Joint Energy Efficient and QoS-aware Path Allocation and VNF Placement for Service Function Chaining

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Abstract—Service Function Chaining (SFC) allows the forwarding of a traffic flow along a chain of Virtual Network Functions (VNFs, e.g., IDS, firewall, and NAT). Software Defined Networking (SDN) solutions can be used to support SFC reducing the management complexity and the operational costs. One of the most critical issues for the service and network providers is the reduction of energy consumption, which should be achieved without impact to the quality of services. In this paper, we propose a novel resource (re)allocation architecture which enables energy-aware SFC for SDN-based networks. To this end, we model the problems of VNF placement, allocation of VNFs to flows, and flow routing as optimization problems. Thereafter, heuristic algorithms are proposed for the different optimization problems, in order find near-optimal solutions in acceptable times. The performance of the proposed algorithms are numerically evaluated over a real-world topology and various network traffic patterns. The results confirm that the proposed heuristic algorithms provide near optimal solutions while their execution time is applicable for real-life networks.

Index Terms—Software Defined Network (SDN), Service Function Chaining (SFC), Quality of Service (QoS), Energy Consumption, VM Placement;

I. INTRODUCTION

Traffic congestion may need to pass through different hardware middle-boxes (e.g., IDS, proxy, and firewall) in the real-world networks. This phenomenon is commonly referred to as Service Function Chaining (SFC) \(^1\). Network Function Virtualization (NFV) replaces hardware middle-boxes with flexible and innovative software applications known as Virtual Network Functions (VNFs) to reduce the capital and operational expenditures and increase the flexibility of providing the services \(^2\). On the other hand, Software Defined Networking (SDN) paradigm overcomes the traditional ossification of computer networks and introduces interesting, flexible, and novel service abstractions such as SFC.

VNF chains or simply chains are required to process large volumes of traffic within a very short period of time to facilitate real-time streaming applications that comprise majority of traffic in today’s networks. Failure to provide the desired throughput of a chain may lead to violating of the service level agreements (SLAs) incurring high penalties. Hence, achieving high throughput of VNFs is of paramount importance. Consequently, numerous works focus on providing SFC in SDNs. An SFC taxonomy that considers architecture and performance dimensions as the basis for the subsequent state-of-the-art analysis is introduced in \(^3\).

On the other hand, the high energy consumption by computer networks incurs high costs for providers. Furthermore, some countries set carbon tax on the emitted \(\text{CO}_2\) to enforce the environmental sustainability \(^4\). Therefore, considering the amount of energy consumed as a parameter of resource (re)allocations algorithm helps service providers to reduce the energy and carbon cost as a major sector of their total cost \(^5\). In this context, different natural questions arise, such as: Is it possible to propose resource (re)allocation architecture to cover SFC over SDN switches? How to optimally trade-off between energy consumption of servers and network (re)allocation side effects on SDN switches? How to properly implement SFC without affecting the Quality of Service (QoS) parameters in real-world network? The goal of this paper is the shed light on these issues. More in detail, we propose a resource (re)allocation architecture and a set of novel energy-aware SFC algorithms for SDN networks. To this end, the problem of resource (re)allocation is divided into four main subproblems: i) VM placement, ii) VM Migration, iii) flow routing, and iv) flow rerouting. We mathematically formulate these problems and propose a heuristic algorithm for each of them. In a nutshell, our main contributions are as follows:

- we propose a new resource allocation architecture consisting of two different components (i.e., resource allocation and resource reallocation).
- we mathematically formulate the problem of resource (re)allocation for the proposed architecture. The corresponding problems are cross-layer optimization problems considering energy, SFC, and QoS parameters.
- we show that the aforementioned optimization problems belong to the class of Integer Non Linear Programming (INLP), which are challenging to be solved. Therefore, we detail how the non linear constraints can be linearized.
- we propose optimal solutions and near-optimal heuristics to solve the aforementioned optimization problems. We also show that the heuristic approaches are applicable in real-world networks.
- we propose a VM migration and a VM placement algorithm. VM migration algorithm uses the current statistics of network traffic to route the flows in a way that reduces the energy consumption by switching the servers between IDLE and ACTIVE modes. On the other hand, the VM placement algorithm exploits the network history, to specify the supported VMs on each server in a way
that minimizes the power consumption by turning on or off the VMs on each server.

- finally, we implement a traffic/resource generator to create flows with different requirements (e.g., VNF chaining, tolerable delay, flow size, servers’ functionalities, etc.) based on mathematical distribution.

We believe that this work can be the first step towards the deployment of algorithms tailored to the energy-aware management of network traffic with SFC considerations. Future work will be dedicated to making the algorithms robust against burst traffics. Another field of future interest would be considering the queuing delay of the switches and the processing delay of the server to improve the quality of users experiment.

The remainder of the paper is organized as follows: In Section II, the related work is discussed. Section III states the proposed architecture and an outline of the proposed schemes. Section IV discusses the system model, parameters, objective function and constraints. Additionally, the proposed VM placement and routing approaches are discussed in Section IV. The performance analysis of the proposed schemes are presented in Section VI. Finally, Section VII concludes the paper and presents future directions.

II. RELATED WORK

This section is divided into three different categories: VM placement problems, routing and service function chaining, and green service function chaining. From now on we refer to service function as VNF (Virtual Network Function). In the following, we will briefly discuss each category.

A. VM Placement

In this category, the problem is to optimize the placement of VMs in a way that an objective is gained, e.g., maximizing network throughput or minimizing energy consumption. Some works focus on proposing measurements to compare different VM placement algorithms, e.g., [6] and [7]. More in detail, authors in [7] compare several algorithms to evaluate their capabilities on balancing resource usages versus total number of used physical machines. They present the relation between the data center characteristics, size of the cloud services and their diversity and the performance of the heuristics.

Focusing on VM placement algorithms, authors of [8] study the problem of deploying SFCs over NFV architecture. Specifically, they investigate virtual network function placement problem for the optimal SFC formation across geographically distributed clouds. Moreover, they set up the problem of minimizing inter-cloud traffic and response time in a multi-cloud scenario as an Integer Linear Programming (ILP) optimization problem, along with some other constraints such as total deployment costs and SLAs.

Besides, authors of [9] use ILP to determine the required number and placement of VNFs that optimize network operational costs and utilization without violating SLAs. In [10] an approximation algorithm for path computation and function placement in SDNs is proposed. Similar to [9], they propose a randomized approximation algorithm for path computation and functions placement. In addition, the paper [11] considers offline batch embedding of multiple VNF chains. They adopt the objectives of maximizing the profit by embedding an optimal subset of requests or minimizing the costs when all requests need to be embedded.

There are lots of VM placement algorithms for data centers [12]–[15]. The authors of [12] state a VM placement algorithm for data center networks to make a trade-off between the energy consumption of the network and the SLA performance. Similarly, in [13] a Mixed ILP (MILP) traffic-aware VM placement for data center Networks is presented. The authors of [14] propose an approach which jointly optimize both topology design and VM placement in order to make an scalable solution. To this end, they exploit MILP to formulate the problem. Additionally, they propose a heuristic based on Lagrange relaxation decomposition.

The authors of [16] formulate the VM placement as an optimization problem and propose a two-tier approximate heuristic to solve the problem. Furthermore, they compare the impact of the network architectures and the traffic patterns on the performance of their approach.

These methods are interesting in structure and SDN problem formulation, however, none of them considers the problem of service function chaining with respect to the energy consumption of the VMs in SDN.

B. Routing and Service Function Chaining

In this category, the problem is to find a routing in which SFC requirements are met, i.e., all required VNFs deliver to the flows. To this end, it is possible to define some extra objectives such as minimizing the network congestion. There are lots of works in this category e.g., [17]–[25].

The authors of [17] propose a heuristic algorithm to find out a solution for VNF chaining. It employs two-step flow selection when a SFC with multiple network functions needs to scale out. Furthermore, authors in [18] introduce a VNF chaining which is implemented through segment routing in a Linux-based infrastructure. To this end, they exploit IPv6 segment routing network programming model to support SFC in a NFV scenario. Moreover, authors of [19] propose a scheme which provides flexibility, ease of configuration and adaptability to relocate the VNFs with minimal control plane overhead. Reference [20] focuses on enabling telco infrastructures to orchestrate and manage SFC toward cloud infrastructures.

Moreover, in [21] a optimization model based on the concept of Γ-robustness is proposed. They focus on dealing with the uncertainty of the traffic demand. In [22] an optimization model to deploy a chain in a distributed manner is developed. Their proposed model abstracts heterogeneity of VNF instances and allows them to deploy a chain with custom throughput without concerning about individual VNF’s throughput.

On the other hand, the paper [24] solves a joint route selection and VM placement problem. They design an offline algorithm to solve a static VM placement problem and an online solution traffic routing. More in detail, they expand the Markov approximation to gain their objectives. In [25] a joint
resource allocation and service function chaining is proposed. The authors use a cost model to make a trade-off between service performance and network costs. They exploit MILP to model the problem and propose a heuristic to solve it.

Although the aforementioned solutions in this category are interesting, non of the them considers the problem of service function chaining with respect to the energy consumption of the VMs.

C. Green Service Function Chaining

In this category, the problem of routing or VM placement in SFC is considered, while the objective is to assign resources such that energy consumption of the network is minimized. In detail, the authors in [26] introduce an optimization model to minimize the energy consumption while considering a set of VNF chains. The model explicitly provides robustness to unknown or imprecisely formulated resource demand variations.

To gain this, it powers down unused routers, switch ports and servers, and calculates the energy optimal VNF placement. The most challenging part of this work is that they do not consider ordering for the VNFs. In other words, it is impossible to guarantee that the flow meets VNF $x$ before VNF $y$.

On the other hand, authors of [27] present an energy-aware VM placement algorithm to maximize the admitted traffic delivered to mobile clients and minimize the jointly computation and communications energy consumption in cloud data centers. Although the approach is interesting, they do not consider the impact of traffic pattern in their algorithm. In [5] an energy-aware VM placement method for geographically distributed cloud data centers is proposed. The authors investigate parameters that have impact on carbon footprint and energy cost and formulate the total energy cost as a function of the energy consumed by servers plus overhead energy.

Similar to [5], [27], authors of [28] and [29] propose two algorithms for the VM placement problem in data centers which optimize the energy consumption. To be specific, in [28], authors propose a hybrid genetic algorithm for VM placement problem considering the energy consumption in both communication network and physical machines. Similarly, authors of [29] mathematically formulate the VM placement problem and propose a heuristic to solve it. Both [5] and [28] focus on VM placement and ignore real-time routing of the traffic flows.

The authors of [30] propose a scheme that uses three different algorithms to do the VNF placement, SFC routing, and VNF migration in response to changing workload. Their objective is to minimize the rejection of SFC bandwidth and reduce the energy consumption. Although their work is pretty interesting, there are several weak points in their approach. First of all, their approach is applicable for networks with predicatable traffic, i.e., they suppose that the traffic pattern is repeated in a time interval. Moreover, they assume the amount of network traffic demands for all slots of the time interval and based on this knowledge, they turn on or off servers. Finally, the authors considers all of the possible physical path as an input to their algorithm which is not an applicable assumption for medium and big networks.

III. Reference Scenario

In this section, the proposed resource (re)allocation architecture is discussed by illustrating the architectural components and providing an outline of the main considered procedures. In general, we assume that a Network Operator is managing an SDN/NFV enabled network and it is allocating resources (e.g. processing capacity in nodes, bandwidth capacity on network links) to a set of flows that needs to be processed by the network. We consider here “macro-flows” or “aggregated” flows, i.e. flows that have a relatively long life. For example VPN connections or classes of user traffic that need to be processed in the same way... We can also refer to the “aggregated” flows as traffic demands. Each flow/traffic demand is associated with: an ingress point and an egress point in the operator network; a set of VNFs that needs to be executed on the flow, this is typically a chain of VNFs, that is an ordered list; a required capacity (flow rate), this can be known in advance or unknown (and in the latter case it can be estimated when the flow is active); QoS requirements (e.g. maximum tolerable delay). According to the NFV principles, the VNFs (processing service) are executed by Virtual Machines (VMs) that are running on physical servers. The operator needs to map the chain of VNFs associated with the flow to a set of VM instances, which needs to be located on physical servers. Moreover, thanks to the SDN approach, we assume that the Network Operator can explicitly configure the routing of the flows in its network, i.e. the path that the packets of a flow take to go from the ingress point to the first VNF, then from a VNF to the next VNF in the chain and finally from the last VNF of the chain to the egress point.

[TO BE REVISED]In general the operator when allocating the resources to the flows the Network Operator tries to optimize one or more objective functions: reducing costs due to energy consumption, maximizing the QoS, balancing the links’ load, minimizing the maximum link utilization.

In our approach, the Network Operator can use as objective function which is a combination of energy consumption and network reconfiguration cost. We consider as constraints the maximum link utilization, the maximum utilization of the processing modules, the maximum end-to-end sum of fixed link delays. In this work we are focusing on the minimization of energy consumption so in our experiments we will not consider the network reconfiguration cost in the objective functions. As for the energy consumption, in the proposed model the physical servers on which the VMs can be run can be turned ON and OFF; and this is supposed to be a relatively "long term" operation as it requires some time for a server to boot/shutdown. Moreover, a server which is in the ON state can be either ACTIVE (i.e. fully operational, the VMs can run on it) or IDLE (i.e. no VMs are running, but the VMs can be instantly reactivated when there is a requirement).

We consider different resource allocation procedures. Single Flow Resource Allocation is used when a single new flow needs to be supported by the Network Operator on top of a running configuration. In this case, we do not consider any reallocation of the active flows and the optimization problem only consider a single flow. Then we consider different
types of Global Reallocation procedures that can potentially reallocate the running flows. In this case the optimization is performed globally on the set of flows. We consider two types of global reallocation procedures: in one type we can turn on and off the servers (long-term energy management), in the second type we can only change the status of ON servers from ACTIVE to IDLE and viceversa (short-term energy management). Moreover, depending on the time scale in which we can run the reallocation procedure, we consider online and offline approaches. In cases that the network should be reconfigured in a real-time manner, e.g. following a congestion event, the online algorithms will be invoked. On the other hand, the offline algorithms can be used to periodically reconfigure the network based on the traffic history and predictions. These can be used for example to plan different resource (re)allocation for different times of the day (e.g. at the midnight the demands always reduces, therefore, an offline algorithm can specify state of the processing nodes for midnight hours).

A. Architecture

In this section, the proposed architecture and its components is presented. The architecture is conceptually aligned with the SDN layering discussed in [31]. With reference to Fig. 1 we consider three different layers. The Infrastructure layer consists of networking and processing devices and corresponds to the Forwarding Plane and Operational Plane presented in [31]. The Control layer interacts with the networking devices in order to program their behavior from a logically centralized perspective. It corresponds to the Control Plane and Management Plane in [31]. Finally, the Application layer includes the applications and services that define the overall network behavior.

Looking at Fig. 1 the Infrastructure Layer includes the networking devices and the servers on which we can run the VMs. We refer to the networking devices as switches, following an SDN-based terminology, but these devices could also act as routers. The servers are connected to a switch, multiple servers can be connected to the same switch. The switches can also operate as networking nodes only, without any connected server. We refer to the pair (switch, server) as a node.

We assume that there is a logically centralized SDN controller in the Control layer, connected to the set of SDN switches via the Southbound protocols (examples of Southbound protocols are shown in Fig. 1). The main role of the SDN controller is to setup the forwarding tables of the single networking devices in order to properly configure the packet forwarding. The SDN controller interacts with the networking devices and gathers information on the topology and on the network traffic. The SDN controller can include additional functionality, that we represent as additional modules in Fig. 1. In particular, in our architecture we consider two monitoring modules. These modules are considered as a part of the controller to speed up the process and reduce the overhead of gathering information from the switches.

The Control layer offers a set of functionality to the Application layer, through the Northbound API. The application and services in the Application layer use this API in order to implement the desired behavior. In our architecture, the proposed resource allocation/reallocation modules are included in the Application layer. These modules takes the decisions about the mapping of VNF chains into servers/VMs and the path selection and request the Control layer to enforce them through the Northbound API. In the other direction, the Control layer provides the Application layer with the information about topology and network traffic.

As can be seen in Fig. 1 the proposed architecture has the following modules:

- **Resource allocator**: this module belongs to the application layer. When a new flow enters to the network, resource allocator assigns the required resources to the flow. This module does not reroute existing flows and only focus on newly arrived ones.
- **Resource reallocator**: this module belongs to the application layer. It is capable to perform a reallocation of some flows in order to react to some event (like congestion) or periodically to optimize the use of resource or the user perceived QoS.
- **Knowledge Base**: this module is used to gather information about the previous states of the network and to predict the future state of the network.
- **Server/Network configurator**: this module in the Control Layer enforces the processing nodes and networking equipment to act based on the decision made in application layer. It will be mapped in an SDN controller.
- **Congestion detector/predictor**: this module generates a reconfiguration request in two cases: i. when there is a congestion in the network or the traffic load on links go across a predefined link utilization, and ii. when based on the network history and traffic pattern it predicts that network will face congestion in future. This module is a part of the Control Layer, it can be also seen of a module of the SDN controller of choice.
- **Network monitoring**: this module periodically monitors the links status, updates the “knowledge base”, and provides traffic matrix for other modules. The switches allow with the forwarding of the packets do some simple traffic measurements and forward these measurements to the controller. Similar to the congestion detector/predictor, this module is a part of control layer and can be considered as a module of the SDN controller.

B. Outline of the resource management algorithms and procedures

In this subsection, a brief overview of the total process of allocation and reallocation of the resources is provided. As shown in Fig. 1 different algorithms can be used inside the Single Flow Resource Allocator and Global Resource Reallocator modules. In this context, the long-term algorithms specify whether a server is ON or OFF and the the placement of VMs on the servers, by considering the network history

1Note that monitoring modules and traffic prediction algorithm are out of the scope of this paper.
information (called knowledge base). On the other hand, short-term algorithms specify whether a VM is ACTIVE or IDLE on a server (but cannot turn on or off a server), by using current status of the network (i.e., traffic load and link utilization).

Single Flow Resource Allocation is an online and short-term algorithm in which resources are assigned to the newly arrived flows in an instantly manner. We mathematically formulate this problem as “SFRA” in section IV-B. On the other hand, Resource Reallocating module reassign resources to the flows in a way that the energy consumption is optimized while the QoS constraint is considered and the network congestion is controlled. We mathematically formulate this problem as “GRR” in section IV-C.

Since the optimization problems that we have defined (both SFRA and GRR) are NP-hard problems, several heuristics and relaxed versions are proposed for the different variants of resource allocation and reallocation procedures that we have considered. In the following, the proposed algorithm for each element is presented.

- **Single Flow Resource Allocator**: this module is mathematically formulated as 3 different sub-problems in section IV-B. In the first scenario, we consider QoS and SFC Constraints without VNF Ordering. Then, the formulation is extended to consider priority between different VNFs (ordering). Finally, in the third scenario, the energy consumption is optimized. The input of Single Flow Resource Allocation is one flow as a pair of (source, destination), the average rate of flows until now, and the current state of the network. The output is a set of links and servers assigned to that flow. When a new flow enters to the network, this algorithm should assign the required resources to the flow instantly, hence, in section V-A we propose a fast heuristic called “Nearest Service Function first (NSF)”, which focuses on the second scenario. Since when a new flow arrives there is no information about the size of the flow, NSF does not focus on minimizing the energy consumption, otherwise, it may cause congestion for big flows. Also, NSF considers one flow at each time.
- **Online Long-Term Resource Re-allocator**: if some links are congested or a congestion in a near time interval is predicted, then an online long-term reconfiguration algorithm will be invoked. It should be mentioned that in this case, there is an estimation of the rates of the flows based on the current status of the network. “VM Placement and Energy-aware NSF (VP-ENSF)” is the fast reallocation algorithm which performs this long-term...
reallocation. VP-ENSF considers all flows simultaneously (i.e., it can reconfigure the network for all flows at once). This algorithm does not only specify the routing of the network, but also changes the state of servers from ON to OFF or vice-versa. This algorithm is described precisely in section [V-C2]. The input of this algorithm is similar to the Online Short-Term Resource Re-allocation, however, the output is selected path for each flow, the state of all servers (ON or OFF) and the placement of VMs.

- **Online Short-Term Resource Reallocator**: when the network needs to be reconfigured in an online manner, an heuristic algorithm called “Energy-aware NSF (ENSF)” is invoked (section [V-C1]). ENSF reroutes flows and changes the state of servers that are in ON state in terms of ACTIVE or IDLE. ENSF is invoked periodically in order to update the configuration of the networks into an optimized energy consumption. This algorithm considers all flows, simultaneously (like VP-ENSF). It is notable that ENSF does not only specify the new routing of existing flows but also sends some servers in-to/out-of IDLE mode. The input of this algorithm is the current state of network (the measured rate of active flows, the sources and destinations of active flows, the state of servers: ON (Active, IDLE) or OFF, the VNFs that can be supported on the servers, and the network topology). The output is the reassignment of resources to the flows (selected path for each flow and the state of currently ON servers (IDLE or ACTIVE)).

- **Offline Long-Term Resource Reallocator**: in order to propose an offline Global Resource Reallocator, we relaxed the mathematical formulation proposed in section [V-C] defining a new optimization problem called “Relaxed Resource Reallocator (3R)” (section [V-B1]). We can solve this problem with a standard ILP solver and we refer to this procedure as 3R algorithm. If the 3R algorithm is invoked along with the knowledge base information (the predicted rate of flows) and network topology then it will perform an offline long-term resource re-allocation. In this case, the 3R algorithm is considered as a long-term algorithm since it specifies whether a server is in ON or OFF state.

- **Offline Short-Term Resource Reallocator**: If the 3R algorithm is invoked along with the current state of network (the measured rate of active flows, the state of servers: ON (Active, IDLE) or OFF, supported VNFs per servers, and network topology), it performs an offline short-term reconfiguration. In this case, the 3R algorithm is considered as a short-term algorithm since it specifies whether an ON server be in IDLE or ACTIVE state. In brief, if we specify whether the servers are in ON or OFF state along with the placement of the VMs on the servers, then 3R works as a short-term algorithm, however, if it is not specified then the 3R output is a long-term reconfiguration.

Algorithm [1] presents an outline of the proposed management workflow. There is a timer called Long_Term_timer that calls 3R algorithm which turns on or off the servers based on the predicted rate of flows (lines 2-4 of Algorithm [1]). We call it Long_Term_timer because the impact of invoking 3R algorithm has a long term impact on the energy consumption of the networks. There is another event that may trigger the offline resource reallocation algorithm which is congestion prediction (lines 5-7). In this way, if a link utilization crosses a predefined threshold then the 3R algorithm is invoked with current state of the network as the input parameter. The current state of the network consists of the measured rate of active flows, the state of servers: ON (Active, IDLE) or OFF, supported VNFs per servers, and network topology.

On the other hand, three different events may enforce the scheme to perform an online reaction: 1) the arrival of a flow (line 9-11, NSF algorithm is invoked), 2) congestion detection/prediction (line 12-14, VP-ENSF algorithm is invoked), and 3) a predefined timer for network reconfiguration (line 15-18, ENSF algorithm is invoked). It is notable that the knowledge base is updated periodically (lines 20-22).

**Algorithm 1 Outline**

1. while true do
2.   if Long_Term_timer elapses then
3.     3R(Knowledge Base)
4.     Reset Long_Term_timer
5.   else if Congestion_Avoidance_Alarm elapses then
6.     3R(Current state)
7.     Reset Long_Term_timer
8.   else
9.     if new flow arrives then
10.    NSF()
11.   end if
12.   if congestion is detected or predicted then
13.    VP-ENSF()
14.   end if
15.   else if GRR_timer elapses then
16.    ENSF()
17.    Reset GRR_timer
18.   end if
19.   end if
20.   if Update_timer elapses then
21.    Update_Knowledge_Base()
22.   Reset Update_timer
23.   end if
24. end while

**IV. Problem Formulation**

In this section, the components of the proposed architecture are discussed in detail. As can be seen in Fig. [2] two types of algorithms are used in the proposed architecture: 1) Single Flow Resource Allocation (SFRA), and 2) Global Resource Reallocation (GRR). The Single Flow Resource Allocation algorithms considers one flow at a time. The output of these algorithms provide the new entries to be inserted into the forwarding tables of the switches to route the new flow. On the other hand, the Global Resource Reallocation algorithms consider all flows, simultaneously, i.e., they consider the
impact of flows on each other. GRR algorithms updates the forwarding tables of switches to reroute existing paths. When there is no information about the rate of a new flow, SFRA algorithms are invoked to allocate the resources to this new flow. On the other hand, GRR algorithms are used to reallocate resources based on the estimated rates of the existing flows. In algorithm NSF is a Single Flow Resource Allocation algorithm while ENSF, VP-ENSF and 3R are Global Resource Reallocation algorithms.

![Software Architecture](image)

Fig. 2: Software Architecture.

Briefly, in Fig. 2 if a new flow arrives at a switch, the controller uses an SFRA algorithm to route the flow. Thereafter, the controller configures the switches that on the selected path by sending controlling messages to them. On the other hand, if the network gets congested (or, if a predefined time intervals elapsed), a global reconfiguration help to reduce the congestion and/or the energy consumption, improve the throughput, and ensure that the requirements of the flows are fulfilled. The (re)configuration algorithms are executed in the Application layer. To this end, the controller collects the information and detects/predicts the congestion and informs the application layer. Thereafter, the controller will receive the instructions from the Application Layer and enforce these decisions by communicating with the switches.

### A. System Model and Assumptions

We assume an SDN-based network using a southbound protocol to dynamically program the switches. Each flow requires to pass through a sequence of VNFs in its path from the source switch to the destination switch (SFC requirements of a flow). As for QoS constraints, each flow has a maximum tolerable propagation delay that should be guaranteed and the utilization of each link should be maintained below a given threshold. The servers have three different modes: OFF, ON-IDLE (referred as IDLE), ON-ACTIVE (referred as ACTIVE).

In the OFF mode, the energy consumption of server is zero while in the ACTIVE mode the server works on its full performance and the energy consumption is the same as full rate working energy consumption. Finally, in the IDLE mode the energy consumption is a fraction of the energy consumption in ACTIVE mode. The network is (re)configured in a way that optimizes the energy consumption and the flow table changes and simultaneously meets QoS constraints and SFC requirements.

#### Table I: Main Notation.

| Symbol   | Description |
|----------|-------------|
| \( A \)  | Set of switches (and servers) |
| \( F \)  | Set of flows |
| \( X \)  | Set of VNFs |
| \( N \)  | Number of switches: \(|X| = N\) |
| \( F \)  | Number of of flows: \(|F| = F\) |
| \( X \)  | Number of different VNFs : \(|X| = X\) |
| \( E \)  | Number of links |
| \( i, j \) | indexes of switches |
| \( x \)  | indexes of VNFs |
| \( f \)  | indexes of flows |
| \( \psi \) | Maximum number of required VNFs for each flow |
| \( K^f \) | Sequence of required VNFs of flows |
| \( B_{ij}^f \) | Matrix of link capacity between \(i^{th}\) and \(j^{th}\) switches |
| \( B'_{ij}^f \) | Current bandwidth load on link \((i, j)\) |
| \( D_{ij}^f \) | Links propagation delay between \(i^{th}\) and \(j^{th}\) switches |
| \( C_f \) | Bandwidth requirement matrix of \(f^{th}\) flow |
| \( T_f \) | Maximum tolerable propagation delay of \(f^{th}\) flow |
| \( s_f \) | Vector of source switch of \(f^{th}\) flow |
| \( d_f \) | Vector of destination switch of \(f^{th}\) flow |
| \( A_0(f) \) | Current routing matrix between \(i^{th}\) and \(j^{th}\) switches of \(f^{th}\) flow |
| \( \mu_i \) | Maximum link utilization ratio |
| \( \cPi \) | Maximum server utilization ratio |
| \( FP_x \) | Required processing of \(x^{th}\) VNF |
| \( NC_i \) | Servers processing capacity of \(i^{th}\) server |
| \( \mu_{x,i} \) | Current processing load per \(x^{th}\) VNF on \(i^{th}\) server |
| \( FX_{i,x} \) | VNF \(x\) associated with \(i^{th}\) server |
| \( B_{r_{ij}}^0 \) | Requested VNFs for \(f^{th}\) flow |
| \( E_s \) | Energy consumption of \(s^{th}\) server |
| \( CE \) | Previous status of servers (ACTIVE/IDLE or OFF/ON) |

The vectors \(s_f\) and \(d_f\) determine the source and destination of flows, respectively. The matrix \(A_0(N \times N \times F)\) is the current routing matrix, e.g., if \(A_0(f)_{ij} \in \{0, 1\}\) is equal to 1 then the flow \(f \in F\) crosses the link \(i \rightarrow j\). The new routing matrix \(A_{N \times N \times F}\) specifies the path selected for each flow, e.g., if we
set \( f = 1, s^1 = 1, \) and \( d^1 = 4 \), then the matrix \( A^1 \) is as follows:

\[
A^1 = \begin{bmatrix}
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0
\end{bmatrix},
\]

where \( s^1 = 1 \) indicates that the source of the flow is the switch number 1. Therefore, we should trace the path from the first row of \( A \). As can be seen, the third element of \( A^1 \) in the first row is one which means that the flow should leave the switch 1 toward the switch 3. At this point, the third row of \( A^1 \) should be checked. Since the 5th column of the third row is 1, the flow will leave switch number 3 to reach the switch number 5. Finally, the flow enters to its destination from switch number 5 (because, the destination is switch number 4 and the fourth element of row 5 in matrix \( A^1 \) is one).

On the other hand, matrix \( AP_{(N,N,F)}^1 \) is the priority-based rerouting matrix in which \( AP_{(i,j)}^{f} \) states whether flow \( f \in F \) crosses link \( i \) to \( j \) (or \( j \) to \( i \)) or not. Therefore, \( AP_{(i,j)}^{f} \) specifies the number of previously crossed switches, if flow \( f \) crosses the link \( i \) to \( j \), otherwise, it is zero. Besides, \( AP_{(d^f,d')^l} \) is the path length for each flow (number of switches through the selected path). Accordingly, it can be written as

\[
AP^1 = \begin{bmatrix}
0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 2 \\
0 & 0 & 0 & 4 & 0 \\
0 & 0 & 0 & 3 & 0
\end{bmatrix}.
\]

In the \( AP^1 \) matrix, since the third column of the first row is one, the flow should leave the source switch to reach the switch number 3. Also, value 2 in the third row of the matrix specifies that the flow in the second step will leave switch number 3 to reach the switch number 5. Similarly, value three in the fifth row states that as the third step the flow will leave switch number 5 to reach to the switch number 4 which is the destination of such flow. Since the number of crossed switches in this path is four, the value of \( AP_{4,4}^1 \) is four.

The flow bandwidth requirement vector \( C_F \) specifies flows requirements. The \( i^{th} \) row of the mentioned vector defines the bandwidth requirement of the \( i^{th} \) flow. Similarly, vector \( T_F \) specifies maximum tolerable propagation delay of flows. Considering \( X \) different VNFs, each flow can request at most \( \psi \leq X \) VNFs. Matrix \( R_{F \times X} \) shows the requested VNFs for each flow. Indeed, if the VNF \( x \) is requested for the flow \( f \), then \( R_{(f,x)} \) is 1, otherwise, it is 0. The sequence of the required VNFs for all the flows is expressed by matrix \( K_{F \times \psi} \) where \( K_{(f,\omega)} \) specifies the \( \omega^{th} \) required VNF for flow \( f \). As an example, considering \( X = 4 \) and \( \psi = 3 \), taking for example flow \( f = 1 \), the matrix \( R^1 \) and \( K^1 \) are as follows:

\[
R^1 = \begin{bmatrix}
0 & 1 & 1 & 0
\end{bmatrix}, \quad K^1 = \begin{bmatrix}
3 & 2 & 0
\end{bmatrix},
\]

The required processing power of each VNF is expressed by \( FP_X \), where \( FP_x \) specifies the required processing power of VNF \( x \in X \). The matrix \( NC_N \) identifies the servers processing capacities for each server. The current processing load of each link is stated via \( NC_{N \times X} \), where \( NC_{(i,x)} \) specifies the current processing load of VNF \( x \) on server \( i \). The VNFs associated with each server are identified by matrix \( FN_{N \times X} \), therefore, \( FN_{(i,x)} \) specifies whether VNF \( x \) is supported by server \( i \) or not. We consider a server (or a cluster of servers) connected to each switch. If no server is connected to switch \( i \) then \( \sum_{x=1}^{X}(FN_{(i,x)}) = 0 \) (similarly for an OFF server). \( U_{N \times X}^F \) assigns servers’ resources to the flows. In other words, if \( U_{(i,x)}^F \) is 1, then flow \( f \) receives service from VNF \( x \) on server \( i \). Taking \( f = 1 \), the matrix \( U^1 \) is as following:

\[
U^1 = \begin{bmatrix}
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0
\end{bmatrix}.
\]

The third element of \( U^1 \) in the first row is one, it means that the flow uses the VNF 3 in the server 1. Similarly, since the second column of the fourth row is one, the VNF 2 will be delivered to the flow in server 4. The matrix \( E_N \) states the energy consumption of servers, where \( E_i, i \in N \) specifies the energy consumption of servers \( i \). \( O_{N}^F \) and \( O_N \) specify the previous and next state of servers (ON/OFF or IDLE/ACTIVE), respectively. Finally, \( \mu \) and \( \mu' \) state the maximum link and server utilization, respectively.

### B. Single Flow Resource Allocation (SFRA)

In order to simplify the understanding of Single Flow Resource Allocation (SFRA) formulation, we divide it into three parts:

- formulation of QoS constraints, unordered SFC constraints (i.e., the order of VNFs for flows is not important) and objective function related to the number of forwarding table entries
- formulation of SFC constraints with VNF Ordering
- formulation of objective function related to the energy consumption of the network

The first part is modeled as a Binary Linear Programming (BLP) while the other two parts are in the form of Integer Quadratic Programming (IQP). In Section IV-B4 the nonlinear equations are converted to linear form, therefore, the SFRA is modeled as an ILP. It should be mentioned that in this subsection, we have only one flow, therefore the flow rate vector reduces to a scalar \( C^f \triangleq C \).

1) **QoS and SFC Constraints without VNF Ordering:** In the formulation reported in this section we define the constraints that force the solution to satisfy the QoS requirements of flows (i.e., delay and bandwidth). Moreover we guarantee that the required VNFs for each flow will be crossed by the selected path for that flow. The proposed formulation is as follows:

\[
\min_A \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{f=1}^{F} A_{(i,j)}^f,
\]

(1)
subject to:

\[ \sum_{i=1}^{N} U_{(i,x)}^{f} \geq R_{z}^{f}, \forall x \in \mathcal{X}, \forall f \in \mathcal{F}, \quad (2) \]

\[ \sum_{i=1}^{N} A_{(i,j)}^{f} \geq U_{(j,x)}^{f}, \forall x \in \mathcal{X}, \forall j \in \mathcal{N} - \{s^{f}\}, \forall f \in \mathcal{F}, \quad (3) \]

\[ U_{(i,x)}^{f} \leq FN_{(i,x)}, \forall f \in \mathcal{F}, \forall i \in \mathcal{N}, \forall x \in \mathcal{X}, \quad (4) \]

\[ \sum_{i=1}^{N} U_{(i,x)}^{f} \leq 1, \forall f \in \mathcal{F}, \forall x \in \mathcal{X}, \quad (5) \]

\[ \sum_{x=1}^{X} \left( \sum_{f=1}^{F} \left( U_{(i,x)}^{f} \cdot C^{f} \cdot FP_{x} + NC_{0}^{f}(i,x) \right) \right) \leq \mu_{i} \cdot NC_{i}, \forall i \in \mathcal{N}, \quad (6) \]

\[ \sum_{j=1}^{N} A_{(i,j)}^{f} - \sum_{j=1}^{N} A_{(j,i)}^{f} = \begin{cases} 1 & i = s^{f} \\ 0 & i \neq s^{f}, d^{f} \\ -1 & i = d^{f} \end{cases}, \forall f \in \mathcal{F}, \forall i \in \mathcal{N}, \quad (7) \]

\[ \sum_{j=1}^{N} A_{(i,j)}^{f} \leq 1, \forall i \in \mathcal{N}, \forall f \in \mathcal{F}, \quad (8) \]

\[ \sum_{j=1}^{N} \sum_{i=1}^{N} \left( A_{(i,j)}^{f} \cdot D_{(i,j)} \right) \leq T^{f}, \forall f \in \mathcal{F}, \quad (9) \]

\[ U_{(i,x)}^{f}, A_{(i,j)}^{f} \in \{0, 1\}, \forall i \in \mathcal{N}, \forall f \in \mathcal{F}, \forall x \in \mathcal{X}. \quad (10) \]

The objective function (1) minimizes the number of elements that should be imported into forwarding tables of switches. In practice, this minimizes the number of hops that a flow will cross from source to destination. The constraint (2) indicates that each flow crosses a valid VNF chain while passing through the switches (without considering the order of VNFS). Moreover, constraint (3) imposes that the VNF is delivered only on crossed servers. Constraint (4) checks whether the requesting VNF is supported on the specified server. Constraint (5) is used to prevent gaining a VNF more than once for each flow. Constraint (6) controls the capacity of servers to provide a VNF. Focusing on the link capacity, constraint (7) checks the link capacity between each pair of the switches. Focusing on the flow conservation, constraint (8) presents the flow management limitations. Indeed, in turn, the first inequality prevents returning to the source or leaving the destination. Moreover, the second inequality imposes leaving the source switch and entering to the destination switch for each flow. Also, the third inequality forces the input and output of each server to be equal (except for the source and destination). In order to prevent loops for each flow, constraint (9) is applied. Focusing on the propagation delay, constraint (10) is used to control the propagation delay for each flow.

2) Formulation of SFC Constraints with VNF Ordering:

In the second optimization problem, we present the SFC by considering an ordered sequence of VNFs. The optimization problem is simplified as follows:

\[ \min_{A} \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{f=1}^{F} \left( A_{(i,j)}^{f} \right), \quad (11) \]

subject to:

\[ AP_{(i,j)}^{f} \geq A_{(i,j)}^{f}, \forall f \in \mathcal{F}, \forall i, j \in \mathcal{N}, \quad (12) \]

\[ AP_{(i,j)}^{f} = AP_{(i,j)}^{f} \cdot A_{(i,j)}^{f}, \forall i \in \mathcal{N} - \{d^{f}\}, j \in \mathcal{N}, \forall f \in \mathcal{F}, \quad (13) \]

\[ \sum_{j=1}^{N} AP_{(i,j)}^{f} = \sum_{j=1}^{N} AP_{(j,i)}^{f} + \sum_{j=1}^{N} A_{(j,i)}^{f}, \forall f \in \mathcal{F}, \forall i \in \mathcal{N} - \{s^{f}, d^{f}\}, \quad (14) \]

\[ \sum_{j=1}^{N} AP_{(s^{f},j)}^{f} = 1, \forall f \in \mathcal{F}, \quad (15) \]

\[ \sum_{j=1}^{N} \sum_{i=1}^{N} \left( AP_{(i,j)}^{f} \cdot U_{(i,K)}^{f} \right) \geq \sum_{i=1}^{N} \sum_{j=1}^{N} \left( AP_{(i,j)}^{f} \cdot U_{(i,K)}^{f} \right), \forall f \in \mathcal{F}, \forall V^{f} \in \{1, \ldots, len(K^{f})\}, \quad (16) \]

\[ AP_{(i,j)}^{f} \in \mathbb{Z}^{\geq 0}, \forall i, j \in \mathcal{N}, \forall f \in \mathcal{F}. \quad (17) \]

where constraint (11) indicates that the value of the priority matrix should be higher or equal to the rerouting matrix. Also, constraint (12) hints that if the value of matrix \( A_{(i,j)}^{f} \) is zero, then \( AP_{(i,j)}^{f} \) becomes zero. Due to the fact that for the destination switch all output links are zeros, constraint (13) is added. Constraint (14) enforces that if a flow enters to a switch in its \( a^{th} \) step, then it would leave that switch in the \( (a+1)^{th} \) step, however, source and destination switches are exceptions. Since the value of \( AP_{(s^{f},j)}^{f} \) should be the number of crossed switches, constraint (15) is considered. Focusing on the integrity of the priority matrix, constraint (16) assures that flows leave the source switch. Constraint (17) guarantees the sequence of VNF chaining. To this end, for each VNF, constraint (17) checks whether the VNFs with higher priority are delivered to the flow in one of the crossed servers or not. In this way, constraint (17) exploits i) variable \( V^{f} \) and ii) set \( Z_{V}^{f} \). Variable \( V^{f} \) states the index of each required VNFs...
for flow $f$. The set $Z^f_i$ contains all required VNFs with a higher priority than $V^f_i$. For example if $K = \{1, 2, 3, 4\}$ then $V^f \in \{1, 2, 3, 4\}$. If we consider $V^f = 3$ then $Z^f_V$ is a member of $\{1, 2\}$.

3) Formulation of Energy Consumption based objective function: In the third optimization problem, we present the SFC-aware congestion control system with minimizing the number of engaged server in order to preserve energy consumption of the SDN. Therefore, the following optimization problem presents:

$$\min_{O,A,U} \left( \sum_{i=1}^{N} (1 - O_i^0) \cdot O_i \cdot \mathcal{E}_i \right),$$

Subject to:

$$\text{Eq. (2) - (17)},$$

$$O_i \leq \sum_{j=1}^{F} \sum_{x=1}^{X} U^f_{i,(x)} \quad \forall i \in N,$$  \hspace{1cm} (19)

$$O_i \cdot \sum_{f=1}^{F} \sum_{x=1}^{X} U^f_{i,(x)} = \sum_{f=1}^{F} \sum_{x=1}^{X} U^f_{i,(x)}, \quad \forall i \in N.$$  \hspace{1cm} (20)

where the objective function (18) minimizes the number of servers that are required to be turned on just for this flow. Matrix $O$ specifies the required servers for just one flow while $O^0_i$ specifies the required servers for all flows that are currently in the network. Therefore, it is impossible to use $\sum_{i=1}^{N} (O_i - O^0_i)$ to find the number of recently turned on servers. In this way, one can use $\sum_{i=1}^{N} \left[ (1 - O^0_i)\cdot O_i \right]$ to find the number of recently turned on servers. Similarly, $\sum_{i=1}^{N} \left[ (1 - O^0_i)\cdot O_i\cdot \mathcal{E}_i \right]$ calculates the amount of energy that is imposed on the network just for the current flow (i.e., the amount of energy that is required for servers that are turned on just for the current flow).

Constraint (19) specifies the redundant servers and puts them in the IDLE mode. To this end, all servers that deliver no VNF to this flow are considered unnecessary. On the other hand, Constraint (20) specifies the essential servers for such flow (i.e., those servers that deliver at least one VNF to the flow should be in ON mode).

4) Converting Nonlinear Constraints to Linear Forms:

In the proposed formulation, constraints (12), (17), and (20) are nonlinear (i.e., just the first sub-problem “QoS and SFC Constraints without VNF Ordering” is linear). In order to make the scheme scalable, without loss of generality, these constraints are converted into linear form. Constraint (12) is aimed to ensure that if $A^f_{i,(j)}$ is zero, then $AP^f_{i,(j)}$ becomes zero. Since a flow at most traverses all servers, the value of $AP^f_{i,(j)}$ is always less than or equal to $N$. Therefore, constraint (12) can be substituted with constraint (21).

$$AP^f_{i,(j)} \leq N \cdot A^f_{i,(j)}, \quad \forall i \in N - \{d^f\}, \quad j \in N, \forall f \in F.$$  \hspace{1cm} (21)

In order to rewrite constraint (17) as a linear one, constraint (22) is considered. In constraint (22), since the value of $\sum_{j=1}^{N} A^f_{(i,j)}$ is always less than $\left(2n - 1\right)^2$ if one of $U^f_{(i,K_{v^f})}$ or $U^f_{(1,K_{v^f})}$ is zero, then the equation is true. The destination has a flow to itself with a step of at most $N + 1$. Therefore, in cases that both $U^f_{(i,K_{v^f})}$ and $U^f_{(1,K_{v^f})}$ are equal to one if and only if the value of $\sum_{j=1}^{N} A^f_{(i,j)}$ is greater than $\sum_{j=1}^{N} A^f_{(i,j)}$, the constraint is met. This means that the server which delivers the higher priority VNF is met before servers that deliver lower priority VNFs.

$$\left(1 - U^f_{(i,K_{v^f})}\right) \cdot (2N - 1) + \sum_{j=1}^{N} AP^f_{i,(j)} \geq \left(U^f_{(1,K_{v^f})} - 1\right) \cdot (2N - 1) + \sum_{j=1}^{N} AP^f_{i,(j)},$$

$$\forall f \in F, \forall V^f \in \left\{1, \ldots, \text{len} \left(K^f\right)\right\},$$

$$\forall Z^f_i \in \left\{1, \ldots, V^f - 1\right\}, \forall I, i \in N.$$  \hspace{1cm} (22)

Finally, a proper substitution for constraint (20) is stated in the following. In the mentioned constraint, the value of $\sum_{f=1}^{F} \sum_{x=1}^{X} U^f_{i,(x)}$ is always less than $(1 + F \cdot X)$. Considering the aforementioned inequality, the constraint (22) is satisfied if and only if the value of $O_i$ is one for servers that deliver VNFs to the flows (i.e., servers that have $\sum_{f=1}^{F} \sum_{x=1}^{X} U^f_{i,(x)} > 0$). Otherwise, (i.e., if $\sum_{f=1}^{F} \sum_{x=1}^{X} U^f_{i,(x)}$ be equal to zero) the value of $O_i$ is zero.

$$\left(1 + F \cdot X\right) O_i \geq \sum_{f=1}^{F} \sum_{x=1}^{X} U^f_{i,(x)}, \forall i \in N.$$  \hspace{1cm} (23)

C. Global Resource Reallocation (GRR)

In this subsection, the problem of resource reallocation is presented to optimize jointly the energy consumption and the network reconfiguration overhead. Network reconfiguration overhead (or, precisely, the flow rerouting overhead) depends on the number of rerouted flows. Increasing the number of rerouted flows not only may result in the network instability, but also it may increase the packet loss and end-to-end delay. The GRR formulation is as follows:

$$\min_{A,O,U} \left( \alpha \left( \sum_{i=1}^{N} \sum_{j=1}^{N} \sum_{f=1}^{F} \left| A^f_{i,(j)} - A^0_{i,(j)} \right| \right) + \left(1 - \alpha\right) \left( \sum_{i=1}^{N} O_i \cdot \mathcal{E}_i \right) \right),$$

$$\text{Subject to:}$$

$$\text{Eqs. (2) - (5), (8) - (11), (13) - (16), (19), (21) - (23)},$$

$^2$The value of $\sum_{j=1}^{N} AP^f_{i,(j)}$ is always less than $2N - 1$ because in the worst case, the flow meets all switches which means the value of $\sum_{j=1}^{N} AP^f_{i,(j)}$ is at most to $(N - 1) + N$. 


\[ \sum_{f=1}^{F} \sum_{x=1}^{X} (U_{(i,x)}^f \cdot FP_x \cdot C^f) \leq \mu \cdot NC_i, \forall i \in \mathcal{N}, \quad (25) \]
\[ \sum_{f=1}^{F} (A_{(i,j)}^f \cdot C^f) \leq \mu \cdot B_{(i,j)}, \forall i,j \in \mathcal{N}. \quad (26) \]

where the objective function (24) optimizes the energy consumption and network reconfiguration overhead. To this end, the first part of the objective function optimizes the number of the elements of the forwarding table that are going to be changed. Constraint (25) controls the capacity of servers on providing a VNF. Focusing on the link capacity, constraint (26) checks the link capacity between each pair of the switches.

1) GRR is NP-hard: Suppose that the energy consumption of all servers are zero, \( F = 1, X = 0, \) and \( R^1 = \emptyset. \) For any types of network, we define \( B', A0' \) as follows:

\[ B'_{(i,j)} = \begin{cases} 
0 & B_{(i,j)} = 0 \\
1 & B_{(i,j)} \neq 0 
\end{cases} \quad \text{and} \quad A0' = 0 \times A0 \]

consider a network with the following input parameters \( B', A0', X, F, \) and \( R. \) The problem is to find a path where end-to-end delay should be less than a predefined threshold with respect to the length of the path (number of forwarding table elements). As can be seen, the problem is mapped to the weight constrained shortest path problem (WCSSP) which is an NP-hard problem [32].

V. HEURISTICS

In this section, for each component of the Fig. 1 a fast heuristic algorithm is proposed.

A. Nearest Service Function first (NSF)

Since the process of assigning resources to the newly arrived flows is a real-time one, a heuristic algorithm is proposed to estimate SFRA in a real-time manner. To this end, Nearest Service Function first (NSF) is stated in this subsection. Algorithm 2 presents an outline of NSF. The algorithm finds the nearest server which supports the VNF with the highest priority and sends the flow to that server. Thereafter, NSF removes that VNF from the chain and finds the nearest server that supports the new highest priority VNF and so on.

In Algorithm 2 for each flow \( f \) (line 1) a path \( SP^f \) is selected. To this end, in the line 4, for each required VNF \( k \in K \) the following procedure is done:

- **NSF** finds the nearest server that supports that VNF (line 5; function ‘Find_Nearest_Providers’ is precisely described in Algorithm 3).
- The shortest path to the selected server is added to the \( SP^f \) and the current status is changed to the selected server (lines 6 and 7).
- Function Reduce_Capacity decreases the network capacity by the value of MFS (line 8). MFS is the median of recently communicated flows. This value is calculated using the data that is stored by the network monitoring component in the knowledge base.

```
Algorithm 2 Nearest_Service_Function_first (NSF)

INPUT: \( K, s, d, \mathcal{N} \)
OUTPUT: \( SP \) \( \triangleright SP \) is the selected path

1: for each flow \( f \in \mathcal{F} \) do
2: \( SP^f = \emptyset; \)
3: \( CN = s; \) \( \triangleright CN \) is the current server
4: for each VNF \( k \in K \) do
5: \( [v,p] = \text{Find_Nearest_Providers}(CN,k,\mathcal{N}); \)
6: add \( p \) to \( SP^f \)
7: \( CN = v; \) \( \triangleright MFS: \) median of flows size
8: \( B = \text{Reduce_Capacity}(B, MFS, p); \)
9: end for
10: \( p = \text{Shortest_Path}(CN,d); \)
11: add \( p \) to \( SP^f \)
12: \( B = \text{Reduce_Capacity}(B, MFS, p); \)
13: end for
14: return \( SP \)
```

- After receiving all required VNFs, the algorithm finds the shortest path to the destination and updates the links capacity matrix (lines 10-12).

```
Algorithm 3 Find_Nearest_Providers

INPUT: \( CN, k, OP \) \( \triangleright CN \) is the current server
OUTPUT: \( v, p \) \( \triangleright k \) is requested VNF

1: \( [P, Cost] = \text{Dijkstra}(CN,k, \text{Prune}(B)); \)
2: \( \triangleright P: \) set of nearest paths from \( CN \) to \( v \)
3: \( \triangleright OP: \) other required parameters
4: \( \triangleright Cost: \) costs of nearest paths from \( CN \) to other servers
5: for each server \( v \in \mathcal{N} \) do
6: \( \triangleright APP: \) Available Processing Power
7: \( \triangleright RPP: \) Required Processing Power
8: if \( FN_{(k,v)} = 0 \) OR \( APP(v) < RPP(MFS) \) then
9: \( Cost_v = \infty; \)
10: end if
11: \( p = P_v; \)
12: return \( [v,p] \)
```

In the first line of Algorithm 3 using Dijkstra, the shortest path to all servers are calculated. It should be mentioned that just those links that have a capacity greater than the median of recently communicated flows are considered as valid links (i.e., function \( \text{Prune} \) removes links that have less than MFS capacity). Thereafter, servers that have the following conditions are eliminated (lines 2-8): i) Do not support the requested VNF; and, ii) have a processing power less than the processing power required for processing the MFS. At this point, the nearest server to the current server is selected as destination (lines 9,10).

B. Offline Resource Reallocation

Since there is knowledge base in the proposed architecture, the scheme is able to calculate a long-term estimation of the
traffic pattern. Therefore, it can use these estimated information to turn off or on servers at the start of next time slot. Although GRR could find the optimal solution in this part, it is computationally complex and due to our experiment it is not applicable in medium and big size networks. Therefore, in this subsection, a near optimal solution called 3R is proposed.

1) Relaxed Resource Reallocation (3R): Since GRR considers the impact of flows on other flows and tries to find an optimal solution considering all flows simultaneously, the computational complexity increases dramatically for complicated networks with large number of flows. Therefore, a relaxed version of GRR called 3R is proposed to find a near-optimal solutions and provides a trade-off between the optimality gap and computational complexity. To this end, instead of considering the impact of all flows on each other, the impact of each flow on all flows that are already rerouted is considered, i.e., 3R reallocates the resource to the flows one-by-one. Algorithm 4 reports the 3R.

Algorithm 4 Relaxed Resource reallocation (3R)

```
INPUT: OP
OUTPUT: SP
1: for each flow f in F do
2: \( SP^f \) = SFRA\((B, f, C^f)\);
3: for each link \((i \rightarrow j)\) in \( SP^f \) do
4: \( B_{(i,j)} = B_{(i,j)} - C^f \);
5: end for
6: end for
7: return \( SP \)
```

It is notable that SFRA is unaware of the size of the flows, however, since 3R is a reconfiguration algorithm, it has information about the size of flows. In lines 1 and 2 of Algorithm 4, for each flow, 3R reallocates the resources using the gathered information about the flows’ size. Thereafter, the network status is updated by decreasing the available capacity of the links that are placed in the selected path. At this point, 3R reroutes the next flow using the same approach and so on.

C. Online Resource Reallocation

This component is designed to handle real-time requirements of the network. As a result, the algorithms which are used in this subsection should have a low computational complexity. To this end, two heuristic approach are proposed: i) ENSF: it reconfigures the network to reduce the energy consumption in a predefined time intervals, and ii) VP-ENSF that reconfigures the network in case of network congestion. In the following, these two heuristic approaches are discussed precisely.

1) Energy-aware NSF (ENSF): Although the computational complexity of 3R is sufficiently lower than GRR, it is still time consuming for real-time network reconfiguration. Therefore, a fast heuristic algorithm is proposed to reallocate the resources in real-time. To this end, a greedy approach is exploited. For each flow, in each step, a server which minimizes the energy consumption of the network for the next required VNF is selected. If there are multiple servers that have equal energy consumption, then the server which is closer to the current status is selected.

Algorithm 5 Energy-aware Nearest Service Function first (ENSF)

```
INPUT: k, OP
OUTPUT: SP
1: \( SP = \text{empty} \);
2: \( CN = s; \)
3: for each flow \( f \in F \) do
4:     for each VNF \( k \in K \) do
5:         \([\text{costs}, \text{paths}] = \text{Dijkstra}(CN, k, \text{Prune}(B));\%
6:         \text{Remove Redundant servers}
7:         if \( FN_{(k,i)} == 0 \) then
8:             \( \text{cost}_i = \infty \);
9:         end if
10:     end for
11:     energy = Energy\_Consumption(N);
12:     \([v, p] = \text{ENS}(\text{paths, costs, energy});\%
13:     add p to \( SP^f \)
14:     \( CN = v; \)
15:     \( B = \text{Reduce\_Capacity}(B, C^f, p); \)
16: end for
17: \( p = \text{Shortest\_Path}(CN, k, \text{Prune}(B));\%
18: \text{add p to } SP^f \)
19: \( B = \text{Reduce\_Capacity}(B, C^f, p); \)
20: end for
21: return SP
```

For each VNF per flow, the shortest path from the current server to all other servers are calculated (line 5). It should be mentioned that just those links that have a capacity greater than the size of the flow are considered as valid links (i.e., function Prune removes links that have a capacity less than \( C^f \)). In lines 6-10, all servers that do not support the requested VNF are omitted from the list by setting the cost of reaching them infinity (i.e., the cost is the propagation delay of paths). Afterward, the amount of extra energy that would be imposed by each server is calculated in line 11. Accordingly, if server \( i \) is currently ON, then the variable \( \text{energy}_i \) is zero. Otherwise, it is the energy consumption of the server. In line 12, ENS finds the nearest ON server which supports the required VNF (in the sake of cost). If there is not such a server, ENS seeks for servers that are in IDLE status. In this way, it finds the server with the minimum energy consumption.

At this point, the selected path \( p \) is added to \( SP^f \) (line 13) and the current status is updated to the selected server (line 14). Besides, the available capacity of the links used in the selected path is reduced by the size of the flow. After meeting all required VNFs, the algorithm uses the shortest path to directly move to the destination (lines 17-19).

2) VP Placement & ENSF (VP-ENSF): ENSF is supposed to change servers’ status from ACTIVE to IDLE and vice versa, however, when the network is congested it may be required to switch a server from OFF status to ON (AC-
TABLE II: Traffic Generator Notation and Inputs.

| Notation | Definition | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 | Scenario 5 |
|----------|------------|------------|------------|------------|------------|------------|
| $B_l$    | Ratio of flow size to link capacity | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 |
| $\gamma$ | Ratio of servers that can host VNFs | 0.7 | 1 | 0.7 | 0.7 | 0.5 |
| $R_l^I$  | Ratio of VNFs that a flow needs | 2.5 | 1.5 | 1.5 | 2.5 | 2.5 |
| $X_o$    | Ratio of VNFs hosted by a server | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| $R_{min}^I$ | Minimum number of requested VNFs per flow | 2 | 2 | 2 | 2 | 2 |
| $R_{max}^I$ | Maximum number of requested VNFs per flow | 5 | 5 | 5 | 5 | 5 |
| #f       | Number of flows | 22 | 25 | 26 | 28 | 45 |
| $\tau$  | Edge switches ratio | 1 | 1 | 1 | 1 | 1 |
| $\tau_s$ | Ratio of edge switches that are source of a flow | 1 | 1 | 1 | 1 | 1 |
| $\tau_d$ | Ratio of edge switches that are destination of a flow | 1 | 1 | 1 | 1 | 1 |
| $F_s$    | Coefficient of number of generated flows per source | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| $F_m$    | Maximum number of generated flows per source | 10 | 10 | 10 | 10 | 10 |
| $X$      | Number of different VNFs | 10 | 10 | 10 | 10 | 10 |

TIVE/IDLE) status. This will happen based on the fact the amount of traffic load on the network will increase more than the capacity of ON servers. As a result, VP-ENSF is proposed in which the servers can switch between three different possible states. The outline of the algorithm is similar to ENSF, however, the function \( ENS \) in line 12 of the Algorithm 5 is completely different. \( ENS \) in this algorithm seeks for a server which is already in ACTIVE status, if it is not possible then a server with minimum energy consumption would be selected. If neither possible, a nearest OFF server would be activated to handle the request.

D. Mathematical Computational Complexity

**NSF:** The order of line 1 of Algorithm 3 is \( O(N \cdot \log N + |E|) \) while it is \( O(N) \) for lines 2 and 9. Therefore, the order of the Algorithm 3 is \( O(2N + N \cdot \log N + |E|) \approx O(N \cdot \log N + |E|) \). Similarly, in Algorithm 2 the order of lines 3, 4, and 6 are \( O(\psi) \), \( O(N \cdot \log N + |E|) \), and \( O(N) \), respectively. Therefore, the total computational complexity of NSF is in order of \( O(\psi \cdot (N \cdot \log N + |E|) + N) \approx O(\psi \cdot (N \cdot \log N + |E|)) \).

**ENSF:** The computational complexity of lines 3 and 4 of Algorithm 5 are in order of \( O(F) \) and \( O(\psi) \), respectively. The order of each of lines 5 and 17 is \( O(N \cdot \log N + |E|) \) while it is \( O(N) \) for each of lines 6, 11-15, 18, and 19. Therefore, the total computational complexity of ENSF is \( O(F \cdot \psi \cdot (N \cdot \log N + |E|)) \).

VI. Numerical Results

In this section, the proposed schemes are evaluated under different network traffic patterns and a real-world network topology called Abilene [33]. In this way, the traffic generator and the simulation setup are discussed in the upcoming subsections.

A. Traffic-Demand Generator

In order to investigate the performance of these resource allocator/reallocator algorithms, a traffic-demand generator is proposed. It takes multiple input parameters and generates network traffic flows with different specifications: rate, source and destination, VNF requirements, and end-to-end tolerable delay. Table III presents these input parameters of the traffic generator. It is important to note that the algorithm generates the traffic pattern (no traffic packets).

Note that the flows are unidirectional. Besides, \( \tau \) specifies the percentage of switches that are as edge switches. In other words, \( \tau \) is a variable stands for the percentage of switches that can be source or destination of a flow. As an example, \( \tau = 1 \) means that all switches can be considered as an edge switch while \( \tau = 0 \) means that there is no edge switch. Therefore, the number of edge switches is \( \tau \times N \). Similarly, the variables \( \tau_s \) and \( \tau_d \) are the percentage of edge switches that can be considered as the source or the destination of a flow, respectively, i.e., the number of source switches is at most \( \tau_s \times \tau \times N \). The maximum number of source-destination pairs is \( (\tau \times \tau_s \times N) \times (\tau \times \tau_d \times N) \).

Moreover, \( F_s \) and \( F_m \) are input parameters that control the number of generated flows per source switches. More precisely, the number of generated flows for each source switch follows a truncated geometric distribution [34] with \( 1/(F_s \times \tau \times N) \) as the success probability and \( F_m \) as the maximum number of flows. In addition, to check the impact of VMs’ number on each server, several values for \( \gamma \) is considered. Specifically, \( \gamma \) is the ratio of servers that can host VNFs, therefore, \( \gamma \times N \) is the number of servers that can host a VNF. On the other hand, \( X \) is the ratio of VNFs hosted by a server, meaning that a server can host at most \( X \gamma \times X \) different VNFs, where \( X \) is the number of different types of VNFs, \( R_l^I \times X \), \( R_{max}^I \), and \( R_{min}^I \) are the average, maximum, and minimum number of VNFs that a flow needs, respectively. The average bandwidth demand of a flow is a fraction \( B_l^I \) of the capacity of the link, i.e., it is \( B_l^I \times \text{link capacity} \). Rate of generated flows follows a uniform distribution between 0 and 2 times of the average rate of flows.
Since there is a relation between the energy consumption, the average path length of the flows, and the network reconfiguration side-effect, therefore, these three measures are compared in five different traffic scenarios. The different traffic scenarios are presented in Table II. In order to investigate the impact of the flow size, two different values for $B^f$ is considered. By changing the value of $R^f$, impact of flow requirements on the network is investigated. To investigate the impact of servers’ capacity, three different values for $\gamma$ is considered.

**B. Simulation Setup**

In this subsection, the system configuration and the network topology used in our simulations is described. Table III states the PC configuration setup in which the simulation is experimented.

**TABLE III: Hardware Configuration.**

| Name     | Description                  |
|----------|------------------------------|
| Processor| Intel(R) Core(TM) i5-2410M CPU @ 2.30GHz |
| IDE      | Standard SATA AHCI Controller |
| RAM      | 4.00 GB                       |
| System Type | 64-bit Operating System, Windows 10 |

The network topology used in the simulation is called Abilene [33] which is a real-world topology. Figure 3 illustrates the aforementioned topology. We consider the capacity of all links to be equal to $1\text{ Gbps} (B_{(i,j)} = 2^{30}, \forall i, j \in \mathcal{N})$. Each server has three modes: ACTIVE (i.e., the energy consumption is full rate energy consumption), IDLE (i.e., the energy consumption is a constant and low value), and OFF (i.e., it has no energy consumption). The processing power of a server $NC_i$ is a factors of the input line rate. Similarly, the energy consumption $E_i$ is a factor of processing power.

**C. Simulation Results**

In this subsection, the focus is on the reconfiguration part, therefore, in order to compare the results of different algorithms, we suppose NSF is aware of the size of flows. 1) Power, Path Length, and Reconfiguration Side-effect: In these set of test scenarios, In Fig. 4, x-axis elements are the labels of different traffic scenarios stated in Table II. The energy consumption of servers in the IDLE mode is 60 percent of its energy consumption in the ACTIVE mode. In order to compare the energy consumption of the heuristics, servers are not allowed to be turned off.

**Fig. 5: Traffic Scenario 2**

In all of the test cases, ENSF energy consumption is near optimal, however, in scenario 2 the optimality gap is increased. In this scenario, the ratio of servers that can host VNFs are increased to 1, which means that all servers are able to host VNFs. Conversely, the reconfiguration side-effect optimality gap between ENSF and GRR is reduced in scenario 2 (see Fig. 4a). The average path length of the fast heuristic approaches (i.e., NSF and ENSF) is better than mathematical approaches (i.e., GRR and 3R) in all test cases (see Fig. 4b).

2) Server and Link Utilization: In this subsection, the proposed schemes are compared via the link and server utilization measurements. To this end, the average utilization and maximum utilization of both links and servers are calculated for different iterations. In each iteration, the flow rate is increased.
using uniform distribution with average of 10 percent (between 0 and 20 percent) of the flow rate. We select two different scenarios and compare these measures among them in Fig. 6 and Fig. 7, respectively.

As can be seen, in all test cases the average and the maximum server utilization of NSF and ENSF are lower than GRR and 3R while the total throughputs are similar. This happens because the focus of GRR and 3R are on the energy consumption, therefore, they try to minimize the number of active servers. As a result, the server utilization goes higher than the heuristic approaches. Since NSF tries to find the nearest VNFs in sake of delay and path length, the average path length and consequently the average link utilization of NSF is lower than the other approaches.

3) Computational Complexity: In this subsection, the execution time of the heuristic algorithms and the optimal solutions are compared. Table IV presents the configuration of the system used to execute the algorithms. The results are stated in Table IV. As can be seen, the execution time of NSF and ENSF are very low, hence, they can be used as real-time heuristics to reconfigures the network for short-time resource reallocation. On the other hand, 3R can be used for long-time resource reallocation.

TABLE IV: Computational Complexity.

| Flow | GRR  | RRR [s] | NSF [s] | ENSF [s] |
|------|------|---------|---------|---------|
| 10   | 221.942 s | 333.892 | 0.005   | 0.005   |
| 250  | ≥ 1 Day | 821.056 | 0.097   | 0.101   |
| 500  | ≥ 1 Day | 1641.296| 0.196   | 0.204   |
| 750  | ≥ 1 Day | 2443.520| 0.298   | 0.312   |
| 1000 | ≥ 1 Day | 3252.865| 0.395   | 0.426   |
| 1500 | ≥ 1 Day | 4871.391| 0.675   | 0.608   |
| 2000 | ≥ 1 Day | 6494.061| 0.871   | 0.812   |

Fig. 6: Traffic Scenario 5

VII. CONCLUSION AND FUTURE WORKS

In this paper, we proposed a novel resource (re)allocation architecture for joint VM placement/migration and routing in the SDN-based networks. Besides, the problem of service function chaining with the goal of minimizing the energy consumption and network reconfiguration overhead is addressed. To this end, we divided the main problem into four subproblems and mathematically formulated these problems and proposed several heuristics to solve them. The objective is to minimize the energy consumption and the side-effect of network reconfiguration while the flow requirements are met. Simulation results showed that the proposed schemes (re)allocate the network resource in a way that the energy consumption is near to the optimal solution. Future work will be dedicated on making the algorithms robust against burst traffics. Another field of future interest would be considering the queuing delay of the switches and the processing delay of the server to improve the QoSs.

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REFERENCES

[1] J. Halpern and C. Pignataro, “Service function chaining (sfc) architecture,” Tech. Rep., 2015.
[2] A. Fischer, J. F. Botero, M. T. Beck, H. De Meer, and X. Hesselbach, “Virtual network embedding: A survey,” IEEE Communications Surveys & Tutorials, vol. 15, no. 4, pp. 1888–1906, 2013.
[3] A. M. Medhat, T. Taleb, A. Elmagoush, G. A. Carella, S. Covaci, and T. Magedanz, “Service function chaining in next generation networks: State of the art and research challenges,” IEEE Communications Magazine, vol. 55, no. 2, pp. 216–223, 2017.
[4] C. Hepburn, “Regulating by prices, quantities or both: an update and an overview,” Oxford Review of Economic Policy, vol. 22, no. 2, pp. 226–247, 2006.
[5] A. Khosravi, L. Andrew, and R. Buyya, “Dynamic vm placement method for minimizing energy and carbon cost in geographically distributed cloud data centers,” IEEE Transactions on Sustainable Computing, 2017.
[6] K. Mills, J. Filiben, and C. Dabrowski, “Comparing vm-placement algorithms for on-demand clouds,” in Cloud Computing Technology and Science (CloudCom), 2011 IEEE Third International Conference on. IEEE, 2011, pp. 91–98.
[7] S. Filiposka, A. Mishev, and C. Juiz, “Balancing performances in online vm placement,” in ICT Innovations 2015. Springer, 2016, pp. 153–162.
[8] D. Bhamare, M. Samaka, A. Erbad, R. Jain, L. Gupta, and H. A. Chan, “Optimal virtual network function placement in multi-cloud service function chaining architecture,” Computer Communications, vol. 102, pp. 1–16, 2017.
[9] M. F. Bari, S. R. Chowdhury, R. Ahmed, and R. Boutaba, “On orchestrating virtual network functions,” in Network and Service Management (CNSM), 2015 11th International Conference on. IEEE, 2015, pp. 50–56.

[10] G. Even, M. Rost, and S. Schmid, “An approximation algorithm for path computation and function placement in sdn,” in International Colloquium on Structural Information and Communication Complexity. Springer, 2016, pp. 374–390.

[11] M. Rost and S. Schmid, “Service chain and virtual network embeddings: Approximations using randomized rounding,” arXiv preprint arXiv:1604.02180, 2016.

[12] S. Xu, B. Fu, M. Chen, and L. Zhang, “An effective correlation-aware vm placement scheme for sla violation reduction in data centers,” in International Conference on Algorithms and Architectures for Parallel Processing. Springer, 2015, pp. 617–626.

[13] L. Rocha and F. Verdi, “A network-aware optimization for vm placement,” in Advanced Information Networking and Applications (AINA), 2015 IEEE 29th International Conference on. IEEE, 2015, pp. 1–9.

[14] Y. Zhao, Y. Huang, K. Chen, M. Yu, S. Wang, and D. Li, “Joint vm placement and topology optimization for traffic scalability in dynamic datacenter networks,” Computer Networks, vol. 80, pp. 109–123, 2015.

[15] N. M. Calcavecchia, O. Biran, E. Hadad, and Y. Moatti, “Vm placement strategies for cloud scenarios,” in Cloud Computing (CLOUD), 2012 IEEE 5th International Conference on. IEEE, 2012, pp. 852–859.

[16] X. Meng, V. Pappas, and L. Zhang, “Improving the scalability of data center networks with traffic-aware virtual machine placement,” in INFOCOM, 2010 Proceedings IEEE. IEEE, 2010, pp. 1–9.

[17] B. Zhang, P. Zhang, Y. Zhao, Y. Wang, X. Luo, and Y. Jin, “Co-scaler: Cooperative scaling of software-defined nfv service function chain,” in Network Function Virtualization and Software Defined Networks (NFV-SDN), IEEE Conference on. IEEE, 2016, pp. 33–38.

[18] A. AbdelSalam, F. Clad, C. Filsfils, S. Salsano, G. Siracusano, and L. Veltri, “Implementation of virtual network function chaining through segment routing in a linux-based nfv infrastructure,” arXiv preprint arXiv:1702.05157, 2017.

[19] S. Kulkarni, A. Arumaiturai, K. Ramakrishnan, and X. Fu, “Neo-nsh: Towards scalable and efficient dynamic service function chaining of elastic network functions,” in Innovations in Clouds, Internet and Networks (ICIN), 2017 20th Conference on. IEEE, 2017, pp. 308–312.

[20] J. Soares, C. Gonçalves, B. Parreira, P. Tavares, J. Carapinha, J. P. Barraca, R. L. Aguair, S. and Sargento, “Toward a telco cloud environment for service functions,” IEEE Communications Magazine, vol. 53, no. 2, pp. 98–106, 2015.

[21] M. M. Tajiki, B. Akbari, and N. Mokari, “Optimal qos-aware network reconfiguration in software defined cloud data centers,” Computer Networks, vol. 120, pp. 71–86, 2017.

[22] V. S. Reddy, A. Baumgartner, and T. Bauschert, “Robust embedding of vnfservice chains with delay bounds,” in Network Function Virtualization and Software Defined Networks (NFV-SDN), IEEE Conference on. IEEE, 2016, pp. 93–99.

[23] M. Ghaznavi, N. Shahriar, R. Ahmed, and R. Boutaba, “Service function chaining simplified,” arXiv preprint arXiv:1601.00751, 2016.

[24] J. W. Jiang, T. Lan, S. Ha, M. Chen, and M. Chiang, “Joint vm placement and routing for data center traffic engineering,” in INFOCOM, 2012 Proceedings IEEE. IEEE, 2012, pp. 2876–2880.

[25] L. Wang, Z. Lu, X. Wen, R. Knopp, and R. Gupta, “Joint optimization of service function chaining and resource allocation in network function virtualization,” IEEE Access, vol. 4, pp. 8084–8094, 2016.

[26] A. Marotta, F. D’Andreaiovanni, A. Kasler, and E. Zola, “On the energy cost of robustness for green virtual network function placement in 5g virtualized infrastructures,” Computer Networks, 2017.

[27] M. Shojaifar, N. Cordeschi, and E. Baccarelli, “Energy-efficient adaptive resource management for real-time vehicular cloud services,” IEEE Transactions on Cloud Computing, vol. PP, pp. 1–14, 2016.

[28] M. Tang and S. Fan, “A hybrid genetic algorithm for the energy-efficient virtual machine placement problem in data centers,” Neural Processing Letters, vol. 41, no. 2, pp. 211–221, 2015.

[29] L. Gu, D. Zeng, S. Guo, and B. Ye, “Joint optimization of vm placement and request distribution for electricity cost cut in geo-distributed data centers,” in Computing, Networking and Communications (ICNC), 2015 International Conference on. IEEE, 2015, pp. 717–721.

[30] V. Marotta, E. Mandic, M. Ammar, K. Kasler, and G. Lavacca, “An approach for service function chain routing and virtual function network instance migration in network function virtualization architectures,” IEEE/ACM Transactions on Networking, 2017.

[31] E. Haleplidis, K. Pentikousis, S. Denazis, J. H. Salim, D. Meyer, and O. Koufopavlou, “Software-defined networking (sdn): Layers and architecture terminology,” Tech. Rep., 2015.

[32] I. Dumitrescu and N. Boland, “Algorithms for the weight constrained shortest path problem,” International Transactions in Operational Research, vol. 9, no. 1, pp. 15–29, 2001.

[33] “Ablene network,” Jun 2007. [Online]. Available: https://web.archive.org/web/20120324103518/http://www.internet2.edu/pubs/200502-IS-AN.pdf

[34] X. Zou, “Computer communication networks cs 6/7520/2 g1 project source traffic modeling and generation.”

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