network resources and requirements of the functions. Another work [25] is similar to [24], but focuses on VNF orchestration within a data center. In [25], eigen-decomposition of adjacency matrices has been used to reduce complexity and convergence time in placing a desired sequence of VNFs. In [26], the authors have performed

VNF placement, VNF chaining and traffic flow routing at the same time of content caching for a cellular wireless network. Specifically, a heuristic scheme has been proposed to proactively cache popular video content at a NFVI node, in anticipation of changes in traffic route due to user mobility. In [27], VNF orchestration efficiency is measured in terms of the number of admitted traffic flows. For better efficiency, the authors have allowed multiple function chains to share a single VNF instance, which is running at a node. While this idea may be trivial, it can lead to a VNF chain taking a longer route and thus, suffers from an increased latency. The paper has taken into account the interplay between VNF utilization and communication latency. All these papers reviewed above are solely in the context of SDN/NFV and have not dealt with smart grid communications.

The work [28] has discussed a few use cases of SDN for smart grid communications and has described a testbed for a particular use case. A comprehensive survey on the use of SDN in smart grid has been presented in [29]. As summarized in [29], the use of SDN can potentially improve efficiency and resiliency of a smart grid. The flexibility and quick reconfiguration of a software-defined communication network can facilitate dynamic communication route adjustment for control command transmissions in response to changes in network quality of service [30]. As an example, [31] has argued that the fast re-routing capability of SDN can reduce the chance of out-of-order packet delivery and hence, has proposed a heuristic scheme to establish multiple disjoint routes for reliable communications in smart grid. But, these routes are not node-disjoint nor power-disjoint. Similar to [30] and [31], [32] has exploited the agility of SDN for fast communication route recovery in response to a single communication link failure in a wide area measurement system. In [32], data are collected from phase measurement units. In a separate effort that also focuses on phase measurement data collection, [33] has utilized SDN to classify traffic flows into different classes, and to apply content-aware active queue management algorithm on them. As such, critical traffic flow can be assured an tolerable communication latency.

The work [34] has proposed to exploit the intrinsic availability of global information at a SDN controller to perform communication load balancing at the same time of electricity load balancing through demand response. In [35], SDN has been used to build an auto-configuring power substation which has eliminated traditional manual network management routines. In most of the existing works, SDN is applied to the entire smart grid. Instead of deploying a complete software-defined network for the entire smart grid communication network, [36] has proposed a framework that allows only a partial deployment of software-defined network. Following the framework, a hybrid network can be formed with software-defined virtual functions co-exist with traditional network functions. For efficient smart grid communications, a tool has been developed in [37] for VNF placement to minimize communication latency and data center usage cost, but without taking into account VNF chaining. Similar to our work in this paper, [37] has considered a case of establishing multiple disjoint communication routes. However, these routes are only node-disjoint instead of power-disjoint.

Compared to power-disjoint routes, the problem of finding node-disjoint routes is more commonly studied in the literature although such routes cannot prevent cascading failures in interdependent power and communication network. Traditionally, the problem of finding node-disjoint routes can be studied as a network flow problem, and it can be formulated as a max-flow-min-cut optimization. Such classical optimization formulation can be solved as a linear program, but it is for cases of a single flat network. Specifically, a classical max-flow-min-cut optimization cannot account for the interdependence between power and communication network and thus, is not readily useful in finding power-disjoint routes. Apart from classical network flow optimization, node-disjoint routing has been studied in [38]–[40] but not in the context of smart grid communication networks. For smart grid, [41] has proposed a heuristic algorithm to find a maximally disjoint backup route for a primary communication route. The algorithm takes into account multiple criteria, such as equipment age, type of power and communication cables, etc. While the maximally disjoint route has the largest difference from the primary route, they are not necessarily node-disjoint. According to [42], multiple node-disjoint routes can be formed by simply making sure that these routes traverse completely different communication networks of different telecommunication service providers. The work [43] has formulated an integer linear program to find the optimal network topology for a software-defined network. Here, the optimal topology should use the smallest number of communication links given that each communicating pair has two disjoint routes. But, these routes are only link-disjoint, which is a weaker requirement as compared to both node-disjoint and power-disjoint.

The usefulness of power-disjoint routes in preventing propagation of cascading failures across communication network and power grid, has been proofed in [15]. Also, [15] has developed a scheme to optimally configure the interdependence relation between power grid and communication network to maximize the number of power-disjoint routes. Here, the interdependence relation indicates which power node supplies electricity to which communication node; and which communication node connects which power node to the control center. This optimal configuration problem has been formulated as a linear program and solved using the simplex algorithm. However, [15] has not considered the VNF orchestration requirements in an SDN/NFV environment. In a previous work [44], we have developed a scheme to find the communication routes between a power node and the control center, which minimizes the impact of lost electrical load in the power grid. Similar to [15], this work has also considered interdependence between power grid and communication network. But, the established routes are not power-disjoint and the communication network is not software-defined. There is no existing work that has studied the problem of power-disjoint routing for smart grid in an SDN/NFV environment. This paper has made a contribution in solving this research challenge.

## III. System Model

Similar to [45], we consider a community smart grid with a control center which remotely monitors and dynamically control distributed power generations to avoid an excessive supply-demand gap. The smart grid consists of two interdependent networks, namely a power grid and a software-defined communication network. Each of the two networks is modeled as a set of nodes interconnected by links. In the power grid, the nodes are substations and the links are power lines. In the communication network, the nodes are NFVI nodes and the links are high-speed optical fibers. The software-defined communication network is private to the smart grid operator, but it is established on a multi-tenant communication infrastructure, which is owned by a separate telecommunication service provider. For better utilization, the telecommunication service provider may share the communication infrastructure with non smart grid applications and other unrelated networks.

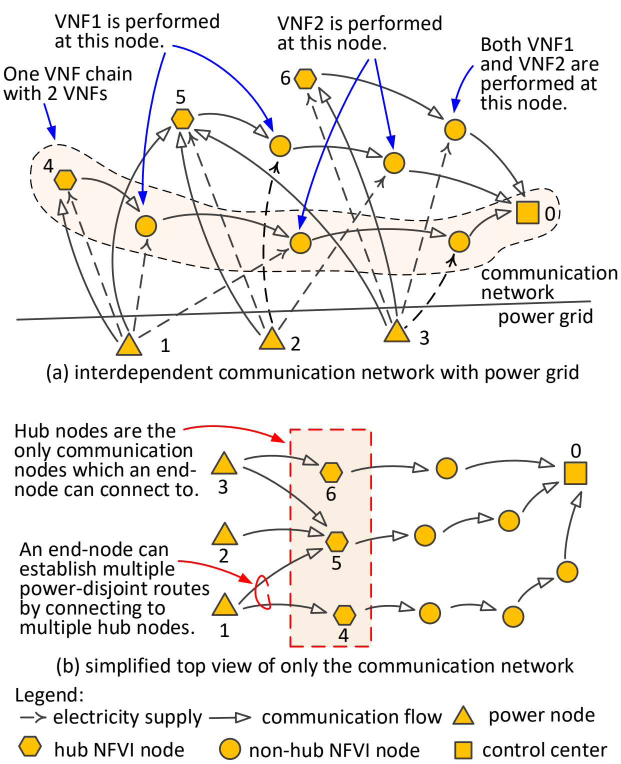


Fig. 1. An illustration of system model with power-disjoint routes and VNF chains. Power node 1 establishes 2 power-disjoint routes by connecting its end-node to NFVI hub node 4 and 5. The route from hub 4 draws electricity supply from power node 1 and 3. The route from hub 5 draws electricity supply from only power node 2. Power node 2 has only 1 power-disjoint route via hub 5 because both hub 4 and 6 are not within its reach. Each route has a VNF chain with 2 VNFs, before terminating at the control center.

In the power grid, $\mathcal{V}_p$ denotes the set of power nodes, where each node represents a substation which connects a number of downstream distribution circuits to the main power grid. Each of the circuits may include a combination of renewable generators and electrical load. By tapping on these circuits, the communication network can obtain its electricity supply from the power grid. As illustrated in Fig. 1, a power node may supply electricity to multiple communication nodes, but each communication node depends on only a single power node as it electricity source.

In the communication network, $\mathcal{V}_c$ denotes the set of communication nodes, which include NFVI nodes, control center and end-nodes. Here, end-nodes are sensors and actuators, which generate data and execute control commands. There is an end-to-end traffic flow between each end-node and the control center. These end-nodes are installed at the substations and therefore, each power node has a co-located communication end-node. As such, we use the variable $\mathcal{V}_p$ which has been introduced earlier to represent power nodes, to also represent end-nodes in the communication network. This common use of terms does not alter the fact that power node and end-node are two different but co-located entities, with one exists in power grid and the other one exists in communication network.

Each NFVI node is a physical computing hardware that hosts virtual machines to perform VNFs, and it can be configured as a bridge, switch or router. The set of NFVI nodes is divided into two groups, namely hub and non-hub nodes. With reference to Fig. 1, these hub nodes are at the edge of the communication network, and they are the only communication nodes that an end-node can be connected to. As a subset of all NFVI nodes, these hub nodes are no different from other NFVI nodes, and they should not necessarily suffer from a higher computation load as compared to other NFVI nodes.

Each hub is connected to the control center through other non-hub nodes, which form a multi-hop communication route. We use $\mathcal{H}$ and $\mathcal{R}$ to denote the set of hub and non-hub nodes, respectively. We further use the index 0 to represent the control center. As such, the set of communication nodes is denoted as $\mathcal{V}_c = \{0, \mathcal{V}_p, \mathcal{H}, \mathcal{R}\}$. Following the convention in graph theory [46], a communication link that supports directional transmissions from node $a \in \mathcal{V}_c$ to node $b \in \mathcal{V}_c$ is represented by an arc $(a, b)$. For each node $i \in \mathcal{V}_c$, its set of incoming and outgoing links are represented by $\mathcal{A}_i^+$ and $\mathcal{A}_i^-$, respectively. Also, we use $\mathcal{A} = \{\mathcal{A}_i^+ \cap \mathcal{A}_i^- | i \in \mathcal{V}_c\}$ to denote the set of all communication links in the network.

## IV. Problem Formulation and Solution

Our focus in on establishing multiple power-disjoint routes for communication robustness and thus, we have left it to the smart grid operator to decide on how to use these multiple routes. As an example, for the case of two routes from an end-node, the operator is free to use either one-plus-one or one-to-one scheme. In one-plus-one scheme, the end-node sends each packet on both routes at the same time such that, the control center may receive a copy of the sent packets despite failure in one of the routes. In one-to-one scheme, the end-node sends packets only on one route at each time and switches over to another route when the current route is broken. Quantitatively, our objective is to establish the maximum number of power-disjoint routes between each end-node and the control center, while satisfying the VNF orchestration requirements. Our strategy is to maximize the number of hubs each of which has a power-disjoint route, and then connect each end-node to as many hubs as possible. In pursuing the strategy, we need to satisfy traffic flow routing, VNF chaining and VNF placement requirements. These three requirements are formulated next.

### A. Traffic flow routing

Following our strategy, each hub is an origin for a potential power-disjoint route. We define $x_{i,a}$ as a binary variable to indicate that a communication link $a \in \mathcal{A}$ is used in a power-disjoint route from hub $i \in \mathcal{H}$. Since each hub $i \in \mathcal{H}$ can be the origin of only one power-disjoint route, not more than one of its outgoing links $a \in \mathcal{A}_i^-$ can be in use as expressed below:

$$\sum_{a \in \mathcal{A}_i^-} x_{i,a} \leq 1, \forall\ i \in \mathcal{H}. \tag{1}$$

In our formulation, each route is represented by a unit traffic flow. Hence, binary variable $x_{i,a}$ is also an indicator of the existence of the flow from hub $i$ in link $a$. For a given route, at any of its intermediate node, the incoming flow must equal to the outgoing flow to satisfy the flow conservation requirement as specified below:

$$\sum_{a \in \mathcal{A}_j^+} x_{i,a} = \sum_{a \in \mathcal{A}_j^-} x_{i,a}, \forall\ i \in \mathcal{H}, j \in \mathcal{R}. \tag{2}$$

At the control center, which is the destination of all routes, there must an incoming flow from a hub, if the hub has a power-disjoint route. This condition is formulated as follows:

$$\sum_{a \in \mathcal{A}_0^+} x_{i,a} = \sum_{a \in \mathcal{A}_i^-} x_{i,a}, \forall\ i \in \mathcal{H}. \tag{3}$$

In addition to the three flow conservation requirements, namely (1), (2) and (3), we must also formulate the necessary conditions for a set of routes to be power-disjoint with each other. For this purpose, we define $\beta_{i,k}$ as a binary variable to indicate that NFVI node $i \in \{\mathcal{H}, \mathcal{R}\}$ draws its electricity supply from power node $k \in \mathcal{V}_p$. We further define $\beta'_{j,k}$ as a function that returns binary value 1 if any NFVI node in the route originates from the $j$-th hub, draws its electricity supply from power node $k \in \mathcal{V}_p$, and returns value 0 otherwise. Given $\beta_{i,k}$, $\beta'_{j,k}$ can be determined as follows:

$$\beta'_{j,k} = \min\left\{\beta_{j,k} + \sum_{i \in \mathcal{R}} \beta_{i,k} \sum_{a \in \mathcal{A}_i^+} x_{j,a}, 1\right\}.$$

In the equation above, the first two terms in $\min\{\cdot\}$ count the number of times the power node $k$ is used in the route originates from the $j$-th hub. Given $\beta'_{j,k}$, all established routes are power-disjoint if following condition can be satisfied:

$$\sum_{j \in \mathcal{H}} \beta'_{j,k} \sum_{a \in \mathcal{A}_j^-} x_{j,a} \leq 1,\ \forall\ k \in \mathcal{V}_p. \tag{4}$$

The left hand side of inequality (4) counts the number of routes that draw electricity supply from a power node $k$, and this number cannot exceed 1 to satisfy power-disjointness requirement. Nevertheless, this requirement allows a power node to supply electricity to multiple communication nodes on a same route.

### B. VNF chaining

Every network equipment vendor or organization may have a different opinion about what SDN/NFV exactly is, and different products that they offer. There is no standardization on what virtual functions should be included in forming a particular network service, such as routing. For this reason, we have used only general expression to represent a function chain and its constituent VNFs. We use $\mathcal{F}$ to denote the set of all VNF types in the communication network. For a route originates from the $i$-th hub, its VNF chain is denoted as $\mathcal{F}_i = \{f(i,1), f(i,2), \cdots, f(i,\delta_i)\}$, where $f(i,j) \in \mathcal{F}$ is the $j$-th VNF in the function chain, and $\delta_i$ is VNF chain length, which is the number of VNFs in the chain. We may remove subscript $i$ from $\delta_i$ when all VNF chains have a same length $\delta$. For VNF chaining on the $i$-th route, we need to ensure the proper VNF order such that $f(i,j)$ is performed before $f(i,j+1)$.

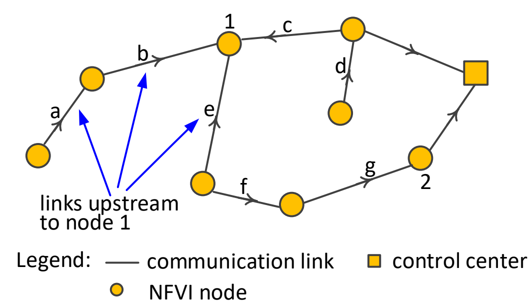


Fig. 2. An illustration of upstream links. In the figure, the set of links that are upstream to node 1, i.e., $\pi(1) = \{a, b, c, d, e\}$. The set of links that are upstream to node 2, i.e., $\pi(2) = \{f, g\}$.

As illustrated in Fig. 2, we use $\pi(k)$ to denote the set of links that are upstream (predecessors) to node $k \in \{\mathcal{H}, \mathcal{R}\}$. Then, the hop count from hub $i$ to a node $j$ can be determined as the number of links in $\pi(j)$ used by the $i$-th route, and this number is calculated as $\sum_{a \in \pi(j)} x_{i,a}$. For a VNF chain $\mathcal{F}_i$, we can ensure that VNF $f(i,j)$ is performed at node $k$ earlier than VNF $f(i,j+1)$ at node $r$, as long as node $k$ has a hop count which is not larger than the hop count of node $r$. Let $y_{i,j,k}$ be a binary variable indicates that the $j$-th VNF of the chain $\mathcal{F}_i$ is performed at NFVI node $k$. Then, the VNF ordering requirement can be formulated as follows:

$$\sum_{k \in \mathcal{R}} y_{i,j,k} \sum_{a \in \pi(k)} x_{i,a} \leq \sum_{r \in \mathcal{R}} y_{i,j+1,r} \sum_{a \in \pi(r)} x_{i,a}, \forall\ j < \delta_i, i \in \mathcal{H}. \tag{5}$$

Other than facilitating in the proper function ordering, $y_{i,j,k}$ being a binary variable, has an additional feature of enforcing that each VNF will be performed only once in a route. This feature is important because it can avoid splitting of a VNF across multiple physical NFVI nodes.

As illustrated in Fig. 3, a flow may visit multiple NFVI nodes between two consecutive VNFs. Let $\phi_{a,b}$ be the communication latency from node $a$ to node $b$. If the two nodes are not adjacent, communication latency is the sum across

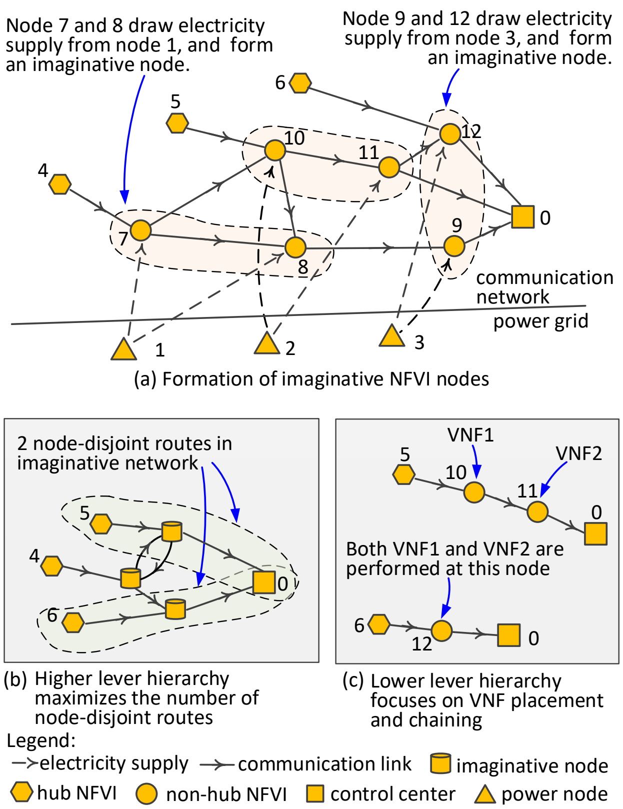


Fig. 3. An illustration of VNF chaining and placement requirements. In the figure, there are two VNF chains, namely $\mathcal{F}_1 = \{f(1,1), f(1,2), f(1,3)\}$ and $\mathcal{F}_2 = \{f(2,1), f(2,2), f(2,3)\}$, where $f(1,1) = f(2,1)$ and $f(1,2) = f(2,2)$.

all links between them. Consider any two consecutive VNFs, namely $f(i,j)$ and $f(i,j+1) \in \mathcal{F}_i$ are hosted at node $k$ and node $r$, respectively. We require the communication latency between these two consecutive VNFs does not exceed $\Phi$ as stated below:

$$\sum_{k\in\mathcal{R}}\sum_{r\in\mathcal{R}} y_{i,j,k}y_{i,j+1,r}\phi_{k,r} \leq \Phi, \forall\ i\in\mathcal{H},\ j<\delta_i. \quad (6)$$

### C. VNF placement

Since all routes end at the control center, as depicted in Fig. 3, the final VNF for all chains are performed there. For other VNF of type $i \in \mathcal{F}$, an amount of $\theta_i$ CPU cycles are required to execute each of its initiated instances. Let $\Theta_k$ be the available CPU cycles at node $k \in \mathcal{R}$. Then, a VNF instance may be hosted at a node only if there is sufficient CPU cycles as expressed below:

$$\sum_{i\in\mathcal{H}}\sum_{1\leq j<\delta_i} y_{i,j,k}\theta_{f(i,j)} \leq \Theta_k, \forall\ k\in\mathcal{R}. \quad (7)$$

In addition to CPU cycles, computation memory is an important resource at NFVI nodes. We have not explicitly stated memory capacity as a separate constraint because it has a same linear characteristic as the CPU constraint. Implicitly, (7) can enforce both CPU constraint and memory constraint. Practically, we can simply duplicate (7) to add a separate constraint for memory capacity.

For each type of VNF, multiple instances may be initiated at different NFVI nodes. We use binary variable $\alpha_{i,j}$ to indicate that an instance of VNF $i\in\mathcal{F}$ is already running at a NFVI node $j \in \mathcal{R}$ prior to the establishment of power-disjoint routes. As highlighted in Fig. 3, these pre-existing VNF instances are initiated by cross traffic from other applications and networks, which share the multi-tenant communication infrastructure.

A VNF can only be performed at a node if there is an instance of the same function type at the node. If such a VNF instance does not exist, a new instance must be initiated. Let $z_{i,j}$ be a binary variable to indicate that a new instance of VNF $i \in \mathcal{F}$ must be initiated at a NFVI node $j\in\mathcal{R}$. Then, the need to initiate a new VNF instance is formulated as follows:

$$y_{i,j,k} \leq \alpha_{f(i,j),k} + z_{f(i,j),k}, \forall\ k\in\mathcal{R}, j<\delta_i, i\in\mathcal{H}. \quad (8)$$

### D. Optimization formulation

A cost $w_{i,j}$ is incurred in initiating a new VNF instance of type $i \in \mathcal{F}$ at NFVI node $j \in \mathcal{R}$. Hence, the total cost of initiating new VNF instances can be determined as $\sum_{i\in\mathcal{F}}\sum_{j\in\mathcal{R}} z_{i,j}w_{i,j}$. As described earlier at the beginning of this section, we want to maximize the number of power-disjoint routes in a cost efficient manner. Therefore, we define an objective function as the number of power-disjoint routes normalized by the total new VNF initiation cost. Multiple power-disjoint routes must also be node-disjoint, because if they share a common router, they must have at least one common electricity supplier, which supplies the common router. Given this characteristic and the flow conservation requirement, the number of established power-disjoint routes equals to the number of incoming flows at the control center. Hence, we can quantify the objective function as the ratio of sum of flows at the control center to the total cost, i.e., $\sum_{i\in\mathcal{H}}\sum_{a\in\mathcal{A}_0^+} x_{i,a}/\sum_{i\in\mathcal{F}}\sum_{j\in\mathcal{R}} z_{i,j}w_{i,j}$. Let $\mathbf{x}$, $\mathbf{y}$ and $\mathbf{z}$ be a vector of $x_{i,a}$, $y_{i,j,k}$ and $z_{j,k}$, respectively. Then, we formulate the following constrained optimization problem:

$$\max_{\mathbf{x},\mathbf{y},\mathbf{z}} \frac{\sum_{i\in\mathcal{H}}\sum_{a\in\mathcal{A}_0^+} x_{i,a}}{\sum_{i\in\mathcal{F}}\sum_{j\in\mathcal{R}} z_{i,j}w_{i,j}} \quad (9)$$
$$\text{s.t.}(1)-(8).$$

Optimization (9) is an non-linear integer programming problem. The non-linearity exists in the objective function, constraints (4), (5) and (6). Such a problem is impractical to solve directly due to its overwhelming complexity. The main sources of complexity are non-linear non-convex objective function, non-linear constraints, binary variables, and discrete nature of the constraint (4). The binary part of the problem is similar to the integer commodity flow problem in graph theory, which has been known to be NP-hard. Here, our problem is even harder because it has a non-linear objective function, some non-linear constraints and a discrete-nature constraint. In addition, it requires enforcing a visit order of nodes for function ordering as part of VNF chaining and accounting for initiation cost of new VNF instances. The discrete nature of $\min\{\cdot\}$ in constraint (4) is problematic because it is capable of ruling out the possibility to directly find a solution through an optimization solver, and preventing any solution strategy based on relaxation, i.e., allowing a binary variable to take real-numbered values within range from 0 to 1.

In the absence of a specific algorithm for solving optimization (9), we quantify its complexity through the size of its solution space. For optimization variables $x_{i,a}$, $y_{i,j,k}$ and $z_{j,k}$, the solution space is as big as $|\mathcal{H}| \times |\mathcal{A}|$, $|\mathcal{H}| \times |\mathcal{F}| \times |\mathcal{R}|$ and $|\mathcal{F}| \times |\mathcal{R}|$, respectively. Hence, the complexity in big O notation is $O(2^{2(|\mathcal{H}|+|\mathcal{F}|+|\mathcal{R}|)+|\mathcal{A}|})$. The complexity increases exponentially with the number of nodes and links in the network as well as the number of functions in a VNF chain. Since we are considering the worst case, which may not be dependent on the selection of a particular optimization solver and thus, variable $y_{i,j,k}$ and $z_{j,k}$ may become redundant. Specifically, we may remove variable $z_{j,k}$ and calculate the new VNF initiation cost as $\max\{y_{i,j,k} - \alpha_{j,k}, 0\}w_{j,k}$. In this case, we can reduce the complexity to $O(2^{2|\mathcal{H}|+|\mathcal{F}|+|\mathcal{R}|+|\mathcal{A}|})$, which is still an exponential function of node, link and VNF numbers. Consider a small network of 2 hubs, 9 NFVI nodes, 1 control center, 5 power nodes, 20 communication links and 5 VNF types. We observe that it takes an average of 1.32 ms on Intel i7 Core, to verify a candidate solution against constraints (1)-(8). Then, finding the optimal solution for such a small network can take about 4,199 days to exhaustively check all candidate solutions. Obviously, we need a practical and efficient algorithm in solving the optimization.

Our idea is to divide the problem into two levels of hierarchy, with each level focuses on a linear objective function. More specifically, the higher level hierarchy focuses on maximizing the number of power-disjoint routes. On the other hand, the lower level hierarchy focuses on satisfying the various VNF chaining and placement requirements. Next, we briefly introduce the main idea of the proposed solution approach before describing its details.

At the higher hierarchy level, as illustrated in Fig. 4(a), all NFVI nodes that draw electricity supply from a same power node are grouped into an imaginary node. With these imaginary nodes acting as intermediate nodes, the problematic constraint (4) can be removed and the problem of finding power-disjoint routes can be transformed into one that finds node-disjoint routes as depicted in Fig. 4(b). This is beneficial because node-disjoint problem can be efficiently solved as a linear maximum flow problem. Given power-disjoint routes found in the higher hierarchy level, as shown in Fig. 4(c), the lower level can then focus on minimizing the cost of each route by choosing within each imaginary node, which NFVI node to host which VNF while satisfying the set of VNF chaining and placement requirements. For each power-disjoint route, the number of NFVI nodes is significantly fewer than that in the entire network. With fewer nodes and a lower computational complexity, we can solve the lower hierarchy level problem using a modified Dijkstra's algorithm to construct a sequence of minimum spanning trees. Such an approach removes the troublesome non-linear constraints (5) and (6). We provide details of this two-level solution scheme in the rest of this section.

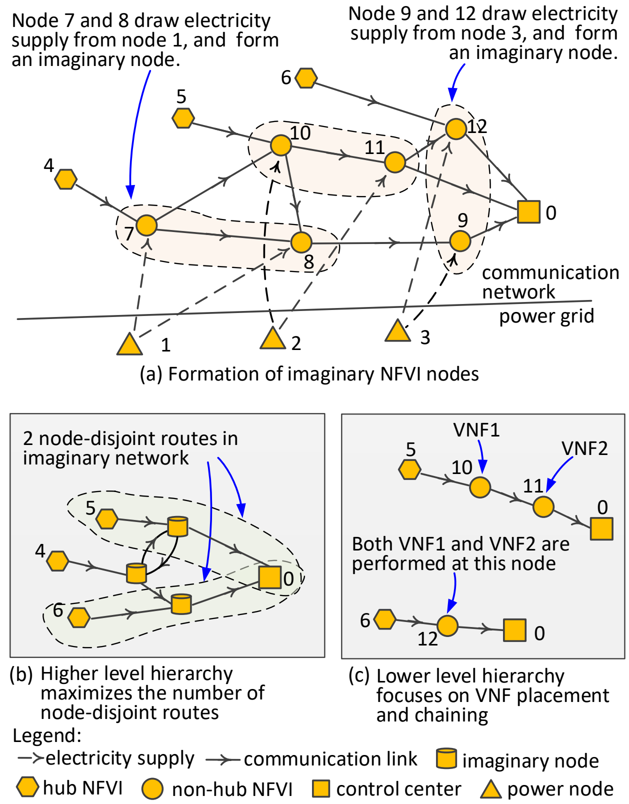


Fig. 4. An illustrative example of the proposed two-level solution scheme. The higher level hierarchy focuses on maximizing the number of power-disjoint routes. The lower level hierarchy focuses on satisfying the various VNF chaining and placement requirements

### *E. Higher level hierarchy solution*

As introduced in the previous paragraph, we define an imaginary communication node $\mathcal{R}'(k)$ to represent all non-hub NFVI nodes that draw electricity supply from power node $k \in \mathcal{V}_p$, such that $\mathcal{R}'(k) = \{i \mid i \in \mathcal{R}, \beta_{i,k} = 1\}$. With reference to the example in Fig. 4, a total of three imaginary nodes are formed. NFVI node 7 and 8 form the first imaginary node, as they both draw electricity supply from power node 1. Similarly, NFVI node 10 and 11 form the second imaginary node because they obtained electricity supply from power node 2. Given that power node 3 is the source of electricity to both NFVI node 9 and 12, these two NFVI nodes form the third imaginary node. Here, for simplicity in explanation, we assume non-hub and hub NFVI nodes do not have common electricity supplier. If this is not the case, we simply need to create a separate set of imaginary hub nodes, where each node includes all non-hub and hub NFVI nodes with a same electricity supplier. We use $\mathcal{R}' = \{\mathcal{R}'(k) \mid k \in \mathcal{V}_p\}$ to denote the set of all imaginary nodes. Practically, $\mathcal{R}'$ and $\mathcal{V}_p$ are two sets with direct one-to-one mapping because there is an imaginary node for each power node. But, we use two different symbols to represent these two sets to maintain a symbol's relevance to context.

For an imaginary node $\mathcal{R}'(k) \in \mathcal{R}'$, its incoming and outgoing links are determined with respect to its constituent nodes as $\mathcal{A}^+_{\mathcal{R}'(k)} = \{(i,j) \in \mathcal{A} \mid i \notin \mathcal{R}'(k), j \in \mathcal{R}'(k)\}$ and $\mathcal{A}^-_{\mathcal{R}'(k)} = \{(i,j) \in \mathcal{A} \mid i \in \mathcal{R}'(k), j \notin \mathcal{R}'(k)\}$, respectively. In the example in Fig. 4, for the imaginary node formed by NFVI node 7 and 8, its incoming and outgoing links are respectively the aggregate of incoming and outgoing links of both node 7 and 8.

We form an imaginary network by replacing all the non-hub NFVI nodes in the original network with the set of newly defined imaginary nodes. In the example in Fig. 4, three imaginary nodes replace six original non-hub nodes. Compared to the original network in Fig. 4(a) with 10 nodes, the imaginary network in Fig. 4(b) has a total of only seven nodes. In this imaginary network, two node-disjoint routes must be power-disjoint in the original network because they do not have any common electricity supplier. As such, at the higher hierarchy level, our focus is to find the maximum number of node-disjoint routes. For this purpose, we make all links in the imaginary network to have a unit capacity and formulate a fractional maximum flow circulation problem.

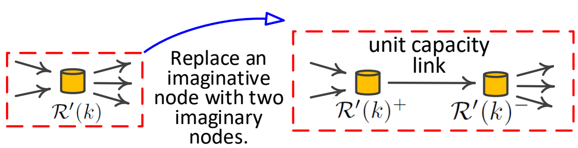


Fig. 5. Replace an imaginary node by two imaginary nodes, which are connected through a unit capacity link.

To formulate a flow circulation problem, we add a node $e$ to the network. From node $e$, we add a unit capacity link $(e,i)$ to each hub $i \in \mathcal{H}$. We add another infinite capacity link $(0,e)$ from the control center to node $e$ to complete a circulation. As illustrated in Fig. 5, we further replace each imaginary node $\mathcal{R}'(k)$ with a pair of imaginary nodes, namely $\mathcal{R}'(k)^+$ and $\mathcal{R}'(k)^-$, such that the two nodes respectively take over the incoming and outgoing links of the original imaginary node. Also, nodes $\mathcal{R}'(k)^+$ and $\mathcal{R}'(k)^-$ are interconnected through a directional link $(\mathcal{R}'(k)^+, \mathcal{R}'(k)^-)$ with unit capacity. As such, for node $\mathcal{R}'(k)^+$, its incoming links is $\mathcal{A}^+_{\mathcal{R}'(k)^+} = \mathcal{A}^+_{\mathcal{R}'(k)}$ and it has only one outgoing link $\mathcal{A}^-_{\mathcal{R}'(k)^+} = (\mathcal{R}'(k)^+, \mathcal{R}'(k)^-)$. Similarly, for node $\mathcal{R}'(k)^-$, $\mathcal{A}^+_{\mathcal{R}'(k)^-} = (\mathcal{R}'(k)^+, \mathcal{R}'(k)^-)$ and $\mathcal{A}^-_{\mathcal{R}'(k)^-} = \mathcal{A}^-_{\mathcal{R}'(k)}$. We use $\mathcal{R}'^+ = \{\mathcal{R}'(k)^+ \mid k \in \mathcal{V}_p\}$ and $\mathcal{R}'^- = \{\mathcal{R}'(k)^- \mid k \in \mathcal{V}_p\}$ to represent the set of imaginary nodes which respectively inherent the original incoming and outgoing links of nodes in $\mathcal{R}'(k)$. Then, we define the set of all nodes in the imaginary network as $\mathcal{V}' = \{0, e, \mathcal{H}, \mathcal{R}'^+, \mathcal{R}'^-\}$.

We require each hub to inject maximum of a unit flow. Then, the problem of finding the maximum number of hubs, each with a node-disjoint route to the control center, becomes the maximum flow circulation problem defined as follows:

$$\max_{\mathbf{x}} \sum_{i \in \mathcal{H}} \sum_{a \in \mathcal{A}^+_0} x_{i,a} \tag{10}$$

$$\text{s.t.} \quad \sum_{a \in \mathcal{A}^-_i} x_{i,a} \leq 1, \forall\, i \in \mathcal{H}. \tag{11}$$

$$\sum_{a \in \mathcal{A}^+_j} x_{i,a} = \sum_{a \in \mathcal{A}^-_j} x_{i,a}, \forall\, i \in \mathcal{H}, j \in \mathcal{V}'. \tag{12}$$

Optimization (10) is a linear programming problem which can be solved efficiently using the traditional simplex method, and the number of identified node-disjoint routes equals to the objective function value. Recall that at this higher level hierarchy, each node-joint route is also power-disjoint, and we will use the terms “node-disjoint” and “power-disjoint” interchangeably hereafter. We use $\mathcal{S}'$ to represent the set of all power-disjoint routes found by solving optimization (10), and use $\mathcal{S}'_i \in \mathcal{S}'$ to represent the route from hub $i \in \mathcal{H}$. At this end of the higher level hierarchy, we have identified the maximum number of power-disjoint routes. But, these routes are built in the imaginary network on the imaginary nodes. Next, we need to translate these imaginary power-disjoint routes to physical routes, which are built on physical NFVI nodes, while taking into account VNF chaining and placement requirements. This is the task of the lower level hierarchy solution.

### F. Lower level hierarchy solution

For each route $\mathcal{S}'_i$ from the $i$-th hub, $\mathcal{M}'_i \subseteq \mathcal{R}'$ denotes the set of imaginary nodes it traverses. There are a number of ways for a route to pass through an imaginary node, because each of the imaginary node may consist of multiple physical NFVI nodes. With reference to the example in Fig. 4, the route from node 5 to the control center (node 0) passes through only one imaginary node, which consists of two NFVI nodes, namely node 10 and 11. Let $\mathcal{M}_i = \{r \in \mathcal{R}'(k) \mid \mathcal{R}'(k) \in \mathcal{M}'_i\} \subseteq \mathcal{R}$ be the set of NFVI nodes covered by route $\mathcal{S}'_i$. At the lower hierarchy level, for each imaginary power-disjoint route $\mathcal{S}'_i$, we want to find a corresponding physical route $\mathcal{S}_i$ that minimizes the VNF orchestration cost while satisfying VNF chaining and VNF placement requirements. Since all the imaginary routes are node-disjoint, $\mathcal{M}_i \cap \mathcal{M}_j = \emptyset, \forall\, i \neq j \in \mathcal{H}$, we can find each of the minimum cost route independently from other routes. To find the minimum cost physical route $\mathcal{S}_i$ for each imaginary route $\mathcal{S}'_i$, we formulate the following constrained optimization:

$$\min_{\mathbf{x},\mathbf{y},\mathbf{z}} \sum_{j\in\mathcal{F}_i}\sum_{k\in\mathcal{R}} z_{j,k}w_{j,k} \tag{13}$$

$$\text{s.t.} \quad \sum_{a\in\mathcal{A}_i^-} x_{i,a} = 1. \tag{14}$$

$$\sum_{a\in\mathcal{A}_j^+} x_{i,a} = \sum_{a\in\mathcal{A}_j^-} x_{i,a}, \forall\, j \in \mathcal{M}_i. \tag{15}$$

$$\sum_{a\in\mathcal{A}_0^+} x_{i,a} = 1. \tag{16}$$

$$\sum_{k\in\mathcal{M}_i} y_{i,j,k} \sum_{a\in\pi(k)} x_{i,a} \le \sum_{r\in\mathcal{M}_i} y_{i,j+1,r} \sum_{a\in\pi(r)} x_{i,a}, \quad \forall\, j < \delta_i. \tag{17}$$

$$\sum_{k\in\mathcal{M}_i}\sum_{r\in\mathcal{M}_i} y_{i,j,k}y_{i,j+1,r}\phi_{k,r} \le \Phi, \forall\, j < \delta_i. \tag{18}$$

$$\sum_{1\le j<\delta_i} y_{i,j,k}\theta_{f(i,j)} \le \Theta_{k,i}, \forall\, k \in \mathcal{M}_i. \tag{19}$$

$$y_{i,j,k} \le \alpha_{f(i,j),k} + z_{f(i,j),k}, \forall\, k \in \mathcal{M}_i, j < \delta_i. \tag{20}$$

In constraint (19), $\Theta_{k,i}$ is the CPU cycles available to the $i$-th route at node $k$, such that $\sum_{i\in\mathcal{H}} \Theta_{k,i} = \Theta_k$. Compared to the original problem (9), optimization (13) has a linear objective function and does not require the problematic constraint (4). Furthermore, optimization (13) has a significantly smaller size of solution space and a lower complexity as a result of focusing only on a power-disjoint route. Unfortunately, despite the smaller size and linearized objective function, it still cannot be solved easily using a solver due to binary variables as well as non-linearity of constraints (17) and (18). We propose to solve optimization (13) using Algorithm 1, which exploits the Dijkstra's algorithm [47] in finding minimum spanning trees.

**Algorithm 1** Find Route Originates From a Hub $i$

1: Initialize set of candidate intermediate nodes $\Lambda = \mathcal{M}_i$;
2: currentHop $= i$;
3: Initialize route $\mathcal{S}_i = \{\text{currentHop}\}$;
4: $j = 1$;
5: **while** $j \le \delta_i$ **do**
6: $\quad \Delta = \text{NodeWithInsufficientCPUCyle}(\Lambda, \theta_{f(i,j)}, \Theta_{k,i})$;
7: $\quad \Lambda' = \Lambda \setminus \Delta$;
8: $\quad \Omega = \text{MinimumSpanningTree}(\Lambda', \text{currentHop})$;
9: $\quad \Gamma = \arg\min_{k\in\Omega} (1 - \alpha_{f(i,j),k}) w_{f(i,j),k}$;
10: $\quad$ **if** $|\Gamma| > 1$ **then**
11: $\quad\quad \text{nextHop} = \arg\min_{k\in\Gamma} \phi_{\text{currentHop},k}$;
12: $\quad$ **else**
13: $\quad\quad \text{nextHop} = \Gamma$;
14: $\quad$ **end if**
15: $\quad \Psi = \text{ExtractPath}(\Omega, \text{currentHop}, \text{nextHop})$;
16: $\quad \mathcal{S}_i = \{\mathcal{S}_i, \Psi\}$;
17: $\quad \Lambda = \Lambda \setminus \Phi$;
18: $\quad j = j + 1$;
19: **end while**
20: return power-disjoint route $\mathcal{S}_i$ originates from hub $i$.

In Algorithm 1, as expressed in line 3, each route $\mathcal{S}_i$ begins at a hub $i \in \mathcal{H}$. The while-do loop runs for $\delta_i$ times, each time is to find the next VNF hosting node and to identify the minimum cost path towards the found hosting node. Each while-do iteration begins by finding the set of feasible nodes $\Lambda'$ to host the next VNF. Practically, $\Lambda'$ is determined as the remaining nodes after removing from $\mathcal{M}_i$, all the used intermediate nodes and other nodes that have insufficient CPU cycles. Line 8 uses the Dijkstra's algorithm to construct a minimum spanning tree extending from the current VNF hosting node to all nodes in $\Lambda'$. This spanning tree $\Omega$ may not eventually cover all nodes in $\Lambda'$ because $\Lambda'$ may not be fully connected. In this case, $\Omega$ is the connected component, which the current hop (VNF hosting node) belongs to. Among all the nodes in $\Omega$, line 9 finds the node $\Gamma$ with minimum new VNF initiation cost, after taking into account an instance of the function may have already been hosted at a node. If there are more than one node with the same minimum cost, $\Gamma$ is a set with cardinality larger than one. In this case, the node with the smallest communication latency is chosen from the set as the next hop (VNF hosting node). Here, if the minimum latency is larger than $\Phi$ as stipulated in constraint (18), no feasible route $\mathcal{S}_i$ may exist. After identifying the next hop, line 15 extracts from the spanning tree $\Omega$, the path $\Psi$ from current hop (VNF hosting node) to the next hop (VNF hosting node). This path $\Psi$ is appended as a segment to the previously found route segments, in constructing the final route $\mathcal{S}_i$. The algorithm terminates when the hosting node for the final VNF, which is the control center is reached. At this point, the route $\mathcal{S}_i$ is returned as the power-disjoint route from the $i$-th hub.

## V. Performance Evaluation

We have evaluated the proposed 2-level hierarchical solution scheme through extensive simulations. In these simulations, the number of communication network nodes and the node degree $\gamma$ are controllable parameters. Given a set of values for these 2 parameters, we generate a random communication network topology following the scale-free network model using the Barabasi-Albert algorithm. In each generated network, 15% of all nodes are hub nodes and there is 1 control center. All the remaining nodes are non-hub NFVI nodes. For each link between two adjacent nodes, the communication latency is a random variable uniformly distributed between 20 ms and 45 ms. For the corresponding power grid, the number of power nodes depends on the number of non-hub nodes in the communication network. Specifically, each power node can supply electricity to an average of 4 different non-hub nodes. In the simulations, each power node randomly picks a random number of non-hub nodes to supply electricity to.

For VNF execution, the available CPU cycles at each communication node is simulated as a random variable within range $[0, 100]$, and this number is dimensionless because it is normalized to a discrete unit. The CPU cycles required to execute a VNF at a node is a random variable between 1 and 10 units. As such, it is feasible to host a few VNFs at a single node. The cost of hosting a VNF at a node is a random variable ranges from 1 to 50, and this cost is a dimensionless value with normalization to the smallest cost. Recall that the cost is incurred only if a new VNF instance is initiated at a node, which has no pre-existing instance of the same VNF type. In our simulations, we allow a VNF to pre-exist at a node with a probability $\mu$, to represent the usage scenario of a shared communication infrastructure owned by a telecommunication service provider.

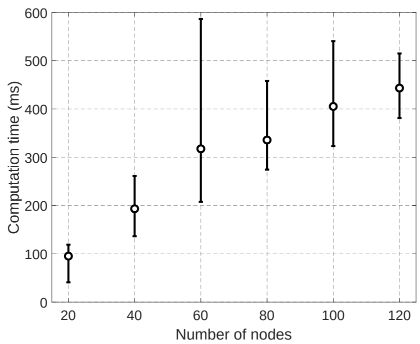


Fig. 6. Computation time in finding power-disjoint routes for different numbers of communication nodes, with node degree $\gamma = 3$, VNF chain length $\delta = 3$ and probability of pre-existing VNFs $\mu = 0.05$.

First of all, we examine the computational efficiency of the proposed scheme in finding power-disjoint routes and lowering cost. Fig. 6 shows the computation time required for different numbers of communication nodes. In the figure, the upper and lower limit of each bar corresponds respectively to the maximum and minimum values from 100 simulation runs for each configuration. The average value from these 100 runs is indicated by the marker within the bar. From the figure, computation time increases with a larger number of nodes. This is understandable, because each node adds extra communication links and expands the solution space. Importantly, despite the increase, computation time is still well below a second for a network with 120 communication nodes. This is a far better result compared to a brute force search, which may require more than 4,000 days to find the optimal number of power-disjoint routes for a network with only 10 communication nodes, as presented earlier in Section IV.

In Fig. 6, all VNF chains have a same length $\delta = 3$, probability of pre-existing VNFs $\mu = 0.05$ and tolerable communication latency $\Phi = 250$ ms. For this same configuration, Fig. 7(a) confirms that the proposed algorithm is capable of enforcing the communication latency requirement between any two consecutive VNFs. In addition, Fig. 7(b) and (c) highlight that an increasing number of communication nodes can bring about more power-disjoint routes, but this comes with an increase in cost. For example, when the node count increases from 20 to 120, cost increases from 59 to 70. Recall that our goal is to maximize the number of power-disjoint routes at the same time of lowering cost. Therefore, increasing node count in a network is probably not an ideal approach for achieving our goal. We will explore below how various parameters can affect differently the two performance indicators.

Fig. 8 shows the effects on VNF initiation cost. Since there is no cost incurred while running a VNF at a node with a same pre-existing VNF, it is reasonable to think that a higher probability $\mu$ can lead to a lower cost. This is confirmed in Fig. 8(a) where the cost drops from 125 to 104 when the chance of pre-existing VNF increases from 0 to 15%. Fig. 8(b) shows that a longer VNF chain can lead to a higher cost. This is because a longer chain has more functions, each incurs an additional cost in execution. On the other hand, Fig. 8(c) shows that the VNF cost is flat with respect to changes in node degree. This is because increasing node degree simply increase the connectivity, which in turn elevates the chance for a node to find a low cost neighbor in hosting the subsequent VNF.

Cross referencing Fig. 8(a) and Fig. 9(b), an increasing $\mu$ can lower the cost but has no effect on the number of power-disjoint routes. This is a good confirmation of the correctness of the proposed algorithm, which prioritizes the maximization of the number of power-disjoint routes. For a smaller $\mu$, the proposed algorithm does not compromise finding more routes to save cost. As seen in Fig. 9(b), a longer VNF chain can lead to fewer power-disjoint routes, because each route may need to involve more intermediate nodes for VNF hosting, but the number of candidate nodes is limited by the power-disjointness requirement and resource constraints. The number of power-disjoint routes can be increased by increasing node degree, as shown in Fig. 9(c). As explained earlier, a bigger node degree increases connectivity and therefore, increases the chances for a node to find a feasible subsequent VNF hosting node. With reference to both Fig. 8(a) and Fig. 9(c), since a larger node degree can increase the number of power-disjoint route while keeping VNF cost flat, it is a better control parameter compared to node count, in achieving our performance objective.

## VI. Conclusion

We have proposed a scalable and computationally efficient scheme to jointly perform VNF orchestration and flow routing in a SDN/NFV environment with interdependent power grid. We have evaluated the scheme through extensive simulations. Results have confirmed that the scheme can find the maximum number of power-disjoint routes with minimum VNF orchestration cost. VNF orchestration cost increases with a lower probability of pre-existing VNF instances, a longer VNF chain and a larger number of NFVI nodes. On the other hand, the number of power-disjoint routes increases with a higher node degree and a larger node population. Notably, we can increase the number of power-disjoint routes while keeping the cost flat, by increasing the node degree among NFVI nodes.

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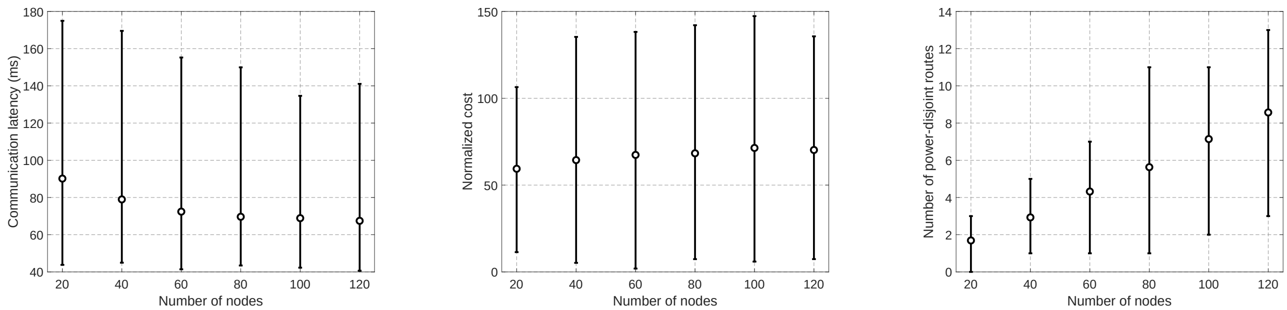
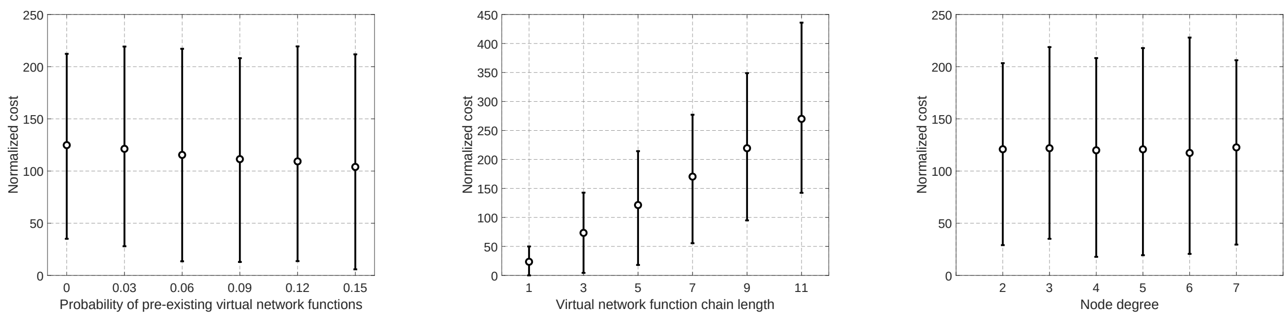


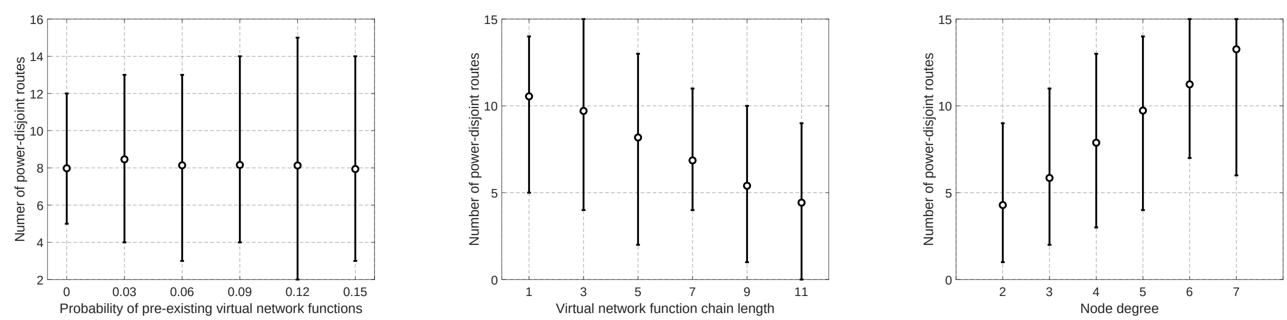

(a) Communication latency (b) Normalized cost (c) Number of power-disjoint routes

Fig. 7. Performance of the proposed algorithm in finding power-disjoint routes for different numbers of communication nodes, with node degree $\gamma = 3$, VNF chain length $\delta = 3$, probability of pre-existing VNFs $\mu = 0.05$, and tolerable communication latency $\Phi = 250$ ms.




(a) $\gamma = 4$, $\delta = 5$ (b) $\gamma = 4$, $\mu = 0.03$ (c) $\delta = 5$, $\mu = 0.03$

Fig. 8. Virtual network function initiation cost for a network with 100 nodes with tolerable communication latency $\Phi = 250$ ms. The costs are determined across different parameters, which include communication node degree $\gamma$, VNF chain length $\delta$, and probability of pre-existing VNFs $\mu$.




(a) $\gamma = 4$, $\delta = 5$ (b) $\gamma = 4$, $\mu = 0.03$ (c) $\delta = 5$, $\mu = 0.03$

Fig. 9. Number of power-disjoint routes found for a network with 100 communication nodes with tolerable latency $\Phi = 250$ ms. The costs are determined across different parameters, which include communication node degree $\gamma$, VNF chain length $\delta$, and probability of pre-existing VNFs $\mu$

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