Failure Aware Semi-Centralized Virtual Network Embedding in Cloud Computing Fat-Tree Data Center Networks

Chinmaya Kumar Dehury, *Member, IEEE*, Prasan Kumar Sahoo, *Senior Member, IEEE*

Abstract— In Cloud Computing, the tenants opting for the Infrastructure as a Service (IaaS) send the resource requirements to the Cloud Service Provider (CSP) in the form of Virtual Network (VN) consisting of a set of inter-connected Virtual Machines (VM). Embedding the VN onto the existing physical network is known as Virtual Network Embedding (VNE) problem. One of the major research challenges is to allocate the physical resources such that the failure of the physical resources would bring less impact onto the users' service. Additionally, the major challenge is to handle the embedding process of growing number of incoming users' VNs from the algorithm design point-of-view. Considering both of the above-mentioned research issues, a novel Failure aware Semi-Centralized VNE (FSC-VNE) algorithm is proposed for the Fat-Tree data center network with the goal to reduce the impact of the resource failure onto the existing users. The impact of failure of the Physical Machines (PMs), physical links and network devices are taken into account while allocating the resources to the users. The beauty of the proposed algorithm is that the VMs are assigned to different PMs in a semi-centralized manner. In other words, the embedding algorithm is executed by multiple physical servers in order to concurrently embed the VMs of a VN and reduces the embedding time. Extensive simulation results show that the proposed algorithm can outperform over other VNE algorithms.

Index Terms—Cloud computing, Virtual Network Embedding (VNE), Fat-Tree data center, resource mapping.

1 Introduction

Virtualization is the key technology that enables Infrastructure Provider (IP) to share the same physical servers or Physical Machines (PMs) among multiple tenants by creating virtual version of the resources such as storage, memory, CPU and network. This allows the system developer to decouple the service instances from the underline hardware resources by placing the virtualization software between the user's operating system and the underlined physical resources [1]. On the other hand, a large number of PMs in a data center is connected through several types of switches and long cables. Fat-Tree [2] network topology is widely used in commercial data centers in order to establish the connection among PMs through core switches, aggregation switches and edge switches as the basic connecting devices. The resources of the PMs are provided to the tenants by creating multiple Virtual Machines (VMs), ensuring the basic privacy properties, better QoS and other user requirements as mentioned at the time of Service Level Agreement (SLA) establishment between the tenant and the IP [3].

The network of multiple VMs that are requested by the cloud users is called Virtual Network (VN). The job of the Cloud Service Provider (CSP) is to provide a set of interconnected PMs onto which the VN can be embedded, which is known as Virtual Network Embedding (VNE) problem [4]. This problem can also be relate to the problem of virtual network function placement [5]. The job of virtual network embedding is to embed VMs and virtual links. VM embedding refers to as selecting a suitable PM by taking location, energy and users' budget constraint parameters into consideration [6]. Virtual link embedding refers to as finding the shortest path between the corresponding PMs taking number of switches, load on the physical links, latency and several other parameters into consideration.

The unexpected failure of resources is one of the major research issues that cannot be ignored by the cloud service provider. Failure in resources has a direct impact on the services. Service failures have direct impact on QoS, energy consumption, SLA violation, and huge revenue loss of CSP [7]. One of the major research issues in VNE is how to avoid the unexpected service failures due to the failure of any hardware module or software module. The failure of resources includes switch failure, physical link failure, and PM failure [8]. The major reasons behind the resource failures could be the wrong input to the user program, high workload on switches and PMs and failure of power supply. It is reported that a single failure (or cloud outage) for one hour could bring more than $336,000 financial loss to cloud providers, such as Amazon and Microsoft [9], [10]. The impact of the potential failure of any physical resource on service availability, productivity, business reputation, etc. [11] must be analyzed before embedding the VN onto the physical network. Here, we are considering the failure of PM, the physical network link and the switches. The VMs of the incoming VN must be distributed in such a way that impact of physical resource failure is minimized by avoiding

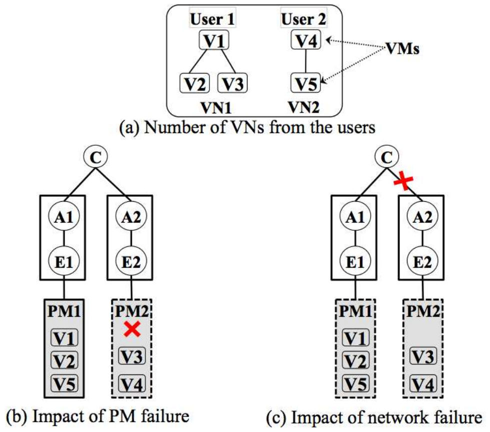
Chinmaya Kumar Dehury was with the department of Computer Science and Information Engineering, Chang Gung University, Guishan, Taiwan. Currently, he is with the Mobile & Cloud Lab, Institute of Computer Science, University of Tartu, Estonia. Email: chinmaya.dehury@ut.ee.
Prasan Kumar Sahoo (Corresponding Author) is with Department of Computer Science and Information Engineering, Chang Gung University, Taiwan. He is an Adjunct Research Fellow in the Division of Colon and Rectal Surgery, Chang Gung Memorial Hospital, Linkou, Taiwan. Email: pksahoo@mail.cgu.edu.tw

potential resource failure. It is also essential to design an algorithm that can embed the VNs considering the failure impact of the physical resources. An efficient VNE algorithm may consume significant time only for the embedding purpose. The nature of the algorithm such as centralized, distributed or semi-centralized also plays a major role in making embedding process faster, resulting in better QoS.

In general, the VNE algorithm is installed in a dedicated server to accomplish the embedding process with the responsibility to embed all incoming VNs onto the physical network in a centralized manner. The major flaws of the centralized embedding algorithms are poor scalability, lower capital message, single point of failure and higher embedding cost [12]. On the contrary, distributed embedding algorithm reduces the embedding cost and delay time, which occurs due to the arrival of a large number of simultaneous VNs, but does not obtain the global view of the physical network. As distributed VNE algorithms are scalable unlike the centralized one, they give better performance as compared to the centralized approaches in the geo-distributed Data Centers (DCs) [12]. Despite several advantages of the distributed VNE algorithms, obtaining an optimal embedding solution without global view of the DC network incurs heavy resource requirement and time consumption. To overcome the disadvantages of the centralized and distributed VNE algorithms, a semi-centralized algorithm may produce a near-optimal embedding solution by considering the global view of the DC network and also can embed multiple VNs in parallel. The entire semi-centralized algorithm is divided into two sub-algorithms, which may run in two stages. If the centralized approach is followed by one sub-algorithm in the first stage, the distributed approach is followed by another sub-algorithm in the second stage. However, if the distributed approach is followed in the first stage, the centralized approach will be followed in the second stage. Multiple constraints such as revenue maximization, guaranteeing SLA with higher QoS and power consumption maximization need to be taken into consideration while designing an efficient semi-centralized VNE algorithm.

1.1 Motivation

As discussed before, VNE problem refers to as embedding of VN onto a set of interconnected PMs. In the process of embedding, CSP needs to consider multiple factors such as resource availability of the PMs, bandwidth availability, utilization of the resources, load balancing among all the PMs, energy consumption of the PMs, network latency etc. Failure probability of the PMs is one of the main factors, which plays a crucial role in the process of embedding. Without considering the PMs' failure probability, CSP may embed the VMs onto the PMs that are most likely to fail in the next time instance. Failure of PMs results in failure of corresponding VMs. As a result, the corresponding services would be interrupted, which may bring a huge monetary loss for the CSP. Though a number of research articles have been proposed recently to address the VNE problems considering different factors, the failure probability of the PMs and impact of resource failure onto the existing users' request has not been studied extensively.



(a) Number of VNs from the users

(b) Impact of PM failure

(c) Impact of network failure

Fig. 1. Impact of resource failure on VNE.

Fig. 1 illustrates the impact of resource failure on the users' request. Let $VN1$ and $VN2$ be the two VNs received by the CSP from two different users as shown in Fig. 1(a). $VN1$ consists of VMs $V1, V2$, and $V3$. $VN2$ consists of VMs $V4$ and $V5$. Considering the example given in Fig. 1, let the CSP consists of two PMs $PM1$ and $PM2$ connected in Fat-Tree topology with number of ports $k = 2$. The two VNs $VN1$ and $VN2$ are embedded onto these two PMs. VMs $V1, V2$, and $V5$ from $VN1$ and $VN2$, respectively, are embedded onto $PM1$. VMs $V3$ and $V4$ from VN $VN1$ and $VN2$, respectively, are embedded onto $PM2$. In this scenario, if physical machine $PM2$ is failed, it has direct impact on both users and VM $V3$ and $V4$ will be affected, as shown in Fig. 1(b). Besides the impact on the VMs, the virtual link between VM $V3$ and $V1$ and the virtual link between VM $V4$ and $V5$ will be affected as the one of the end VMs of those virtual links are inactive or not in running state. As shown in Fig. 1(c), the impact of the failure of network resource onto the existing users is discussed. Failure of a physical link between core switch c and aggregation switch $A2$ has also direct impact on all users, which can affect all five virtual machines hosted by $PM1$ and $PM2$. Failure of this physical link also affects the virtual links $(V1, V3)$ and $(V4, V5)$ of $VN1$ and $VN2$, respectively. Though Fat-Tree network topology offers higher degree of fault tolerant service through multiple physical paths between any two servers, however in a much highly loaded network, failure of one link brings higher impact on the corresponding servers and the VMs. It is assumed that the virtual machines within a VN can be connected in any topology.

Further, several centralized VNE algorithms are not scalable and are mainly designed to deploy on a single PM, which is further responsible for receiving and processing the incoming VNs [13], [14]. This centralized approach makes the algorithm in-scalable and therefore the new VNs may experience delay as the single PM is busy in embedding other VNs that arrived earlier. Here, in-scalable refers to as the lack of ability to handle the growing number of incoming VNs to accommodate itself according to a number of VNs. Besides, this disadvantages in-terms of in-scalability and the knowledge of global view of the entire physical network help the algorithm to make the most efficient embedding solution in terms of the time required to embed the VNs excluding the waiting time. The distributed approach of VNE algorithm is highly scalable. Despite its

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCC.2020.2984604, IEEE Transactions on Cloud Computing

higher scalability nature, it is difficult to obtain an efficient embedding solution as the global view is not available for the PMs executing the embedding algorithm. Considering these two traditional approaches and their disadvantages, it is essential to design a VNE algorithm, which can be highly scalable and must consider the global view of the entire physical network.

The above-mentioned scenario motivates us to revisit the VNE problem by taking the failure of PMs as well as the physical links into account. Accordingly, we have proposed a novel Failure aware Semi-Centralized Virtual Network Embedding (FSC-VNE) scheme with the following goals:

- To design semi-centralized VNE algorithm that can meet the requirement of data centers with large volume of requests arrival rate.
- To minimize the impact of failure of PMs and physical links onto the existing users while embedding VNs by considering the failure probability of the PMs.

The goals can be achieved by embedding the VMs onto the PMs considering the failure probability of each PM. Further, in order to minimize the impact of physical link failure, multiple VMs can be embedded onto a single PM, which eventually eliminates the failure possibilities of corresponding virtual links.

Rest of this paper is organized as follows. In Section 2, we present the recent research articles related to VNE. The system model of this paper is presented in Section 3. The proposed VNE algorithm is discussed in Section 4. In Section 5, performance evaluation of our proposed algorithm is made followed by the concluding remarks in Section 6.

2 Related Works

Extensive researches have been emphasized on different aspects of VNE problem, such as energy-aware [15] location constraint [16], physical network topology [3], etc. Considering the location preferences of the users, authors in [16], formulate the VNE problem as a graph bisection problem, which achieves integrated VM and virtual link mapping. Restricting one PM to host maximum one VM in order to reduce the failure impact onto single VN arises another problem of accumulative failure impact onto all corresponding VNs.

2.1 Resource utilization optimization

In order to reduce the total amount of required physical resources in a multi-cloud environment, priority values are assigned to the user's requests [14]. Here, each PM can be used to host a maximum of one VM from a VN. Such an approach contradicts the goal of minimizing the required physical resources. Assigning multiple VMs onto a single PM can effectively reduce the required amount of resources. In a likewise fashion, degree and clustering information of a VM within a VN are used to embed the user's request onto physical network with the objective to minimize the network utilization and maximize the acceptance ratio as in [17]. However, the dependencies among the VMs are not considered, resulting in inefficient mapping solution.

In a multi-service cloud environment, resource allocation and provisioning algorithms are presented in [18] considering the SLA, service cost, system capacity and resource demand. However, considering only VM resources without network resource may not fit into the real-life scenario. Authors in [19] propose a novel VNE algorithm considering the link interference due to bandwidth scarcity. The major advantage of the proposed I-VNE algorithm is that the temporal and the spatial network topology information are taken into consideration and the VNs are embedded with low interference.

To efficiently utilize the computing resources and increase the acceptance ratio, authors in [6] presented a unique approach to embed the VN. This is done by simply placing the same VM onto multiple PMs and distributing the input data onto corresponding PMs. However, this approach required extra network resource and the number of PMs required for a VN is more than the number of VMs present in the VN. VNF placement problem is further studied in different scenarios, such as 5G network slicing framework [20], Network Function Virtualization (NFV) [15]. Authors in [21] address the Virtual Network Functions (VNFs) placement problem with Deep Reinforcement Learning approach to obtain a near-optimal solution. However, the proposed algorithm does not consider the impact of the failure of physical resources that may bring a more significant effect on the VNFs and the resource utilization.

In federated cloud, taking minimization of the network latency as the major goal, authors in [22] propose network-aware VNE scheme. The proposed algorithm ignores the fact that the single PM can be used to execute multiple VMs, which eventually eliminate the network resource demand without compromising the QoS and other user's requirements. Similarly, the proposed congestion-aware VNE scheme with Hose model abstraction in [23], has the restriction to embed only one VM onto one PM. As a result, the opportunity to minimize the amount of required network resource is ignored. A rank-based VNE algorithm is presented in [24] considering substrate node degree, strength and distance with others. However, its inability to scale and inability to consider the failure probability of the substrate nodes and links makes the VNE approach inefficient.

2.2 Embedding time minimization

Authors in [12] propose a distributed embedding algorithm, which partitions the entire physical network into multiple blocks. Though the embedding cost for each VN is reduced, however, the accumulative computational overhead still exists and the total amount of required computational resources is very high. In order to fasten the embedding process for the VN that follow mess topology, authors in [25], introduced a novel approach that reduces the number of virtual links. However, combining multiple virtual links onto one increases the embedding cost. This trade-off is addressed by proposing reduction algorithms. However, this centralized algorithm may not be able to scale up with the growing number of PMs and hence may degrade the efficiency in terms of embedding time.

The VNE problem can be viewed as multi-objective linear programming problem, as in [26]. Though the authors

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TCC.2020.2984604, IEEE Transactions on Cloud Computing

have achieved the goal to maximize the revenue and minimize the embedding cost, however, the mapping solution may suffer from physical resource fragmentation issue and may not produce efficient result in terms of embedding cost due to the mapping of virtual node followed by the virtual links.

2.3 Cost and Revenue

Two VNE algorithms are presented based on Monte Carlo tree search and multi-commodity flow algorithm in [27] with the objective to maximize the profit of the IP. The proposed centralized VNE algorithm claims to map the virtual nodes and the virtual links without splitting the physical path. However, the centralized approach may produce an inefficient result in terms of embedding time. In [28], a new path algebra strategy is proposed to embed the virtual nodes and the virtual links based on cost and revenue parameter. However, the proposed multi-staged mapping strategy may produce extra computational overhead, resulting higher embedding time.

Authors in [29] address the problem of inefficient bandwidth reservation due to the uncertainty. Though the proposed stochastic approach achieves maximizing the revenue of the CSP, however, author should also consider the failure probability of the physical links.

A number of VNE approaches have been proposed considering dynamic resource requirement, topology of the data center, energy consumption, and revenue maximization. Though the studies in current literature solve many real-life scenarios in cloud, to the best of our knowledge none of the studies propose an embedding scheme, which processes the VNs in semi-centralized manner to fasten the embedding process and minimizes failure impact of the physical resources onto the existing VNs.

3 Problem Formulation

As discussed earlier, it is the job of the CSP to create/embed multiple interconnected VMs onto a set of suitable PMs. In the embedding process, the network topology plays an important role as it defines the network structure and the connectivity of one PM with other PMs. In our study, Fat-Tree network topology is taken into consideration as the data center network topology. It is assumed that the computing and network resources of PMs and the networking devices remain static throughout the execution of the algorithm for any particular VN. In other words, the resource capacities of the PMs and networking devices do not change, when the VNE allocation algorithm runs. The PMs are heterogeneous in nature. The resource requirement of the VN includes the computing and network resource demand of VMs and virtual links, respectively, which do not change over time. Further, the topology of the VN including the number of VMs, virtual links, the resource demand of the VMs and the virtual links are static and hence do not change after the VN request is submitted to the CSP. In further sections, we will discuss the network topology, the VN, and failure impact of physical resources onto the VNs in details. A summary of all the notations is given in Table 1.

TABLE 1
List of notations

Notation	Description
P	Set of m PMs $\{p_1, p_2, \ldots, p_m\}$
S	Set of s switches $\{S_1, S_2, \ldots, S_s\}$
k	number of ports available at each switch
V	Set of n VMs $\{v_1, v_2, \ldots, v_n\}$
x	resource type $\{memory, CPU\}$
α_i^x	Server resource requirements of VM v_i
α_{ij}^e	Bandwidth requirement between VM v_i and v_j
e_{ij}	The virtual link between VM v_i and v_j
β_i^x	Resource of type x available at PM p_i
β_i^n	Network resource available at PM p_i
L_i^j	1 :if there exist a link between PM p_i and switch S_j
L_{ij}	1 :if there exist a link between switch S_i and switch S_j
ω_{ij}	Number of switches present between PM p_i and PM p_j
ψ_i	Workload on PM p_i
$\hat{\alpha}_i^e$	Bandwidth requirement by VM v_i
$I_s^v(p_i)$	The impact of failure of PM p_i onto the set of VMs
κ_i^j	1 :if VM v_j is assigned to PM p_i
λ_{ij}^{qr}	1 : if the virtual link e_{qr} is assigned to physical link Lij or L_i^j
$I_N^n(z_{ij})$	Impact of physical link z_{ij} failure on the set of virtual links
$I_N^v(z_{ij})$	Impact of physical link z_{ij} failure on the set of VMs
$I_w^v(s_j)$	Impact of network switch, s_j, failure onto the set of VMs
$I_w^n(s_j)$	Impact of network switch, s_j, failure onto the set of virtual links
$PE^e(p_i)$	Set of edge layer neighboring PMs of the PM p_i
$PE^a(p_i)$	Set of aggregation layer neighboring PMs of the PM p_i
$PE^c(p_i)$	Set of core layer neighboring PMs of the PM p_i

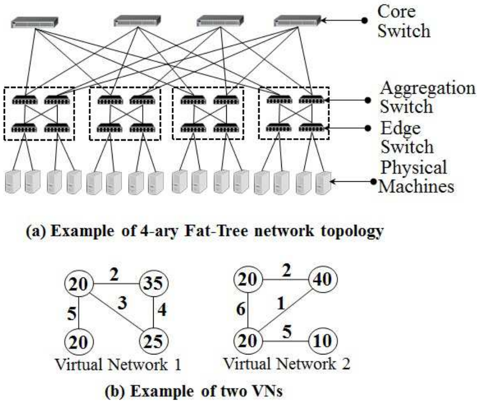
3.1 Fat-Tree data center network

As shown in Fig. 2(a), the switches are mainly organized into three layers, such as core switch, aggregation switch, and edge switch in the Fat-Tree data center network [14]. The number of layers in Fat-Tree can be extended to more than three layers. However, we focus our study considering the basic three-layer Fat-Tree network topology. Let k be the number of ports available at each switch. Being at the root of the network, the number of core switches are $(\frac{k}{2})^2$. The total number of aggregation switches is equal to the total number of edge switches required, which is $\frac{k}{2}$. The maximum number of servers that can be attached to the Fat-Tree topology is $\frac{k^3}{4}$. Let $S = \{S_1, S_2, S_3, ..., S_s\}$ be the set of s number of switches, which includes core switches, aggregation switches, and edge switches. The value of s can be calculated as $s = \frac{5k^2}{4}$.

Let $P = \{p_1, p_2, p_3, ..., p_m\}$ be the set of $m = \frac{k^3}{4}$ number of PMs that are attached to the bottom level of Fat-Tree topology. Let β_i^x be the resource of type $x \in \{memory, CPU\}$ available at PM p_i. For instance, β_2^{memory} represents the amount of remaining memory available at PM p_2. L_i^j is the boolean variable, which represents if there exists a physical link between switch $S_i, 1 \leq i \leq s$ and PM $p_j, 1 \leq j \leq m$. Mathematically,

$$L_i^j = \begin{cases} 1 & \text{if physical link between PM } p_i \\ & \text{and Switch } S_j \text{ exist} \\ 0 & \text{Otherwise} \end{cases} \tag{1}$$

Similarly, L_{ij} is the boolean variable, which indicates if there



(a) Example of 4-ary Fat-Tree network topology

(b) Example of two VNs

Fig. 2. Example of Fat-Tree network topology and virtual network.

exists a physical link between switch $S_i, 1 \leq i \leq s$ and $S_j, 1 \leq j \leq s, i \neq j$. Mathematically,

$$L_{ij} = \begin{cases} 1 & \text{if physical link between switch} \\ & S_i \text{ and } S_j \text{ exist} \\ 0 & \text{Otherwise} \end{cases} \tag{2}$$

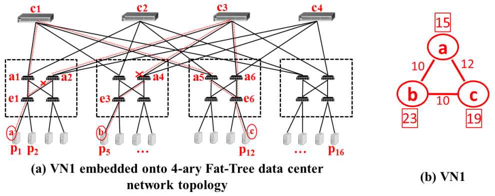
In the three-layer Fat-Tree network topology, the number of links from any PM to any one of the core switches is three. They are (1) the link from the PM to the edge switch, (2) the link from the edge switch to the corresponding aggregation switch, and (3) the link from the aggregation switch to the core switch. The maximum bandwidth capacity of all the links is same according to the characteristics of the Fat-Tree network topology [2]. The physical links at the lower level of the tree structure network topology usually carry less workload as compared to the links at the upper level. The k ports in a switch are divided into two groups of $\frac{k}{2}$ ports. One group is used to connect to the upper layer switches and another group of ports is used to connect to the lower layer switches. This infers the fact that the failure of physical links at the lower level has less impact than the failure of the upper level physical links.

3.2 Virtual Network

As depicted in Fig. 2(b), the VN is represented as undirected weighted graph, where the node represents the VM and the edge (or virtual link) represents the communication between corresponding pair of VMs. Let, $V = \{v_1, v_2, v_3, ..., v_n\}$ be the set of n number of VMs. The resource requirement of the VM $v_i, 1 \leq i \leq n$ is represented as α_i^x, where $x \in \{memory, CPU\}$ defines the resource type. Let, e_{ij} and α_{ij}^e represent the virtual link and the bandwidth requirement between VM v_i and v_j, $i \neq j$, respectively. In the example given in Fig. 2(b), the numeric value within each circle represents the amount of required computing resource and the value beside each edge represents the required network bandwidth between the corresponding VMs.

3.3 Definitions

Definition 1. Remaining Bandwidth at PMs: The remaining available bandwidth at each PM is calculated by finding the minimum remaining bandwidth available along each path, which is originated from the corresponding PM to all core switches. Mathematically,



(a) VN1 embedded onto 4-ary Fat-Tree data center network topology

(b) VN1

Fig. 3. Resource failure impact onto virtual network.

$$\beta_a^n = \min_{\forall S_i, S_j, S_l \in S} \left\{ \begin{array}{c} \gamma^r(p_a, S_i) * L_a^i, \\ \gamma_a^r(S_i, S_j) * L_{ij}, \\ \gamma_a^r(S_j, S_l) * L_{jl} \end{array} \right\} \tag{3}$$

Where, β_a^n represents the remaining bandwidth available at PM p_a. The first term $\gamma^r(p_a, S_i) * L_a^i$ represents the remaining bandwidth available in the physical link between PM p_a and the connected edge switch. The middle term $\gamma_a^r(S_i, S_j) * L_{ij}$ represents the remaining bandwidth available at all physical links between the edge layer switches and the aggregation layer switches that are connected to the same pod, where PM p_a is attached. Similarly, $\gamma_a^r(S_j, S_l) * L_{jl}$ represents the remaining bandwidth available at all physical links between the aggregation switches related to PM p_a and all core switches. For better understanding, let us consider the example given in Fig. 3(a). In order to calculate the remaining bandwidth at PM p_1, we calculate the remaining bandwidth available in all three layers of physical links. Firstly, the link between PM p_1 and the edge switch $e1$, secondly, the physical link between edge switch $e1$ and aggregation switches $a1$ and $a2$, thirdly, the physical links between the aggregation switches $a1$ and $a2$ and all core switches, i.e. physical links $(a1, c1), (a1, c2), (a2, c3)$, and $(a2, c4)$. The minimum bandwidth available among all above-mentioned physical links is the remaining bandwidth available at PM p_1.

Definition 2. Workload on PMs: The workload on the PM p_i, represented as Ψ_i, can be calculated as the ratio between the amount of the physical resources allocated to other VNs and its maximum resource capacity.

Definition 3. Required Bandwidth of VMs: The bandwidth requirement by any virtual machine can be calculated by summing up the bandwidth requirement by the adjacent virtual links. Mathematically,

$$\hat{\alpha}_i^e = \sum_{j=1}^{n} \alpha_{ij}^e \tag{4}$$

For instance, the total bandwidth required by the VM a in Fig. 3(b) is calculated as the bandwidth demand by the virtual link (a, b) and (a, c), i.e. $10 + 12 = 22$. Similarly, the total required bandwidth by the VM b and c is 20 and 22, respectively. In the proposed embedding scheme, it is assumed that the required bandwidth of all the virtual links are time-invariant and don't change over time.

Definition 4. Semi-Centralized VNE: An embedding algorithm is said to be semi-centralized if the algorithm follows both centralized and distributed approach for embedding the VN onto the physical network. The first stage of the proposed VNE algorithm follows centralized approach, where a set of PMs is selected by a single embedder, whereas the second stage of the proposed algorithm follows the distributed approach, where the set of selected PMs executes the same algorithm to pick-out suitable VM. Since the proposed embedding process follows both centralized and distributed approach, it is called semi-centralized VNE algorithm.

3.4 Resource failure impact

We are mainly considering three types of resource failures, such as (a) server or PM resource failure, which includes the CPU, memory, storage, and other physical resources (b) physical link failure, and (c) switch failure. Further, the resource failure impacts are of two types, such as (a) the impact on the VMs, and (b) the impact on the virtual links. In our study, the impact of the failure of physical network resource and switch resource onto both VMs and virtual links are taken into consideration. The impact of failure of PM resources onto the VMs is only taken into account. But, the impact of such failure onto the adjacent virtual links is not considered. However, the impact of server failure onto the virtual links excluding the adjacent virtual links is not taken into account. Here, it is assumed that the failure probability of the servers can be obtained by the CSP by observing the historical information of each server [30]. The failure probability of the physical machines may increase with the increase in their workload, users' interaction etc. The same applies to the physical links also. The more communication and the workload on links may lead to their higher failure probability. Hence it is necessary to consider the failure probability of the physical machines and the physical links, which can minimize the failure impact onto the users' VNs.

3.4.1 PM failure impact

Let, $I_s^v(p_i)$ be the impact of failure of PM p_i onto the set of VMs $V = \{v_1, v_2, \dots, v_n\}$. The PM failure impact is quantified as the value between 0 and 1, and is calculated as the ratio of amount of allocated server resources affected and the total amount of required resource. Mathematically, the impact of physical server resource failure onto the virtual machine is

$$I_s^v(p_i) = \frac{1}{|x|} * \sum_{\forall x} \frac{\sum_{j=1}^{n} \kappa_i^j * \alpha_j^x}{\sum_{j=1}^{n} \alpha_j^x}, \quad x \in \{memory, CPU\} \tag{5}$$

The numerator in Eq. (5) represents the amount of resource of type $x, x \in \{memory, CPU\}$ of the PM p_i is allocated to the VMs of the current VN. The denominator represents the total amount of resource of type $x, x \in \{memory, CPU\}$ is demanded by all VMs. κ_i^j is the boolean variable that indicates if the virtual machine v_j is assigned to the PM p_i.

$$\kappa_i^j = \begin{cases} 1 & \text{if VM } v_j \text{ is assigned to PM } p_i \\ 0 & \text{Otherwise} \end{cases} \tag{6}$$

It is to be noted that equal importance is given to both types of the resources. For better understanding, Let us assume an example of a virtual network consisting of three VMs as a, b, and c with memory and CPU resource demand of $(10, 2), (23, 3)$, and $(15, 1)$ units, respectively. Let, VM a, b, and c be deployed on PM A, B, and C, respectively. The total memory resource demand of all the three VMs is $10 + 23 + 15 = 48$. Similarly, $2 + 3 + 1 = 6$ is the total CPU demand. Here, PM A provides 10 $units$ and 2 $units$ of memory and CPU resources, respectively to the VM a. The failure impact of PM A onto the virtual network can be calculated as $\frac{1}{2} * \frac{10}{48} + \frac{2}{6} = 0.27$. Similarly, the failure impact of PM B and C onto all the VMs can be calculated as 0.49 and 0.24, respectively.

3.4.2 Physical link failure impact

In this subsection, we discuss the impact of physical link failures on virtual links and the VMs.

Physical link failure impact on virtual links: I_N^v and I_N^n be the impact of physical link failure onto the set of VMs and the set of virtual links, respectively. The impact of the physical link failure onto the virtual links is calculated as follows.

$$I_N^n(z_{ij}) = \frac{\sum_{q=1}^{n-1} \sum_{r=q}^{n} \lambda_{ij}^{qr} * e_{qr} * \alpha_{qr}^e}{\sum_{q=1}^{n-1} \sum_{r=q}^{n} e_{qr} * \alpha_{qr}^e}, \quad \forall i, j, i \neq j \tag{7}$$

Where, the boolean variable λ_{ij}^{qr} indicates if the virtual link e_{qr} is embedded onto the physical link z_{ij}, which represents the physical link between two switches L_{ij}, or the physical link between one switch and one PM L_i^j. λ_{ij}^{qr} can be expressed as

$$\lambda_{ij}^{qr} = \begin{cases} 1 & \text{if the virtual link } e_{qr} \\ & \text{is assigned to physical link } z_{ij} \\ 0 & \text{Otherwise} \end{cases} \tag{8}$$

The numerator and denominator of the Equation (7) represent the amount of physical network resource allocated to the VN and the total amount of network resource demanded by all virtual links, respectively.

For the sake of clarity, an example is presented in Fig. 3. Assume VN1 contains three VMs a, b, and c with the computing resource demand of 15 units, 23 units and 19 units, respectively. The network bandwidth demands of the virtual links (a, b), (b, c), and (a, c) are 10 units, 10 units, and 12 units, respectively. Let, the entire physical network consists of 16 PMs. VM a, b, and c are assigned to PM p_1, p_5, and p_{12}, respectively, as shown in Fig. 3. The dotted line in Fig. 3(a) represents the assigned virtual links. For example, the virtual link (a, c) is assigned to the physical path $(p_1, e1, a1, c1, a5, e6, p_{12})$. The virtual link (b, c) is assigned to physical path $(p_5, e3, a4, c3, a6, e6, p_{12})$. Similarly, the virtual link (a, b) is assigned to the physical path $(p_1, e1, a2, c3, a4, e3, p_5)$. Under this virtual network embedding, the impact of failure of the physical link $(e1, a2)$ results in failure of communication between VM a and b. Using Equation (7), the impact can be calculated as $\frac{10}{10+10+12} = 0.31$.

Physical link failure on a single VM: The failures of the physical links have also impacted on the virtual machines as the failures of the virtual links lead to no or delay communication among VMs. The communication among the VMs within a VN is required to finish the assigned jobs and therefore the failure of a single virtual link has the impact on the corresponding VMs and entire VNs [13], [30]. Following equation is used to calculate the impact of physical link failure onto the single VM.

$$\begin{aligned} I_N^v(z_{ij}, v_q) &= \frac{\alpha^e_{qr} * \left(\frac{\alpha^x_q}{\sum_{r=1}^{n} \alpha^e_{qr}}\right)}{\alpha^x_q} \\ &= \frac{\alpha^e_{qr} * \alpha^x_q}{\alpha^x_q * \sum_{r=1}^{n} \alpha^e_{qr}} = \frac{\alpha^e_{qr}}{\sum_{r=1}^{n} \alpha^e_{qr}}, \quad r \neq q \end{aligned} \tag{9}$$

The notation $I_N^v(z_{ij}, v_q)$ represents the impact of failure of physical link z_{ij} onto the VM v_q. The notation z_{ij} is used to represent the physical link L_{ij} or L_i^j. In the example given in Fig. 3, the impact of failure of physical link $(e1, a2)$ onto the VM a can be calculated as $\frac{10}{10+12} = 0.45$.

Physical link failure on all VMs: Extending further, the impact of failure of physical link z_{ij} onto all VMs can be calculated as

$$I_N^v(z_{ij}) = \sum_{q=1}^{n-1} \sum_{r=q}^{n} \lambda^{qr}_{ij} \left[\frac{\alpha^e_{qr} \left(\frac{\alpha^x_q}{\sum_{u=1}^{n} \alpha^e_{qu}} + \frac{\alpha^x_r}{\sum_{u=1}^{n} \alpha^e_{ur}} \right)}{\sum_{u=1}^{n} \alpha^x_u} \right], \tag{10}$$

where, the numerator represents the sum of amount of computing resources of two corresponding VMs of each affected virtual link and the denominator represents the total amount of the resource demanded by all VMs. Applying Eq. (10) onto the example given in Fig. 3, the impact of failure of physical link $(e1, a2)$ onto all VMs can be calculated as $\frac{10}{10+12} + \frac{10}{10+10} = 0.95$.

3.4.3 Switch failure impact

I_w^v and I_w^n be the impact of network switch failure onto the VM and the virtual link, respectively.

The failure of the switches can be considered as the collective failure of the attached physical links. The impact of such failure onto the allocated computing resources or the VMs can be calculated by using the Eq. (10) as follows

$$I_w^v(s_j) = \sum_{i=1}^{s} z_{ij} * I_N^v(z_{ij}), \quad i \neq j \tag{11}$$

Similarly, the impact of switch failure onto the allocated network resources or the virtual links is calculated as follows.

$$I_w^n(s_j) = \sum_{i=1}^{s} z_{ij} * I_N^n(z_{ij}), \quad i \neq j \tag{12}$$

Considering the example given in Fig. 3, failure of the aggregation switch $a4$ results in failure of virtual links (a, b) and (b, c). However, failure of the core switch $c1$ results in failure of the virtual link (a, c).

3.5 Neighbor PMs

Neighbor PMs are used to find the set PMs that are nearer to each other and can be used to embed a VN. As a result, the VMs those are belonged to the single VN are placed as nearer as possible. Neighbor PMs are of three types, such as (a) Edge layer neighbor PMs (b) Aggregation layer neighbor PMs, and (c) Core layer neighbor PMs. These are classified based on the number of intermediate switches.

3.5.1 Edge layer neighbor PM

Two PMs are said to be edge layer neighbor PMs, if both PMs are connected to the same edge switch. Mathematically,

$$PE^e(p_i) = \{p_j | w_i^j = 1\}, 1 \leq i \leq m, 1 \leq j \leq m, i \neq j \tag{13}$$

where, $PE^e(p_i)$ is the set of edge layer of neighboring PMs of the physical machine p_i. w_i^j is the minimum number of intermediate switches present in between the PM p_i and p_j.

3.5.2 Aggregation layer neighbor PM

Two PMs are said to be aggregation layer neighbor PMs, if both PMs are attached to the same pod. In other words, the number of intermediate switches between both PMs is 3. Mathematically,

$$PE^a(p_i) = \{p_j | w_i^j = 3\}, 1 \leq i \leq m, 1 \leq j \leq m, i \neq j \tag{14}$$

where, $PE^a(p_i)$ is the set of aggregation layer neighboring PMs of physical machine p_i.

3.5.3 Core layer neighbor PM

Similar to edge layer and aggregation layer neighbors, the number of intermediate switches among core layer neighbor PMs is 5. This can be represented mathematically as follows.

$$PE^c(p_i) = \{p_j | w_i^j = 5\}, 1 \leq i \leq m, 1 \leq j \leq m, i \neq j \tag{15}$$

3.6 Objective function

In the proposed failure-aware VNE scheme, the failure probabilities of the physical machines are taken into consideration in order to reduce the failure impact on the users' VNs. The failure impact of the physical machines, physical links and switches are considered as calculated in Section 3.4. The failure impact onto the VMs and virtual links are calculated in a balanced model presuming that all the VMs and virtual links are not associated with any additional parameter to decide their importance. However, the VM or virtual link having higher resource demand has direct influence over the failure impact. In other word, VM having higher resource has maximum failure impact and similarly, the virtual link having higher network resource demand has maximum failure impact. The main goal of the proposed work is to reduce the failure impact onto the users' VN. This is done by embedding the VMs onto the PMs in close proximity as discussed above. As a result, along with the overall reduced failure impact, the proposed VNE scheme would be able to minimize the total amount of physical resources. Based on the above problem description, the objective function of the proposed scheme is formulated as follows:

Objective:

$$\min \quad \sum_{i=1}^{m} \Bigg[\varepsilon_1 * I_s^v(p_i) + \varepsilon_2 * \sum_{\forall r} \frac{I_N^v(Z_{ir}) + I_N^n(Z_i r)}{2} + \varepsilon_3 * \sum_{\forall q} \frac{I_w^v(S_q) + I_w^n(S_q)}{2} \Bigg] \quad (16)$$

Constraints:

$$\alpha_j^x \leq \beta_i^x, \quad \forall v_j \in V, \forall p_i \in P, x \in \{CPU, Memory\} \quad (17)$$

$$\hat{\alpha}_j \leq \beta_i^n, \quad \forall v_j \in V, \forall p_i \in P \quad (18)$$

$$\sum_{i=1}^{m} \kappa_i^j = 1, \quad \forall v_j \in V \quad (19)$$

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 1, \quad 0 < \varepsilon_1, \varepsilon_2, \varepsilon_3 < 1 \quad (20)$$

The objective function in Equation 16 is of two-fold. The first part focuses on selecting the PM such that its failure would bring minimum overall impact onto the assigned VN. The second part focuses on selecting the adjacent physical links and the switches such that their failure would bring minimum impact onto the virtual machines and the virtual links. The weight of the impact of the resources can be decided by modifying the values of $\varepsilon_1, \varepsilon_1$, and ε_3. This would allow the CSP to give importance to different resources at different time instances. For example, higher value of ε_2 gives maximum importance to the impact of the physical link failure over the failure of the physical machines and switches. Similarly, equal of all the weight factors give equal importance to the impact of failure of the PMs, physical links, and switches.

While evaluating the objective function, the proposed algorithm must ensure that following constraints are satisfied. Constraint (17) ensures that the available computing resource of the selected physical machine is more than the computing resource demand of the virtual machine. Similarly, Constraint (18) ensures that the total required network bandwidth of a VM is less than the available bandwidth of the PM. Constraint (19) ensures that no VM is embedded onto multiple PMs. In the proposed VNE scheme, we take the advantage of embedding multiple VMs of single VN onto a single PM. This will allow us to ignore the corresponding virtual link from embedding onto the physical network. Constraint (20) restricts the values of $\varepsilon_1, \varepsilon_1$, and ε_3 to be less than 1 and is greater than 0. However, the sum of all the weight factors must be equal to 1.

4 Proposed VNE algorithm

In the above section, we have formulated the VNE problem and have presented the objective function with the aim to minimize the impact of the resource failure onto the virtual networks. In order to meet the objectives mentioned in Equation 16, we propose a novel heuristic two-staged Failure Aware Semi-Centralized Virtual Network Embedding (FSC-VNE) algorithm, which is specially designed for a large number of physical servers connected using the Fat-Tree network topology in a data center. With one VNE request as the input, the entire algorithm works in two stages. First is the PM Cluster Formation (PM-CF) stage, and second is the VM Pick-out (VM-Po) stage. The proposed FSC-VNE algorithm follows the semi-centralized approach for embedding the VN. As discussed in Section 1, the VNs are embedded by the single dedicated server onto thousands of physical servers in the first-come-first-serve manner in a centralized approach, which introduces a waiting time for the VNs those arrive lately. Further, in distributed approach of the embedding process, the VNs are embedded by multiple dedicated servers concurrently, which leaves the synchronization and communication overhead for the physical servers as a major issue. Taking the advantages of both approaches, the PM-CF stage is designed to preprocess the VNs in a centralized manner, whereas the VM-Po stage is designed to work in distributed approach with negligible communication overhead, as described in Lemma 4. It is to be noted that, reducing the embedding time by distributing the incoming virtual networks onto multiple servers is one of our goals. However, being one of the major disadvantages of centralized approach, single-point-failure problem of the proposed FSC-VNE scheme still exist, which is an obvious pitfall of both centralized and semi-centralized algorithms. As a whole, the proposed FSC-VNE algorithm is said to be semi-centralized embedding algorithm.

4.1 PM Cluster Formation (PM-CF) stage

As the name suggests, in this stage a set of PMs is chosen, known as PM cluster. The global view of the entire data center network must be obtained before processing the incoming VNs, essentially in real-time manner. The global information includes the available server resources such as remaining number of CPUs, memory and storage availability. This also includes the bandwidth information in each link. On the other hand, the information regarding the VN includes the computing resource requirement such as memory, CPU requirement. For exchange of intermediate data among VMs, the required bandwidth must be made available. The required bandwidth for each VM is calculated as the sum of bandwidth requirement of each virtual link that is attached to the corresponding VM as defined in Eq. (4). As discussed earlier in Eq. (3), the remaining available bandwidth at each PM is calculated by finding the minimum remaining bandwidth available at each path that is originated from the corresponding PM to all core switches.

Algorithm 1 receives one VNE request at a time and the maximum bandwidth requirement among all VMs is calculated in Line 4 - 7 considering the resource requirement of each VM. The remaining available bandwidth at each PM is then compared with the maximum bandwidth requirement in order to remove PMs with inadequate network resource as given in Line 8. In this process, some PMs may fail to fulfill the maximum bandwidth requirement among all the VMs. However, such PMs may be attached to some physical links with enough bandwidth resources to fulfill the demand of some VMs that require minimum bandwidth among all VMs. We calculate the maximum bandwidth requirement among all VMs as our goal is to select a set of PMs that can fulfill the network resource demand of any VM.

From the resultant list of the PMs, the available server resource and the resource requirement of the VMs are compared. The maximum memory requirement and the maximum number of CPU requirements are calculated. Based on this calculation, multiple PMs are removed further from the list. Now the resultant list of PMs is eligible to host any VMs from the current VN. Preparing the list of such PMs would reduce the embedding time and also ensures that any VM can be embedded onto any PM. The list is further sorted in an ascending order based on any available resource type. Since, all PMs are eligible to host all the VMs, c number of PMs are selected to form the PM cluster. The value of c, the PM cluster size, is calculated based on the number of VMs that are present in the current VN.

The details of the PM-CF stage are mentioned in Algorithm 1. The PM-CF algorithm starts by initializing P and V as set of all PMs and the inter-connected VMs that belong to the current VN, respectively, as in Line 1 - 2. Following this initialization, in Line 4-7, maximum resource requirement among all VMs is calculated. In the proposed algorithm, resource requirement includes memory, CPU, and network bandwidth requirement. The set $\ddot{P}_1$ is used to keep a list of PMs that are eligible to provide enough network bandwidth to all the VMs as in Line 8. Similarly, the set $\ddot{P}_2$ and $\ddot{P}_3$ are used to keep a list of PMs that are eligible to provide required amount of computing resources as in Line 9 and 10. In Line 11, the sorting operation is applied to the intersection of set $\ddot{P}_1, \ddot{P}_2$ and $\ddot{P}_3$. From the resultant sorted list of PMs R, first $n * c$ numbers of PMs are chosen, as in Line 12. Here, n represents the number of VMs present in the current VN, which is calculated in Line 3. We assume that the value of c is decided by CSP satisfying the following conditions.

$$1 \leq c \leq \frac{|\ddot{P}_1 \cap \ddot{P}_2 \cap \ddot{P}_3|}{n} \tag{21}$$

Larger value of c increases the PM cluster size. As a result, larger number of PMs will be involved concurrently in VM pick-out stage.

Algorithm 1: PM Cluster Formation (PM-CF) algorithm

```
1  Initialize: P = {Set of all PMs} ;
2               V = {Set of all VMs} ;
3  $n = |V|$;
4  $VN_{max}^{mem} = \max(\alpha_i^{mem}), \forall i, 1 \leq i \leq n$;
5  $VN_{max}^{CPU} = \max(\alpha_i^{CPU}), \forall i, 1 \leq i \leq n$;
6  $\alpha_i^{nw} = \sum_{j=1}^{n} \alpha_{ij}^{e}, i \neq j$ ;
7  $VN_{max}^{nw} = \max(\alpha_i^{nw}), \forall i, 1 \leq i \leq n$;
8  $\ddot{P}_1 = \{p_i | \beta_i^{n} \geq VN_{max}^{nw}, \forall p_i \in P\}$ ;
9  $\ddot{P}_2 = \{p_i | \beta_i^{mem} \geq VN_{max}^{mem}, \forall p_i \in P\}$ ;
10 $\ddot{P}_3 = \{p_i | \beta_i^{CPU} \geq VN_{max}^{CPU}, \forall p_i \in P\}$ ;
11 $R =$ Sort $\{\ddot{P}_1 \cap \ddot{P}_2 \cap \ddot{P}_3\}$ in ascending order ;
12 $CL =$ {Set of first $n * c$ number of PMs from R} ;
```

4.2 VM Pick-out (VM-Po) stage

VM pick-out algorithm works in a distributed fashion. The central server forwards separate copies of the details of the resultant PM cluster and the VN to each PM. Each PM executes the VM-Po algorithm with own copy of inputs. The details of resultant PM cluster include the load of each PM, the number of networking devices present between each pair of PMs, available amount of computing resources (memory and CPU) on each PM, failure probability of each PM etc. In order to reduce the network failure impact onto current VN, multiple VMs can be placed onto a single PM. As the physical network link at the upper layer of the Fat-Tree topology carries out most of the data transmission, failure of such physical links brings maximum impact onto the entire network. Considering this fact, our objectives are to minimize the required number of switches, physical links and PMs for embedding the VN. When the PMs are allowed to host multiple VMs of single VN, it is obvious that the total number of required PMs will be reduced. We have provided the proof to minimize the required number of physical links and physical switches in Lemma 1-3.

It is assumed that the failure probabilities of the PMs are different. As mentioned in the second part of the objective function in Equation 16, minimizing the required number of switches infers the minimization of the required number of physical links, which is proved in Lemma 1. As discussed earlier, the basic difference between three types of neighbor PMs is the number of switches involved in the communication path. The number of switches involved in the path between edge layer neighbors is 1 as in Equation (13), whereas the number of switches involved in the path between aggregation layer neighbors is 3 and core layer neighbors is 5 as in Equation (14) and Equation (15), respectively.

The Algorithm 2 starts by obtaining the unique machine ID, OD, of the PM where the algorithm is running, as in Line 3. As the algorithm in each PM is executed independently, the value of OD in each PM is different. p^{od} represents the PM, where the algorithm is running as given in Line 4. Each PM forms a set PE^e of edge layer neighbor PMs as in Line 5. In each PM, the elements of the set PE^e are different. Since, the set of edge layer neighbor PMs does not include the PM itself, another set PE is formed with help of union operation of the set PE^e and the PM itself as in Line 6. The reason behind forming the set of PE is to allow the VMs to be embedded onto the nearby PMs. Further, one leader PM is chosen based on the failure probability of all the PMs that belong to the set PE. In other word, the failure of all PMs that are connected to the same edge switch are compared to find the leader PM. In Line 7, the PM with minimum failure probability value fp is chosen for the leader. As all the PMs have the information regarding the failure probability of each PMs, no additional communication is needed to choose the leader. Further, it is obvious that the resultant leader in each PM is same. The leader PM calculates the accumulative failure probability FP by summing the individual neighbor PM's failure probability fp as mentioned in Line 13. This allows us to consider the failure probability of other PMs with the failure probability of leader PM during the embedding process. On the other hand, the PMs that do not satisfy to be the leader have to wait for further instruction from their corresponding leader as in Line 11.

It is possible that there may be multiple leader PMs. Such

Algorithm 2: VM Pick-out (VM-Po) Algorithm

```
Input: Resource requirement of VN,
       Resource availability of all PMs,
       Workload of all PMs,
       Failure probability of all PMs
1  Initialization;
2  $V = \{$Set of VMs belong to current VN$\}$;
3  $OD$: unique id of the PM, where the algorithm is running ;
4  $p^{od}$ = represent the current PM, where the algorithm is running ;
5  Form the set $PE^e(p^{od})$ according to Equation (13).;
6  $PE = \{p^{od} \cup PE^e(p^{od})\}$;
   /* Find the leader PM based on min failure probability. */
7  $pl = min_{\forall p_i \in PE} fp(p_i)$;
8  if $pl = p^{od}$ then
9      goto Line 13
10 else
11     Wait for further instruction from PM $pl$;
12 end
   /* Calculate total failure probability of leader PM */
13 $FP(pl) = \sum_{\forall p_i \in PE} fp(p_i)$;
14 Compare with other leader PMs ;
15 $SP$ = leader PM with minimum $FP$ value as calculated in Step 13;
16 if $SP = p^{od}$ then
17     goto Line 21;
18 else
19     Wait for further instruction from PM $SP$;
20 end
21 $status$ =Pick-out($V$);
22 if $status$ ≠allEmbedded then
23     foreach $pl \in PE^a(p^{od})$ do
24         Remove VMs that are already allocated;
25         Send instruction to PM $pl$ to execute Pick-out($V$) function;
26         if $V$ =empty then
27             Terminate;
28         end
29     end
30     foreach $pl \in PE^c(p^{od})$ do
31         Remove VMs that are already allocated;
32         Send instruction to PM $pl$ to execute Pick-out($V$) function;
33         if $V$ =empty then
34             Terminate;
35         end
36     end
37 end
```

situation may occur, if the PM cluster contains multiple edge switches. For each edge switch, there will be single leader PM. Further, each leader PM obtains the set of other leaders, pl, that are connected to different edge switches. After obtaining the set of leaders and their corresponding accumulated failure probability value FP, the leader PM SP with minimum accumulative failure probability is chosen as mentioned in Line 15. The leader PM SP invokes the function $Pick - out$ as in Algorithm 2 with the argument as the set VMs or the current VN as mentioned in Line - 21. The responsibility of the $Pick - out$ function enables the corresponding PM to pick-out suitable VM(s) without any conflict with other PMs. If the leader PM SP and the PMs that belong to the corresponding set PE pick-out all the VMs present in the current VN, the embedding process terminates. However, if any VM(s) is not picked-out by any PM, other leader PMs that are connected to the same pod or the PMs that are aggregation layer neighbors of the leader PM SP will invoke the function $Pick-out$. The same procedure is repeated for the leader PMs that are core layer neighbors to the leader PM SP.

Algorithm 3: $Pick - out$ algorithm

```
1  if $p^{od} = pl$ then
2      Send instruction to all PM that belong to set PE to execute Pick-out($V$) function;
3  end
4  $p_c = min_{\forall p_i \in PE} \Psi_i$;
   /* Choose PM with minimum load from the set PE */
5  Choose VM pair $(v_1, v_2)$ with maximum bandwidth demand ;
6  $y_a$ = VM with maximum resource requirement between VM $v_1$ and $v_2$;
7  if $\beta_c^x \geq \alpha_a^x$ then
8      Assign $y_a$ to PM $p_c$;
9  else
10     Goto Line 4;
11 end
12 $y_b$ = VM with minimum resource requirement between VM $v_1$ and $v_2$;
13 if $\beta_c^x \geq \alpha_b^x$ then
14     Assign $y_b$ to PM $p_c$;
15 else
16     Goto Line 4;
17 end
18 if $V$ set is Empty then
19     Terminate the $Pick - out$ algorithm.
20 else
21     Repeat from Line 5;
22 end
```

The details of $Pick - out$ function are mentioned in Algorithm 3. Similar to VM-Po algorithm, each PM executes the $Pick-out$ algorithm in a parallel manner. The algorithm starts by receiving the VN as the only argument. Instead of all PMs that are selected by the PM-CF algorithm, a set of edge layer neighbor PMs executes concurrently at any given point of time. The algorithm is named as $Pick - out$ as each PM chooses one or more than one suitable VM independently from a set of VMs without any communication with other PMs. The beauty of this algorithm is that no VM will be chosen by multiple PMs without any communication among them. The PM with minimum workload as given in Line 4 picks out the VMs pair that requires maximum network bandwidth as in Line 5. From the chosen VM pair, the VM with maximum resource requirement as in Line 6 is chosen by the PM as mentioned in Line 8. Similarly, the other VMs are picked-out by the PM based on its remaining resources as mentioned in Lines 12-14. The process of picking VMs is repeated by the PM from Line - 5 till the available resource is enough to host a VM. All PMs follow the same procedure in parallel manner.

In the proposed VNE algorithm and objective function derived in Equation 16, we exploit the opportunity to embed multiple VMs onto a single PM. Assigning the VMs onto an equal number of PMs require higher number of physical links and thus higher number of switches taking the failure probability of the PMs into account. In this scenario, failure of a single PM brings maximum impact onto the single user as multiple VMs of a VN are placed on the single PM. On the contrary, it is observed that allocating multiple VMs onto a single PM could entirely remove the requirement of the network bandwidth and therefore could eliminate the possibilities of any impact onto the corresponding virtual links due to the failure of the physical links or switches. Failure of a PM would definitely have the impact on either one or more users, which cannot be ignored. However, the failure impact of the physical links and switches can be ignored as multiple interconnected VMs can be allocated to one PM.

The proposed algorithm is designed by considering the characteristics of the Fat-Tree network topology, where multiple layers of the core, aggregation, and edge layer switches are used to connect a large number of physical servers. Based on this, the numbers of neighboring PMs are calculated, which play an important role in the embedding process. The approach of the proposed algorithm can be applied to the data center with other network topology. However, the proposed algorithm needs to be modified in the environment with different network topology. For example, in case of the server-centric network topology, the calculation of the physical link and switch failure impact along with the number of neighboring PMs need to be revisited.

As discussed before, the current version of FSC-VNE algorithm cannot be applied to other data center network topologies. Given that the FSC-VNE is modified and implemented in other data center network topologies, the algorithm may not suffer from the scalability issue. In the second stage, while picking out the VMs in a distributed manner, a large number of PMs can be employed to perform the pick-out task. However, a few numbers of PMs will be able to host the VMs based on their failure probability. Furthermore, scaling the proposed algorithm to a larger number of PMs, the embedding time may increase due to the communication overhead during the execution of Algorithm irrespective of the underlined network topology 2 and 3.

Lemma 1. *Minimizing the number of switches eventually minimizes the number of physical links required to embed a VN.*

Proof. In 3-ary Fat-Tree network topology, the PMs are equipped with one network port, i.e. the degree of the server is one. This indicates that one PM can be connected to one network switch. Further, the number of switches required to connect two PMs can be 1, 3, or 5. When two PMs share same edge switch, the length of the path is 1. When two PMs are attached to same pod but different edge switches, the length of the path is 3. Similarly, the length of the path between two PMs attached to different pods is 5. Reducing the number of switches between two PMs refers to as ignoring the use of either core switches or aggregation switches. If the length of path between two PMs containing 5 switches is reduced to 3, the number of links that connect to the core switch is removed. As a result, the total number of required links is reduced. □

Lemma 2. *Giving high preference to edge layer neighbors eventually reduces the number of required physical switches.*

Proof. As discussed earlier, edge layer neighbor PMs share common edge switches. In Fat-Tree data center network topology, the degree of server is 1, which indicates the number of ports required on each server. The PMs that share common edge switch have exactly only one path of minimum distance. In Fat-Tree network topology, the path between any two PMs containing exactly two physical links must have one switch. Hence, it is obvious that embedding the VN onto the edge layer neighbor PMs reduces the number of switches. □

Lemma 3. *Giving higher preference to the edge layer neighbors eventually reduces the number of required physical links.*

Proof. Similar to the Lemma 2, the path between two PMs that are connected to same edge switch contain exactly two physical links, which is the minimum number of physical links between any two PMs. Hence, embedding VMs onto multiple PMs that are connected through one edge switch requires minimum number of physical links. □

Theorem 1. *Reducing the number of PMs considering their failure probability reduces the VN failure probability based on the proposed VNE algorithm.*

Proof. Let, the virtual network VN be embedded onto the set of PMs $p' = \{p_1, p_2, \dots p_a\}, 1 \leq a \leq |CL|$. The failure probability of VN can be written as

$$fp'(VN) = \sum_{\forall p_i \in p'} \frac{1}{|p'|} fp(p_i) \tag{22}$$

Based on the Algorithm 2, the PMs with lesser failure probability are given higher preference to pick-out the VMs. Hence, the following relation can be derived.

$$fp(p_1) < fp(p_2) < \dots < fp(p_a) \tag{23}$$

If embed the same virtual network VN can be embedded onto lesser number of PMs, the resultant PM set would be $p'' = \{p_1, p_2, \dots p_b\}, b < a$. After embedding the VN onto the PM set p'', the new failure probability of VN would be $fp''(VN) = \sum_{\forall p_j \in p''} \frac{1}{|p"|} fp(p_j)$. The above failure probability inequality can be re written as

$$fp(p_1) < fp(p_2) < \dots < fp(p_b) < \dots < fp(p_a) \tag{24}$$

Which implies that,

$$\sum_{\forall p_i \in p''} \frac{1}{|p"|} fp(p_i) < \sum_{\forall p_j \in p'} \frac{1}{|p'|} fp(p_j)$$
$$\Rightarrow fp''(VN) < fp'(VN) \tag{25}$$

□

Theorem 2. *The total impact of physical links failure on virtual links can be minimized by reducing the number of PMs.*

Proof. Let, the virtual network VN consists of a number of VMs and b number of virtual links. According to the proposed FSC-VNE algorithm, the PMs with enough available resources pick-out multiple VMs. Let, VM $v_q, 1 \leq q \leq a$ and $v_r, 1 \leq r \leq a, q \neq r$ be picked-out by a single PM. In such scenario, the bandwidth demand of the virtual link between the VM v_q and v_r can be ignored. Hence, the value of λ_{ij}^{qr} can be rewritten as given in Equation 8.

$$\lambda_{ij}^{qr} = 0, \text{ when } \kappa_i^q = 1, \kappa_j^r = 1, i = j \tag{26}$$

Further, applying above equation onto the Equation 7 for all virtual links, the maximum impact onto the virtual links can be minimized to less than 1. □

Lemma 4. *The communication overhead of the proposed FSC-VNE algorithm is $(n\partial - 1)(m' - 1)$, where ∂ be the amount of memory required to store the current status of one VM and $m' = |CL|$.*

Proof. The VNs are embedded in two stages according to the proposed algorithm. As the first stage follows the centralized approach, there is no communication overhead. However, in second stage, the leader PM with minimum total failure probability sends the updated information regarding all the VMs with other edge layer neighbor PMs and other neighbor PMs. Let, ∂ be the amount of memory required to store the current status of one VM. Current status infers, if a VM is picked-out by any PM. For $m' = |CL|$ number of selected PMs, a total of $2(m'-1)$ number of communications are needed for sending and receiving the messages. The leader PM sends a total of $n * \partial * (m' - 1)$ number of data packets to all neighbor PMs. The leader PM also receives $m' - 1$ number of single data packet messages. Hence, to embed a VN with n VMs, a total of $(n\partial - 1)(m' - 1)$ number of data packets are transmitted over the physical network. □

Theorem 3. *The proposed semi-centralized approach makes the VNE process faster as compared to that of the centralized one.*

Proof. In both centralized and semi-centralized approach, each VN must wait before they are submitted to the embedder. However, the major difference in both aforementioned approaches is the time that every VN needs to spend in the waiting queue. In the centralized version, the VN needs to wait until all the VMs of the previous VN are assigned to the suitable PMs unlike in the semi-centralized approach. Let, t^c units of time be taken in the centralized algorithm to embed a virtual network of n numbers of VMs. In each time slot, let v^T number of VNs be arrived to the system. Since, all the VNs embedding will be carried out by the single server, the total waiting time of the VNs that are arrived in the first time unit can be calculated as $\frac{1}{2}[t^c * v^T * (v^T + 1)] - v^T$. Choosing a set of suitable PMs for the entire VN without considering each VM's resource requirement would take lesser time, which is implemented in the PM-CF stage. Let, $t^{s'}$ be the time required to select a set of PMs for each VN. Hence, each VN needs to wait until the previous VN is processed in the PM-CF stage. Mathematically, $t^c > t^{s'}$.

This infers that a larger number of VNs are being processed by the server at any particular instant of time in the PM-CF stage as compared to the server in the centralized approach. Further, multiple PMs are assigned to embed all the VMs in the VM-Po stage. Let, $t^{s"}$ be the time taken to embed one VM. A VN of n number of VMs would take a total of $n * t^{s"}$ units of time, if all the VMs are processed in a sequential manner. Since, multiple PMs are involved in embedding all the VMs in a parallel manner, the total time required to embed n number of VMs would take $t^{s"}$ units of time. Combining the time required to embed one VN consisting of n number of VMs in the PM-CF and VM-Po stages, the total time can be calculated as $(t^{s'} + t^{s"})$. It is obvious that $(t^{s'} + t^{s"}) < t^c$ as t^c involves the embedding time of all VMs in a sequential manner and $(t^{s'} + t^{s"})$ involves in embedding all the VMs in parallel manner. Taking the above scenario into consideration, the total waiting time of the VNs that are arrived in the first time unit can be calculated as $t^{c'} * (v^T - 1)$, where v^T number of VNs arrives into the system in a single time unit. In the above calculation, the time required to embed in the VM-Po stage is not taken into consideration as different sets of PMs are selected for each VN in the PM-CF stage. This indicates that the VNs are embedded onto the physical network in the proposed semi-centralized approach by taking lesser time, which makes the embedding process faster. □

Theorem 4. *The time and space complexity of PM-CF algorithm are $\mathcal{O}((m \log m) + n)$ and $\mathcal{O}(m + n^2)$, respectively , where m represents the number of PMs and n is the number of VMs in the VN.*

Proof. In PM-CF algorithm, initialization instruction as mentioned in Lines 1-3 takes constant time $\mathcal{O}(1)$. Calculating the maximum resource requirement as in Lines 4-7, it takes $\mathcal{O}(3n)$ running time as we are only considering three types of resource requirement. The time complexity for forming the set $\ddot{P}_1, \ddot{P}_2, \text{and}\ddot{P}_3$ in Lines 8-10 is $\mathcal{O}(3n)$ time as in the worst case scenario, all PMs may satisfy the resource constraint. The time required to sort the set $\ddot{P}_1 \cap \ddot{P}_2 \cap \ddot{P}_3$ as in Line 11 can be minimized to $\mathcal{O}(m \log m)$ by using any existing efficient sorting algorithm. Hence, the total time complexity can be calculated as

$$T(\text{PM-CF}) = \mathcal{O}(3n) + \mathcal{O}(3m) + \mathcal{O}(m \log m) \tag{27}$$

The above time complexity of PM-CF algorithm in worst case scenario can be concluded as $\mathcal{O}(m \log m + n)$.

Let, δ be the constant amount of the space required to store the details of each PM. The total space required to store the entire PM network is $\mathcal{O}(\delta * m)$. Further considering the link representation of the VN, which includes the virtual node and virtual link representation, the space complexity of the PM-CF algorithm is $\mathcal{O}(n^2)$. Hence, the space complexity of the PM-CF algorithm can be concluded as $\mathcal{O}(m + n^2)$. □

Theorem 5. *The time and communication complexity of the VM-Po algorithm are $\mathcal{O}(m' + n^3)$ and $\mathcal{O}(2(m' - 1))$, respectively.*

Proof. VM-Po algorithm executes in $m' = |CL|$ number of PMs in a distributed approach. Before calculating the time complexity of the VM-Po algorithm, it is necessary to analyze the running time complexity of Algorithm 3 as it is invoked from the VM-Po algorithm for multiple times.

In Algorithm 3, finding PM with minimum load as in Line 4 has the time complexity of $\mathcal{O}(m')$. Assuming that the link representation is used to keep the information of VN, in the worst case, $\mathcal{O}(n^2)$ numbers of comparisons are required to find the VM pair with maximum bandwidth, which is repeated for $\mathcal{O}(\frac{n}{2})$ number of times. Here, picking out the VM from the selected virtual edge takes a constant time. Hence, the total running time of the Pick-out algorithm can be concluded to $\mathcal{O}(n^2 * \frac{n}{2}) \approx \mathcal{O}(n^3)$.

In Algorithm 2, forming the set of edge layer PMs in Line 6 requires the running time of $\mathcal{O}(m')$. The running time for calculating the total failure probability as in Line 13 is constant. Following this as in Line 15, finding the leader with minimum FP value takes $\mathcal{O}(m')$ running time. The two *for* loops require $\mathcal{O}(m')$ computational time. As the running time of Pick-out algorithm is $\mathcal{O}(n^3)$, the total time complexity of the VM-Po algorithm can be concluded to $\mathcal{O}(m' + n^3)$.

The communication complexity of the VM-Po algorithm can be seen as $\mathcal{O}(2(m'-1))$ as discussed in Lemma 4. The leader PM that is calculated in Line 13 invokes the Pick-out algorithm and sends the instruction to other $m'-1$ number of PMs in order to execute the Pick-out algorithm. Upon execution of the Pick-out algorithm, $m'-1$ number of messages are received by the leader PM. As a result, the total number of communications established in second stage is $2(m'-1)$. □

5 Performance Evaluation

In this section, we evaluate the performance of proposed FSC-VNE algorithm by using a discrete event Java-based simulator. We compare our algorithm against two popular centralized VNE algorithms VNE-DCC [17] and VIE-SR [31] considering the performance metrics such as acceptance ratio and average number of required resources.

5.1 Simulation Setup

In the simulation environment, one data center is formed with a number of PMs that are connected by the Fat-Tree network topology. The simulation is performed on the small scale data center, where each switch in the data center is equipped with $k = 32$ number of ports. As discussed in Section 3, the maximum number of PMs that can be connected with 32 ports switches is $m = \frac{32^3}{4} = 8192$ and the total number of switches required is 1280 including the core, aggregation, and edge switches. In the simulation, it is assumed that the failure events are independent and random. These events also do not occur frequently. Based on such properties, the number of failure events is modeled as a Poisson process with average number of failures (λ) 0.01. The value of lambda is chosen to be very less to reflect the practical scenarios, where the number of failures occurring in the actual data center is relatively low. In the simulation, assignment of the physical resources such as CPU, memory, and storage follows the Random distribution. The maximum amount of storage and memory of a PM ranges between $1000GB - 2000GB$ and $20GB - 50GB$, respectively. The number of processing units in each PM is randomly distributed between 8 through 32. The maximum bandwidth capacity on each physical link is 100 Gbps.

The number of VMs in each VN ranges between 2 through 10. The arrival rate of the incoming virtual network follows the Poisson distribution with the mean arrival rate of 10 VNs per 100 units of time. The mean arrival rate refers to as the average number of VNs arriving in every 100 time units. Similarly, the lifetime of the VNs follows the exponential distribution with mean lifetime of 250 time units. The lifetime of a VN refers to as the number of time units after which the VN is terminated. No specific topology is followed to construct a VN. However, a probability value is assigned to each virtual link, called virtual link probability. A VN with virtual link probability of 1 results in fully connected VN. The link probability of VNs in the simulation environment ranges between $0.5 - 0.8$. Similar to the physical network, virtual resources are distributed among the VMs by following the random distribution. The resource configurations of the VNs are not strictly heterogeneous, which infers that some VNs can be homogeneous in terms of their resource configurations. The CPU requirement for each VM ranges from 1 through 4 numbers of CPUs. The required amount of memory and storage ranges from $500MB$ through $4GB$ and $8GB$ through $20GB$, respectively. Similarly, the bandwidth requirement for each VN ranges from $50Mbps$ through $1Gbps$.

The performance of the FSC-VNE algorithm is evaluated mainly in three metrics: acceptance ratio, amount of resource allocated, and embedding time. Acceptance ratio is defined as the ratio between the number of VNs accepted and the number of VNs received by the CSP from users. Amount of allocated resource refers to as the number of PMs and physical links required per VN. Embedding time is the time required to embed the VN onto physical network, which involves the waiting time of VN and the time taken by the algorithm to carry-out the embedding procedure. Taking the above-mentioned performance matrices and the simulation environment, the following simulation results are derived.

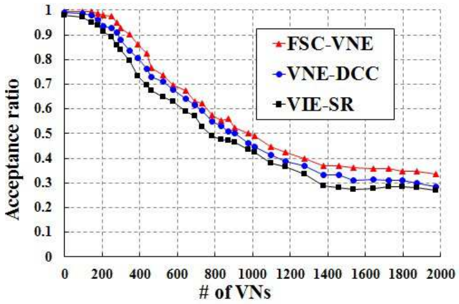
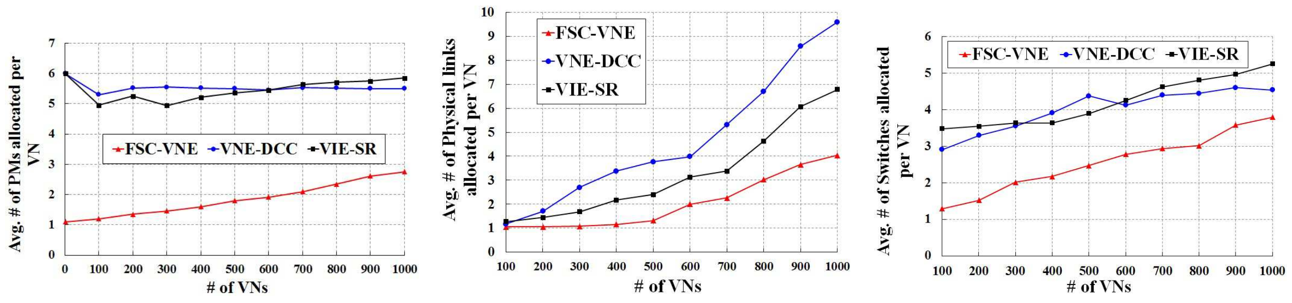


Fig. 4. Acceptance ratio.

5.2 Simulation Results

The performance of proposed FSC-VNE algorithm is evaluated by comparing with that of VNE-DCC and VIE-SR algorithm. Fig. 4 demonstrates the relationship between the



(a) Average number of PMs required per VN (b) Average number of links required (c) Average number of switches required

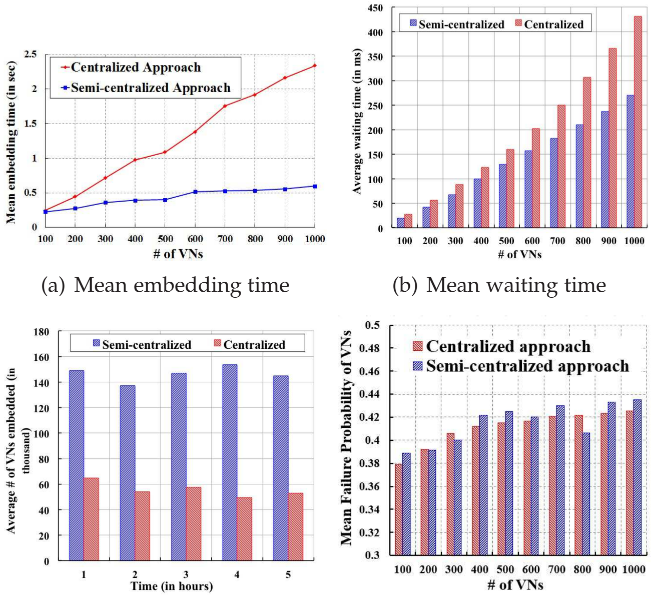
Fig. 5. Average number of resource required.

number of VNs received and the acceptance ratio. It can be observed that, with the increasing number of VNs, the chances for a VN to be accepted decreases. In terms of acceptance ratio, the proposed algorithm outperforms over other VNE algorithms. In case of FSC-VNE algorithm, the acceptance ratio for 2000 VNs is about 0.33, whereas in case of other algorithms the acceptance ratio is less than 0.3.

The relationship of number of VNs with the amount of allocated physical resources is presented in Fig. 5. Here, the physical resource refers to as the number of PMs, and allocated number of physical links and switches. The proposed algorithm allows the multiple VMs from one VN to be hosted by the single PM resulting in the reduction of the number of required physical links and switches. Keeping the total number of PMs constant, the average number of PMs allocated to 100 VNs is 1.1, as shown in Fig. 5(a). The number of PMs increases to 2.7, when the number of VNs increases to 1000. On the contrary, it is observed that the average number of PMs allocated is equal to the number of VMs in case of other algorithms. The average number of PMs allocated to host 100 VNs is 5.5 and 4.9 in case of VNE-DCC and VIE-SR algorithm, respectively. However, the average number of PMs required to embed 1000 VNs is 5.5 and 5.8 in case of VNE-DCC and VIE-SR algorithm, respectively. Such variation along the Y-axis occurs due to the random distribution of the number of VMs in each VN.

The advantage of embedding multiple VMs that belong to same VN onto a single PM can be realized in Fig. 5(b) and 5(c). For upto 100 VNs the average number of physical links required is approximately 1 in case of all three algorithms, as shown in 5(b). However, this number increases with the increasing number of VNs. The performance of the proposed algorithm can be distinguished from other algorithms easily when the number of VNs increases to 1000, where the required number of physical links is 4.0, 9.5, and 6.78 in case of FSC-VNE, VNE-DCC, and VIE-SR algorithm, respectively. Similar trend is observed in Fig. 5(c). The average number of switches involved in embedding the VNs ranges through 100 and 1000 is 1.2 and 3.7 switches, in case of the proposed FSC-VNE algorithm. However, in case of VNE-DCC and VIE-SR algorithm, the average number of switches required to embed 100 VNs is 2.9 and 3.4, respectively. When the number of VNs increases to 1000, the average number of required switches increases to 4.5 and 5.2 switches, respectively.

Embedding time is one of the major performance metrics that needs to be considered while analyzing the performance of the algorithm. Here, embedding time refers to as the time taken by the algorithm in order to embed the incoming VN. The proposed algorithm follows the semi-centralized approach in order to fasten the embedding process. Such approach allows the CSP to increase the number of PMs without compromising the performance of embedding algorithm. The comparison of performance of centralized version and the semi-centralized version of the proposed algorithm is presented in Fig. 6(a). The number of PMs is kept constant at 8192 in the simulation. From the simulation results, it can be clearly observed that the embedding time in case of semi-centralized approach is lesser than that of the centralized approach. The average time required to embed 100 VNs is $0.24sec$, and $0.22sec$, in case of centralized and semi-centralized approach, respectively. However, the average time required to embed 1000 VNs is $2.34sec$ and $0.60sec$.



(a) Mean embedding time (b) Mean waiting time

(c) Mean throughput (d) Mean failure probability

Fig. 6. Comparison between semi-centralized and centralized version of FSC-VNE.

The small improvement in the simulation Fig. 6(a) is obtained from the small scale simulated environment. However, the benefits of this small improvement in embedding time can be realized in the real-time environment, where the number of PMs can reach 1 million and thousands of VNs may arrive at the data center in every second.

Waiting time of VNs and throughput of the FSC-VNE are considered as another matrix to evaluate the performance

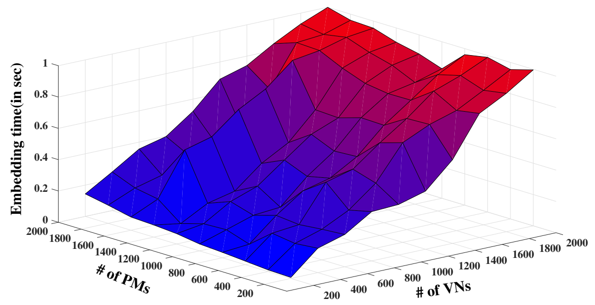


Fig. 7. Embedding time with varying number of VNs and PMs.

of the semi-centralized approach of the VN embedding as shown in Fig. 6(b) and 6(c), respectively. In Fig. 6(b), waiting time refers to as the time spent by the VN before embedding onto the physical network. As shown in Fig. 6(b), average waiting time indicates if the proposed algorithm can achieve its goal of minimizing the waiting time of the VNs and can reduce the embedding time. Reducing the waiting time and fastening the embedding process also improves the QoS of the cloud service provider. By embedding 100 numbers of VNs, the average waiting time in our proposed semi-centralized and centralized algorithms is $20ms$ and $27ms$, respectively. In the semi-centralized version, the mean waiting time increases to $270ms$, when the number of VNs increases to 1000.

On the other hand, in the centralized approach, the mean waiting time increases to more than $400ms$, when the number of VNs increases to 1000. As shown in Fig. 6(c), the throughput that refers to as the number of VNs embedded per unit time, plays a major role in evaluating the performance of the embedding algorithm as reduction in throughput directly affects the users' experience. The mean throughput of the FSC-VNE algorithm is evaluated in each hour for 5 hours. It is observed that the semi-centralized approach can embed more number of VNs as compared to the corresponding centralized approach. In the entire 5 hours of time duration, the average number of embedded VNs ranges between $140,000$ and $160,000$ using the semi-centralized approach, whereas the average number of VNs ranges between $50,000$ and $60,000$ using the centralized approach. From the above-mentioned performance metrics as shown in Fig. 6, it is observed that the semi-centralized approach outperforms over the centralized one. The centralized and semi-centralized approaches of the proposed algorithm are also compared in terms of mean failure probability, as shown in Fig. 6(d). It is observed that the proposed semi-centralized approach has negligible impact onto the objective. In case of centralized approach, the mean failure probability lies between 0.36 and 0.44, when the number of VNs increases from 100 to 1000. Similar trend is observed in case of semi-centralized algorithm. The mean failure probability lies between 0.38 and 0.44 with the same the number of VNs. It is due to the fact that semi-centralized approach is adopted primarily to improve the performance of the algorithm.

Fig. 7 shows the relationship of number of PMs and number of VN with the embedding time. It is observed that the embedding time may increase with increasing number

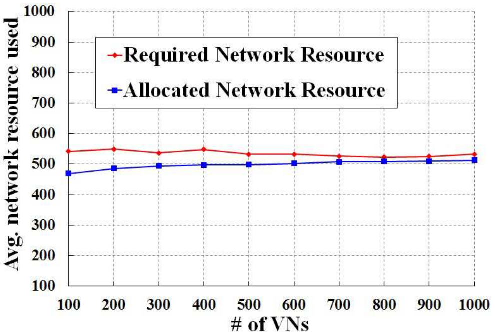


Fig. 8. Comparison of required bandwidth and allocated bandwidth.

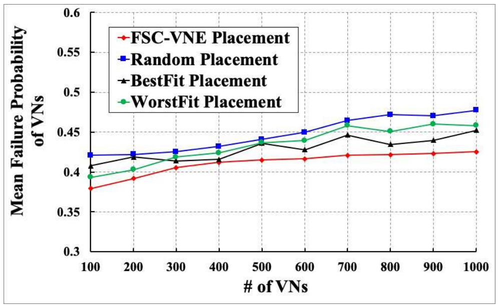


Fig. 9. Mean failure probability of VNs.

of VNs and the PMs. The average time required to embed 200 VNs onto 200 PMs is $0.005sec$. However, the time increases to approximately $1sec$ to embed 2000 VNs onto the same number of PMs, which is mainly due to the first stage of embedding process as it follows the centralized approach.

The bandwidth demand of the virtual links can be ignored by mapping the adjacent VMs onto the single PM. As a result, the total amount of required bandwidth can be more than the total amount of allocated bandwidth as shown in Fig. 8. It is observed that the average network bandwidth demanded by 100 VNs is $542units$. However, only $469units$ of network resource is actually allocated. The same trend is observed even when the number of VNs is increased. The average network resource allocated for 1000 VNs is $513units$ for the demand of $532units$ of network resources.

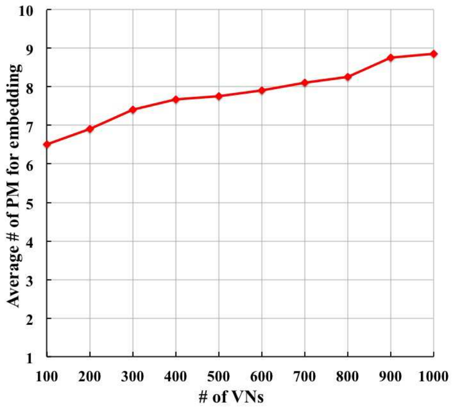


Fig. 10. Average number of PMs used for embedding purpose.

In the second stage of the proposed FSC-VNE algorithm, the PMs are given higher priority based on the failure probability. The PMs with lesser failure probability pick-out the VMs first. Eventually, the VMs are mapped onto the

PMs with less failure probability. The simulation results in Fig. 9 demonstrates the comparison of FSC-VNE placement schemes with three other placement strategies: random, BestFit, and WorstFit. In the BestFit placement strategy, PM with smallest available resource picks-out the VMs. Contrary to this, the PM with largest available resource picks-out the VMs in WorstFit strategy in case of FSC-VNE. In random placement, the PMs randomly pick-out the VMs. In all the three placement strategies, the PMs do not consider their failure probability while choosing a VM. Here, the mean failure probability of the VN refers to as the mean of failure probability of the PMs that are hosting the corresponding VNs. For 100 number of VNs, the mean failure probability is approximately 0.38 in case of FSC-VNE algorithm. Whereas, the mean failure probability ranges between 0.39 and 0.42 for the same number of VNs in all other placement strategies. It is observed that this value increases significantly to 0.41 in case of FSC-VNE, when the number of VNs increases to 300. Following this, a gradual increase is observed for further increase in the number of VNs. The mean failure probability increases to approximately 0.42 when 1000 number of VNs are embedded. On the other hand, a larger mean failure probability is observed in case of other placement strategies, which ranges between 0.45 and 0.48 after 1000 VNs are embedded. Since those three placement strategies do not consider the failure probability in the embedding process, there mean failure probability values fluctuate, as shown in Fig. 9.

The major disadvantage of the semi-centralized approach is the resource requirement to embed the VNs. In Fig. 10, the number of PMs used to embed each VN is presented. It is observed that the average number of PMs ranges between 6 and 9 for 1000 VNs. This is due to the fact that a single server is responsible for embedding all incoming VNs in centralized approach. However, multiple servers are employed to embed each VN in semi-centralized approach. This disadvantage can be handled by restricting the number of PMs to a lower value. Further, this can also be ignored if a significant improvement in embedding is observed while processing a large number of VNs.

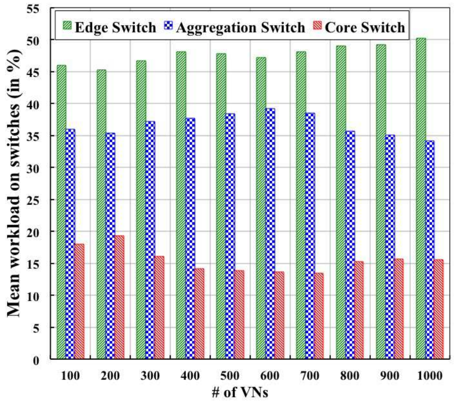


Fig. 11. Workload on different layers of switches.

It is essential to observe the workload on all the three layers of switches, i.e., edge switches, aggregation switches, and core switches. In Fig. 11, X-axis represents the number of VNs and Y-axis represents the workload on different layers of switches. Here, workload refers to as percentage of communication of a VN being carried out by particular type of switch. It is observed that for 100 VNs approximately only 18%, 36%, and 46% of the communications among VMs dependent on core switches, aggregation switches, and edge switches, respectively. Similarly, an average of 16%, 34%, and 50% of the VMs communications for 1000 VNs dependent on core, aggregation, and edge switches, respectively as shown in Fig. 11. The workload on core switches is less than that of the aggregation switches, which is further less than that of the edge switches. This is due to the fact that VMs are embedded onto the PMs with closure distance, which involve lesser number of switches.

6 Conclusions

In this paper, we have investigated the VNE problem on Fat-Tree data center network and have presented a novel and effective Failure-aware Semi-Centralized VN Embedding (FSC-VNE) solution. In the proposed embedding solution, VNs are mapped onto the existing physical network in two-staged semi-centralized manner by taking the advantages of both centralized and distributed embedding approach. Multiple VMs are allowed to be embedded onto the single PM. Further, the VMs are mapped onto a set of PMs with minimum distance. This infers that less number of PMs and switches are used in an embedding solution. The PMs with minimum failure probability are given higher preference to host the VMs. This helps us achieve the goal to minimize the virtual resource failure probability. Besides, extensive simulations are performed and our simulation results are compared with other similar algorithms. The simulation results indicate the superiority and notable strengths of our FSC-VNE over other algorithms in terms of acceptance ratio, minimization of required physical resource, embedding time and VN failure probability. For future work, we endeavor to implement the proposed FSC-VNE solution in real cloud environment in order to verify and improve the simulation results.

Acknowledgment

This work was supported in part by the Ministry of Science and Technology (MOST), Taiwan, under Grant 108-2221-E-182-050 and in part by Chang Gung Medical Foundation, Taiwan under Grant CMRPD 2J0141.

References

[1] W. Cerroni and F. Esposito, "Optimizing live migration of multiple virtual machines," *IEEE Transactions on Cloud Computing*, vol. PP, no. 99, pp. 1–1, 2017.

[2] W. Xia, P. Zhao, Y. Wen, and H. Xie, "A survey on data center networking (DCN): Infrastructure and operations," *IEEE Communications Surveys & Tutorials*, vol. 19, no. 1, pp. 640–656, 2017.

[3] J. Duan and Y. Yang, "Placement and performance analysis of virtual multicast networks in fat-tree data center networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 27, no. 10, pp. 3013–3028, oct 2016.

[4] Y. G. Zeheng Yang, "An exact virtual network embedding algorithm based on integer linear programming for virtual network request with location constraint," *China Communications*, vol. 13, no. 8, p. 177, 2016.

[5] X. Fei, F. Liu, H. Xu, and H. Jin, "Adaptive vnf scaling and flow routing with proactive demand prediction," in *IEEE INFOCOM 2018 - IEEE Conference on Computer Communications*, April 2018, pp. 486–494.

[6] Y. Liang and S. Zhang, “Embedding parallelizable virtual networks,” *Computer Communications*, vol. 102, pp. 47–57, apr 2017.

[7] X. Li, X. Jiang, P. Garraghan, and Z. Wu, “Holistic energy and failure aware workload scheduling in cloud datacenters,” *Future Generation Computer Systems*, vol. 78, no. Part 3, pp. 887 – 900, 2018.

[8] M. N. Cheraghlou, A. Khadem-Zadeh, and M. Haghparast, “A survey of fault tolerance architecture in cloud computing,” *Journal of Network and Computer Applications*, vol. 61, pp. 81 – 92, 2016.

[9] P. T. Endo, G. L. Santos, D. Rosendo, D. M. Gomes, A. Moreira, J. Kelner, D. Sadok, G. E. Gonçalves, and M. Mahloo, “Minimizing and managing cloud failures,” *Computer*, vol. 50, no. 11, pp. 86–90, 2017.

[10] C. Cérin, C. Coti, P. Delort, F. Diaz, M. Gagnaire, Q. Gaumer, N. Guillaume, J. Lous, S. Lubiarz, J. Raffaelli *et al.*, “Downtime statistics of current cloud solutions,” *International Working Group on Cloud Computing Resiliency, Tech. Rep*, 2013.

[11] H. S. Gunawi, M. Hao, R. O. Suminto, A. Laksono, A. D. Satria, J. Adityatama, and K. J. Eliazar, “Why does the cloud stop computing?: Lessons from hundreds of service outages,” in *Proceedings of the Seventh ACM Symposium on Cloud Computing*, ser. SoCC ’16. New York, NY, USA: ACM, 2016, pp. 1–16. [Online]. Available: http://doi.acm.org/10.1145/2987550.2987583

[12] M. T. Beck, A. Fischer, J. F. Botero, C. Linnhoff-Popien, and H. de Meer, “Distributed and scalable embedding of virtual networks,” *Journal of Network and Computer Applications*, vol. 56, pp. 124–136, oct 2015.

[13] P. K. Sahoo, C. K. Dehury, and B. Veeravalli, “Lvrm: On the design of efficient link based virtual resource management algorithm for cloud platforms,” *IEEE Transactions on Parallel and Distributed Systems*, vol. 29, no. 4, pp. 887–900, April 2018.

[14] N. Ogino, T. Kitahara, S. Arakawa, and M. Murata, “Virtual network embedding with multiple priority classes sharing substrate resources,” *Computer Networks*, vol. 112, pp. 52–66, jan 2017.

[15] Z. Xu, F. Liu, Tao Wang, and H. Xu, “Demystifying the energy efficiency of network function virtualization,” in *2016 IEEE/ACM 24th International Symposium on Quality of Service (IWQoS)*, June 2016, pp. 1–10.

[16] L. Gong, H. Jiang, Y. Wang, and Z. Zhu, “Novel location-constrained virtual network embedding LC-VNE algorithms towards integrated node and link mapping,” *IEEE/ACM Transactions on Networking*, vol. 24, no. 6, pp. 3648–3661, dec 2016.

[17] P. Zhang, H. Yao, and Y. Liu, “Virtual network embedding based on the degree and clustering coefficient information,” *IEEE Access*, vol. 4, pp. 8572–8580, 2016.

[18] A. Alsarhan, A. Itradat, A. Y. Al-Dubai, A. Y. Zomaya, and G. Min, “Adaptive resource allocation and provisioning in multi-service cloud environments,” *IEEE Transactions on Parallel and Distributed Systems*, vol. 29, no. 1, pp. 31–42, Jan 2018.

[19] L. Yin, Z. Chen, L. Qiu, and Y. Wen, “Interference based virtual network embedding,” in *2016 IEEE International Conference on Communications (ICC)*. IEEE, may 2016.

[20] Q. Zhang, F. Liu, and C. Zeng, “Adaptive interference-aware vnf placement for service-customized 5g network slices,” in *IEEE INFOCOM 2019 - IEEE Conference on Computer Communications*, April 2019, pp. 2449–2457.

[21] Y. Xiao, Q. Zhang, F. Liu, J. Wang, M. Zhao, Z. Zhang, and J. Zhang, “Nfvdeep: adaptive online service function chain deployment with deep reinforcement learning,” in *Proceedings of the International Symposium on Quality of Service*. ACM, 2019, p. 21.

[22] A. Aral and T. Ovatman, “Network-aware embedding of virtual machine clusters onto federated cloud infrastructure,” *Journal of Systems and Software*, vol. 120, pp. 89–104, oct 2016.

[23] F. Yan, T. T. Lee, and W. Hu, “Congestion-aware embedding of heterogeneous bandwidth virtual data centers with hose model abstraction,” *IEEE/ACM Transactions on Networking*, vol. 25, no. 2, pp. 806–819, April 2017.

[24] H. Cao, L. Yang, and H. Zhu, “Novel node-ranking approach and multiple topology attributes-based embedding algorithm for single-domain virtual network embedding,” *IEEE Internet of Things Journal*, vol. 5, no. 1, pp. 108–120, Feb 2018.

[25] T. Mano, T. Inoue, K. Mizutani, and O. Akashi, “Reducing dense virtual networks for fast embedding,” in *IEEE INFOCOM 2016 - The 35th Annual IEEE International Conference on Computer Communications*. IEEE, apr 2016.

[26] T. Wang and M. Hamdi, “Presto: Towards efficient online virtual network embedding in virtualized cloud data centers,” *Computer Networks*, vol. 106, pp. 196 – 208, 2016.

[27] S. Haeri and L. Trajkovi, “Virtual network embedding via monte carlo tree search,” *IEEE Transactions on Cybernetics*, vol. 48, no. 2, pp. 510–521, Feb 2018.

[28] X. Hesselbach, J. R. Amazonas, S. Villanueva, and J. F. Botero, “Coordinated node and link mapping vne using a new paths algebra strategy,” *Journal of Network and Computer Applications*, vol. 69, no. Supplement C, pp. 14 – 26, 2016.

[29] L. Yu, H. Shen, Z. Cai, L. Liu, and C. Pu, “Towards bandwidth guarantee for virtual clusters under demand uncertainty in multi-tenant clouds,” *IEEE Transactions on Parallel and Distributed Systems*, vol. 29, no. 2, pp. 450–465, Feb 2018.

[30] A. Zhou, S. Wang, B. Cheng, Z. Zheng, F. Yang, R. N. Chang, M. R. Lyu, and R. Buyya, “Cloud service reliability enhancement via virtual machine placement optimization,” *IEEE Transactions on Services Computing*, vol. 10, no. 6, pp. 902–913, Nov 2017.

[31] R. Yu, G. Xue, and X. Zhang, “Towards min-cost virtual infrastructure embedding,” in *2015 IEEE Global Communications Conference (GLOBECOM)*. Institute of Electrical and Electronics Engineers (IEEE), dec 2015.

Chinmaya Kumar Dehury Chinmaya Kumar Dehury received bachelor degree from Sambalpur University, India, in June 2009 and MCA degree from Biju Pattnaik University of Technology, India, in June 2013. He received the PhD Degree in the department of Computer Science and Information Engineering, Chang Gung University, Taiwan. Currently, he is a postdoctoral research fellow in the Mobile & Cloud Lab, Institute of Computer Science, University of Tartu, Estonia. His research interests include scheduling, resource management and fault tolerance problems of Cloud and fog Computing, and the application of artificial intelligence in cloud management. He is also reviewer to several journals and conferences, such as IEEE TPDS, IEEE JSAC, Wiley Software: Practice and Experience, etc.

Prasan Kumar Sahoo Prasan Kumar Sahoo received the B.Sc. degree in physics (with Honors), the M.Sc. degree in mathematics both from Utkal University, Bhubaneswar, India, in 1987 and 1994, respectively. He received the M.Tech. degree in computer science from the Indian Institute of Technology (IIT), Kharagpur, India, in 2000, the first Ph.D. degree in mathematics from Utkal University, in 2002, and the second Ph.D. degree in computer science and information engineering from the National Central University, Taiwan, in 2009. He is currently a Professor in the Department of Computer Science and Information Engineering, Chang Gung University, Taiwan. He is an Adjunct Researcher in the Division of Colon and Rectal Surgery, Chang Gung Memorial Hospital, Linkou, Taiwan since 2018. He has worked as an Associate Professor in the Department of Information Management, Vanung University, Taiwan, from 2007 to 2011. He was a Visiting Associate Professor in the Department of Computer Science, Universite Claude Bernard Lyon 1, Villeurbanne, France. His current research interests include artificial intelligence, big data analytic, cloud computing, and IoT. He is the Lead Guest Editor, special issue of Electronics journal and an Editorial Board Member for the International Journal of Vehicle Information and Communication Systems. He has worked as the Program Committee Member of several IEEE and ACM conferences and is a senior member, IEEE.