Comparison of Placement Variants of Virtual Network Functions From Availability and Reliability Perspective

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***Abstract*—The virtual network function (VNF) is a virtual machine with specific software. A set of related VNFs can be represented as a network service (NS). The placement of all the VNFs of an NS can be in a single host node, and in multiple host nodes. Also, the placement of VNFs of an NS can be done using mixed-mode. In this work, we first analyze the NS availability considering the deployment of NS with the use of multiple host nodes, single host node, and mixed-mode. In the availability analysis, we consider the failure perspective of VNFs as well as the failure perspective of host node(s). Further, we analyze the NS reliability considering the placement of VNFs of NS based in different host nodes, single host node, and mixed-mode. Then we compare the availability as well as the reliability of NS considering these three placement strategies. Comparison results show that the availability, as well as the reliability, are better considering single host node based placement of VNFs of NS.**

***Index Terms*—OpenStack, orchestration, VNF, 5G core network, 4G LTE core network, availability, NS.**

I. Introduction

Cloud computing facilitates the timely delivery of various resources in a cost effective way. There are many cloud computing platforms. OpenStack is one such open source cloud computing platform. With the use of closely related services, OpenStack facilitates the creation of cloud computing infrastructure. Well defined interfaces are provided to access various services of OpenStack. According to the requirement, one can select the services of OpenStack for the creation of a cloud computing setup. There must be at least two types of nodes to configure, such as controller node and compute node, to create a cloud computing setup for placement of VNFs of NS. Node with the maximum services of OpenStack is the controller node. The controller node is the controlling entity of the OpenStack cloud computing setup. The compute node is the host node for VNFs, because compute node is used for the creation of VNFs according to the requirement of users. But the command for VNF creation has to be executed at the controller node. Many VNFs can be created with the use of OpenStack. The VNFs can be created independently or as part of NS. Creation and deletion of VNFs using a single command is possible if the related VNFs are part of an NS [1].

In this work, we use the term VNF to denote a virtual machine that executes specialized software. The total capacity (CPU, memory, and disk) of all the host nodes is used to determine the maximum number of possible VNFs in the system. All the VNFs of an NS can be placed in a host node, which we call here Scenario-1. To place all the VNFs of an NS in a host node, the resource requirement of all the VNFs have to be satisfied by the respective host node. Further, all the VNFs of an NS can be placed in different host nodes, which we call here Scenario-2. In an alternative approach, the VNFs which are directly accessible to users, are placed close to the users and the rest of the VNFs are placed away from the users. In this type of placement of VNFs of an NS, some VNFs are placed in a single host node and some VNFs are placed in different host nodes (Scenario-3). The three approaches of placement of VNFs of NS can be presented as in Fig. 1.

A. Related Works

Here, we focus on the works, which are closely related to this present work. The related works are categorized into three subsections, such as (a) VNF in the context of 4G-LTE and 5G, (b) VNF placement algorithms and resource allocation, and (c) Availability and reliability analysis.

1) VNF in the Context of 4G-LTE and 5G: Any core network node of 4G-LTE and 5G networks can be created as a VNF. The main purpose of VNF creation is to minimize the use of resources and maximize the quality of the user experience.

3GPP LTE-EPC network [2] has two parts. One is the access network and another is the core network. The core network consists of various nodes, such as serving gateway (SGW), pdn gateway (PGW), home subscriber server (HSS), mobility management entity (MME), and policy and charging resource function (PCRF). In the case of a core network with fewer subscribers, the functionality of PCRF can also be part of the PGW node. So, the LTE core network can operate with the use of a minimum of four nodes, i.e., MME, SGW, PGW, and HSS. So four VNFs corresponding to these four nodes can be sufficient for a low capacity LTE network. But for high capacity LTE networks, VNF can be created corresponding to each core network node.

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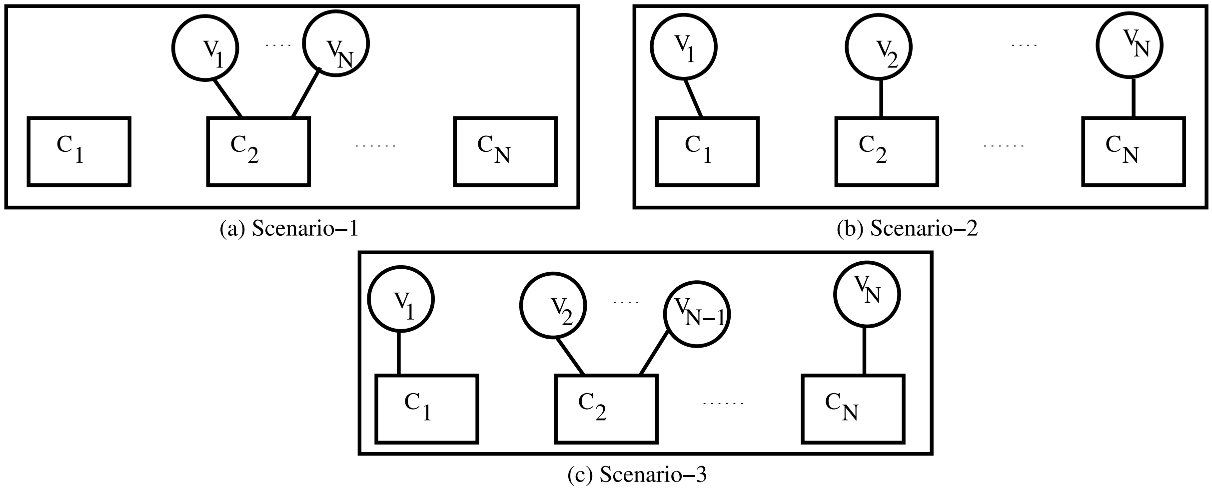

Fig. 1. Conceptual diagram of placement of VNFs: $\{V_1, V_2, \ldots, V_N\}$ of an NS in host nodes: $\{C_1, C_2, \ldots, C_N\}$ (a) multiple VNFs are in one host node and (b) one VNF is in each host node (c) two VNFs are in different host nodes and (N-2) VNFs are in one host node.

Placement of SGW and PGW of LTE networks are discussed in [3]–[7]. The main purpose of SGW and PGW placement in virtualized networks are minimization of various resources, such as: number of VNF instances for SGW and PGW, number of SGW relocations, length of the path between PGW and user, path cost between SGW and users, load in the transport network and delay in the data plane, number of SGW instances depending on the observed mobility of users and their data traffic load, mobility of sessions. Also, the SGW placement and PGW placement consider the maximization of the quality of experience of the user equipment.

In [8], efficient restoration mechanisms are proposed in case of failure of MME VNF of LTE networks. Bulk signalling based restoration mechanism and profile-id based restoration scheme are studied in detail. In case of bulk signalling scheme, one message is used to replace many messages and in case of profile id based scheme, the common information element is replaced by a profile id.

Service based 5G core network [9] has three layers, such as the control layer, data forwarding layer, and storage layers. User plane functions are part of the data forwarding layer. The session management function, authentication server function, policy and charging function, user data management, and access and mobility function are the nodes of the control layer. The unstructured data storage functions and user data repository are part of the storage layer. The user plane function is configured by the nodes of the control layer. The user data management, and policy and charging function can store and retrieve subscriber information and policy data to and from the user data repository. The user data repository and unstructured data storage functions can be co-located in a real deployment. In a real deployment, some other nodes can also be co-located. Corresponding to each 5G core network node one VNF can be created.

In [10], four heuristic algorithms are proposed for the deployment of standby state management function of 5G networks. Proposed algorithms are based on availability greedy, zone greedy, bandwidth greedy, and usage awareness. Comparison results are presented to compare the average availability, total number of standby functions, and link bandwidth usage. In [11], a solution is proposed to increase the reliability performance of service chains of 5G networks. Considering VNF as M/M/m queue and M/M/1 queue, performance results are compared. In [12], the VNF deployment procedure for IoT networks is proposed and the total cost of VNF deployment is discussed.

2) VNF Placement Algorithms and Resource Allocation: The placement of VNFs on physical nodes is used to increase the computational efficiency, availability, reliability, network stability, server utilization, resource usage, and decrease the placement cost, latency of the network, load on the network, energy usage.

In [13], multiple instances of VNF placement is addressed to decrease the load on the network and cost of the network. To solve the placement problem of VNF instances, one distributed algorithm is proposed. This distributed algorithm is beneficial in terms of computational efficiency and cost.

In [14], VNF placement strategy is proposed considering the reliability and availability of NS. Further, the availability of this proposed scheme is compared with the existing schemes of CloudSim cloud simulator, i.e., BinPack, Random strategy, and Sparse strategy for VNF placement. The impact of VNF deployment on the reliability and availability of NS in the NVF platform is addressed. Also, one optimized VNF placement strategy is proposed to increase the reliability and availability of NS.

In [15], a framework is proposed for the reliable deployment of services in physically separated locations, to get better performance in terms of latency, resource utilization, and reliability. In [16], the VNF placement and routing problem are addressed to decrease the load on the link and satisfy the requested delay of users. Also in this study, the totally and partially ordered service function chains are considered.

In [17], queue aware dynamic VNF placement algorithm is proposed. This algorithm is beneficial in terms of placement cost and network stability. In [18], three VNF placement algorithms are proposed to maximize server utilization, minimize delay and minimize cost, considering static traffic types.

Further, the server utilization algorithm is enhanced to take care of the dynamic traffic types.

In [19], a framework for provisioning NFV in data centers is proposed to satisfy the availability requirement assuming heterogeneous distribution for failure and repair process of devices. The proposed algorithm continues to allocate backups corresponding to an SFC request till the availability requirement is satisfied.

In [7], a survey regarding the allocation of resources virtually during the placement of VNFs is presented. Further, this paper discussed virtual machine placement, which is mainly concerned to increase the quality of service, reliability, resource usage, energy, cost, and load balancing. In [20], network function virtualization related resource allocation problems are described in detail. In [21], the framework and requirement for network function virtualization are introduced and described. Resource allocation problems in network function virtualization are discussed in [22]. Further, delay and availability models in NFV resource allocation are also addressed in this work.

3) Availability and Reliability Analysis: The availability of NS and VNF can be analyzed with the use of continuous time Markov chain (CTMC), stochastic Petri net (SPN) and stochastic reward net (SRN). When the CTMC model becomes very large, SPN based modeling is used to present in a better way. Also, SRN is an extension of SPN. Analytical modeling using SPN and SRN can be solved with the use of software package SHARPE [23].

In [23], the definition of availability is formulated with the use of CTMC. The availability derivation present in [23] is the motivation behind this present work. But the present work concerns about the availability of NS. In this present work, the number of states of CTMC are dependent on the number of VNFs of an NS. In [24], VNF placement availability is derived mathematically. The problem of availability aware and delay sensitive VNF scheduling algorithms are addressed in this work. Also, a recursive VNF scheduling algorithm is proposed to address this problem.

In [25], the availability of containerized software systems is analyzed and compared for different configuration models, such as consolidated, homogeneous, and heterogeneous. It is concluded that the heterogeneous configuration, i.e., when instances of different containers share a virtual machine performs better in terms of availability than consolidated and homogeneous configurations. Fault-tree and stochastic reward net are used to analyze the availability of containerized software systems. In [26], analysis of performability of containerized IP multimedia system is presented. Stochastic reward net and reliability block diagram are used for the analysis of performability. It is concluded that the heterogeneous and co-located schemes are better in terms of availability and cost than the homogeneous scheme. In [27], the unavailability aware backup allocation model with shared protection approach is proposed to minimize the unavailability of network functions. Here, backup resources on backup servers are shared by multiple functions. Two heuristics are described to find the solution to the backup allocation problem.

In [28], VNF availability is compared considering the failure of virtual storage. In OpenStack, virtual storage is provided by a cinder node. In case the cinder node goes down, the respective failed storage can be restored with the use of swift nodes, where the backup of virtual storage is stored. In this work, VNF availability is compared, considering the location of the restoration procedure at the controller node and at each VNF. It is proved analytically that, if failure detection time takes more time, then VNF availability is less.

In [29], VNF availability is addressed from the initialization perspective. In this work, VNF availability is analyzed with the use of CTMC. Also, it is analytically proved that the VNF availability is more if the image is part of VNF specific software. In [30], the availability of NS is compared, considering a single host node based placement of VNFs and multiple host nodes based placement of VNFs. But in the availability formulation, only the failure of the host node is considered. Also, the reliability is not addressed in this paper.

B. Motivation and Research Contributions

Any VNF placement strategy we use, VNFs of an NS are generally placed like one of these three schemes such as Scenario-1, Scenario-2, and Scenario-3. During the creation of VNFs or after the creation of VNFs, the host node can be failed or VNFs can also be failed, which will allow the respective service of OpenStack controller to recreate VNFs of NS.

The failure of the host node can be possible due to the power failure of the host node or software failure of the host node. Here, the failure of the host node means the unavailability of VNFs of that particular host node. So the respective VNFs have to be recreated in some other host node(s). The VNFs can be failed independently irrespective of the failure of the host node. So, in case of failure of a VNF, the VNF has to be recreated. Here, considering the failure of host node(s) and failure of VNFs into account, we find an availability expression considering the placement of VNFs of NS with the use of multiple host nodes, single host node, and mixed-mode.

In the absence of any availability comparison result of NS, from the perspective of host node failure and VNF failure, we analyze and compare the availability of NS considering the placement of VNFs of NS with the use of multiple host nodes, single host node, and mixed-mode. Further, in the absence of any reliability comparison result of NS, considering the placement of VNFs of NS with the use of multiple host nodes, single host node, and mixed-mode, we analyze and compare the reliability of NS considering these three modes of placement.

Our major contributions in this work can be noted as follows:

(a) We find the expression of availability of NS, considering all the VNFs of an NS in one host node and all the VNFs of an NS in different host nodes. Further, we find the availability expression of mixed-mode based deployment of VNFs of NS.

(b) We find the reliability expressions of NS, considering the placement of VNFs of NS with the use of different host nodes, single host node, and mixed-mode respectively.

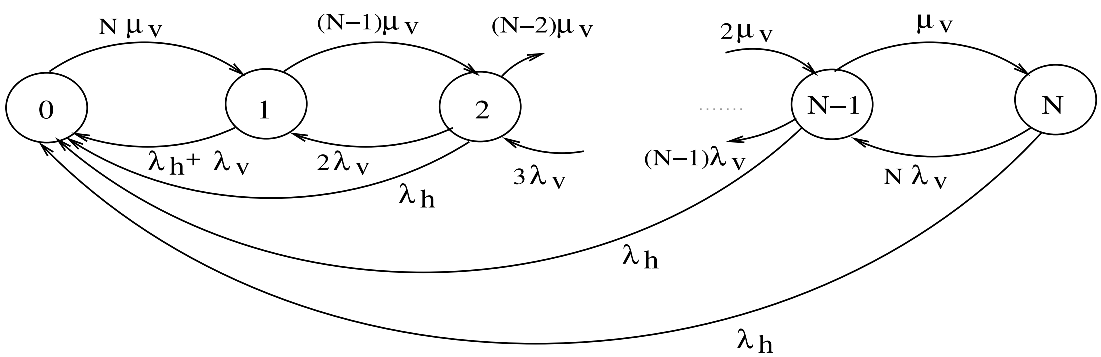

Fig. 2. Transition rate diagram of NS availability with the placement of all VNFs of an NS in a single host node.

TABLE I
SUMMARY OF NOTATIONS

Notation	Meaning
λ_h	Host node failure rate
λ_v	VNF failure rate
μ_v	VNF creation rate
N	Number of VNFs in an NS
$A_{ns}^{sc}(n, \lambda_h, \lambda_v)$	NS availability with n VNFs considering deployment based on single host node
$A_{ns}^{mc}(n, \lambda_h, \lambda_v)$	NS availability with n VNFs considering the placement based on multiple host nodes
$A_{ns}^{md}(n, \lambda_h, \lambda_v)$	NS availability with n VNFs considering mixed-mode based placement
π_n	Steady state probability that n VNFs of an NS are active
$R_n^{mc}(t)$	Reliability of NS with n VNFs considering placement based on multiple host nodes
$R_n^{sc}(t)$	Reliability of NS with n VNFs considering placement based on a host node
$R_{m+n}^{md}(t)$	Reliability of NS with $m+n$ VNFs considering mixed-mode based placement, where m VNFs are in different host nodes and n VNFs are in a single host node

(c) We demonstrate that the single host node based system can provide more than 2.4% availability gain with respect to the multiple host nodes based NS deployment.

(d) Further, we demonstrate that the single host node based NS deployment can provide more than 49% reliability gain with respect to the multiple host nodes based NS deployment.

C. Paper Organization

In Section II, we present the analysis of the availability of NS and in Section III we present the analysis of the reliability of NS. In Section IV, we explain the results, and finally in Section V, we explain the conclusion of this work. Also, the notations used throughout the paper are presented in Table I.

II. Availability Analysis of NS

In this section, we present the analysis of the availability of NS considering the placement of all the VNFs of an NS with the use of multiple host nodes, single host node, and mixed-mode. We use CTMC to find the availability of NS.

Before we proceed, the assumptions and definition on availability of NS are briefly mentioned here.

Assumptions: We assume more than one host nodes are available to facilitate the creation of VNFs, with the use of the controller node, as part of NS creation. Although VNF can be deployed in multiple VMs or in single VM, we assume single VM based VNF deployment.

Definition 1: Availability of NS is defined as the probability that all the VNFs of an NS are available.

A. Scenario-1: VNFs of an NS Are Placed in One Host Node

Here, we present the analysis of NS availability, considering the placement of all the VNFs of an NS in one host node. Assume, the failure time of the host node is Exponentially distributed with mean $\frac{1}{\lambda_h}$ and the failure time of VNF is Exponentially distributed with mean $\frac{1}{\lambda_v}$. The VNF creation time is Exponentially distributed with mean $\frac{1}{\mu_v}$. Assume that the NS contains N VNFs.

We consider $\{Z(t), t \geq 0\}$ as the stochastic process, where $Z(t)$ is used to identify the number of active VNFs of an NS. Initially, the system state is 0, i.e., none of the VNFs are active. After the execution of the NS creation command, all the VNFs try to come up independently with rate μ_v. So the system state 0 changes into state 1 with rate $N\mu_v$. After the creation of one VNF, the system state changes from state 1 to state 2 with rate $(N-1)\mu_v$. Similarly, the system state changes in the forward direction. The system state $(N-1)$ changes into state N with rate μ_v. During the creation of VNFs, failure can happen to the host node. Due to the failure of the host node, all the VNFs of that host node will be failed. So, all the VNFs of a failed host node need to be recreated. So the state of the system changes from any state $(1, 2, \ldots, N)$ to state 0 with rate λ_h. Also at system state n, due to the failure of VNF, the system state can change from state n to state $n-1$ with rate $n\lambda_v$, as n VNFs are active at state n. The transition rate diagram of a single host node based NS deployment can be presented as in Fig. 2.

We present the state transition rate matrix corresponding to Fig. 2, as in equation (1).

$$\mathbf{Q} = \begin{bmatrix} Q(0,0) & Q(0,1) & \cdots & Q(0,N) \\ Q(1,0) & Q(1,1) & \cdots & Q(1,N) \\ \vdots & & & \\ Q(N-1,0) & Q(N-1,1) & \cdots & Q(N-1,N) \\ Q(N,0) & Q(N,1) & \cdots & Q(N,N) \end{bmatrix} \quad (1)$$

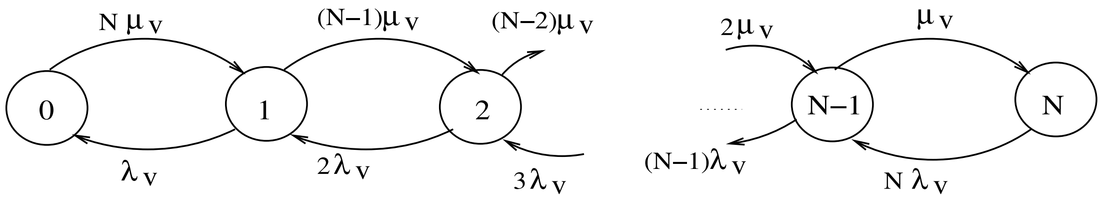

Fig. 3. Transition rate diagram of NS availability with the placement of all VNFs of an NS in a single host node with $\lambda_h = 0$.

with $\sum_{j=0}^{N} Q(i,j) = 0$.

We define *Q*(*i*, *j*) as in equation (2).

$$Q(i,j) = \begin{cases} \lambda_v + \lambda_h, & j = 0, i = 1, \\ \lambda_h, & j = 0, i > 1, \\ (N-i)\mu_v, & j = i+1, \\ i\lambda_v, & j = i-1. \end{cases} \tag{2}$$

Further, we can define *Q*(*i*, *i*) as in equation (3), shown at the bottom of the page.

Now we can solve equations (4) and (5) to get the steady state probabilities π_n, $\forall n = 0, 1, \ldots, N$.

$$\pi \mathbf{Q} = 0, \tag{4}$$

$$\sum_{n=0}^{N} \pi_n = 1, \tag{5}$$

where $\pi = (\pi_0, \pi_1, \ldots, \pi_N)$. Combining the equations (4) and (5), we can get equation (6).

$$\underline{\mathbf{Q}}\underline{\pi} = \underline{\mathbf{K}},$$

i.e.,

$$\underline{\pi} = \underline{\mathbf{Q}}^{-1}\underline{\mathbf{K}}, \tag{6}$$

where $\underline{\mathbf{Q}}$, $\underline{\mathbf{K}}$ and $\underline{\pi}$ are defined in equations (7), (8), and (9) respectively.

$$\underline{\mathbf{Q}} = \begin{bmatrix} Q(0,0) & Q(1,0) & \cdots & Q(N,0) \\ Q(0,1) & Q(1,1) & \cdots & Q(N,1) \\ \vdots & & & \\ Q(0,N-1) & Q(1,N-1) & \cdots & Q(N,N-1) \\ 1 & 1 & \cdots & 1 \end{bmatrix} \tag{7}$$

$$\underline{\mathbf{K}} = \begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix} \tag{8}$$

$$\underline{\pi} = \begin{bmatrix} \pi_0 \\ \pi_1 \\ \vdots \\ \pi_N \end{bmatrix} \tag{9}$$

From equation (6), we can get the steady state probabilities $\pi_0, \pi_1, \ldots, \pi_N$ and we can define the NS availability, $A_{ns}^{sc}(N, \lambda_h, \lambda_v)$ as in equation (10).

$$A_{ns}^{sc}(N, \lambda_h, \lambda_v) = \pi_N. \tag{10}$$

π_N is the steady state probability when the system state is *N*, i.e., when all the VNFs of an NS are available.

Note that, it is difficult to find the steady state probabilities from Fig. 2 using flow balance equations for a large value of *N*. So we have followed matrix based solution method to find steady state probabilities.

There can be two special cases to consider in the case of a single host node based deployment, when there is no chance of host node failure (i.e., $\lambda_h = 0$) and when there is no chance of VNF failure (i.e., $\lambda_v = 0$).

1) Case $\lambda_h = 0$: If we consider the failure rate of the host node, $\lambda_h = 0$, then the transition rate diagram can be presented as in Fig. 3.

The flow balance equations corresponding to Fig. 3, can be written as

$$\begin{aligned} N\mu_v\pi_0 &= \lambda_v\pi_1, \\ (N-1)\mu_v\pi_1 &= 2\lambda_v\pi_2, \\ (N-2)\mu_v\pi_2 &= 3\lambda_v\pi_3, \\ &\cdots \\ 2\mu_v\pi_{(N-2)} &= (N-1)\lambda_v\pi_{(N-1)}, \\ \mu_v\pi_{(N-1)} &= N\lambda_v\pi_N. \end{aligned}$$

After simplification of previous equations we can write,

$$\pi_n = \left(\prod_{i=1}^{n} \frac{(N-i+1)\mu_v}{i\lambda_v}\right)\pi_0, \; n = 1, 2, \ldots, N. \tag{11}$$

Since, $\sum_{n=0}^{N} \pi_n = 1$, we can further simplify and get the NS availability, $A_{ns}^{sc}(N, \lambda_v)$ $(= \pi_N)$ as in equation (12).

$$A_{ns}^{sc}(N, \lambda_v) = \frac{\prod_{i=1}^{N} \frac{(N-i+1)\mu_v}{i\lambda_v}}{1 + \sum_{n=1}^{N}\left(\prod_{i=1}^{n} \frac{(N-i+1)\mu_v}{i\lambda_v}\right)}. \tag{12}$$

$$Q(i,i) = \begin{cases} -Q(i,i+1), & i = 0 \\ -[Q(i,i+1) + Q(i,i-1)], & i = 1 \\ -[Q(i,i-1) + Q(i,0)], & i = N \\ -[Q(i,i+1) + Q(i,i-1) + Q(i,0)], & 1 < i < N \end{cases} \tag{3}$$

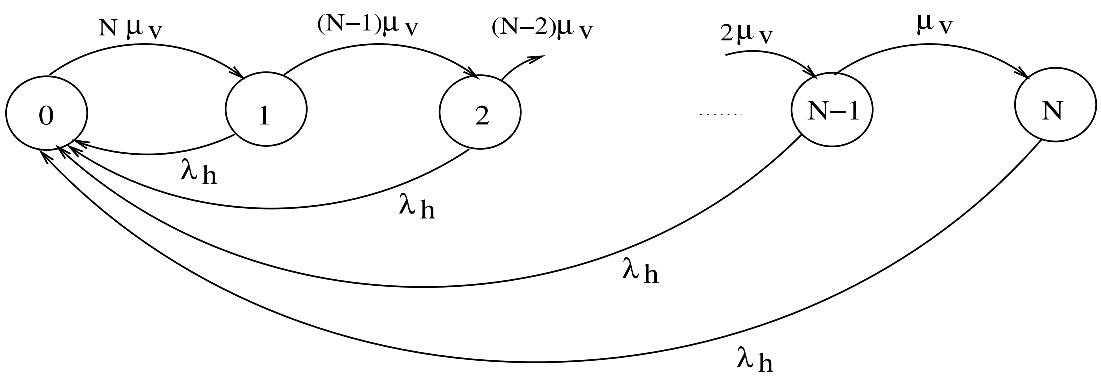

Fig. 4. Transition rate diagram of NS availability with the placement of all VNFs of an NS in a single host node with $\lambda_v = 0$.

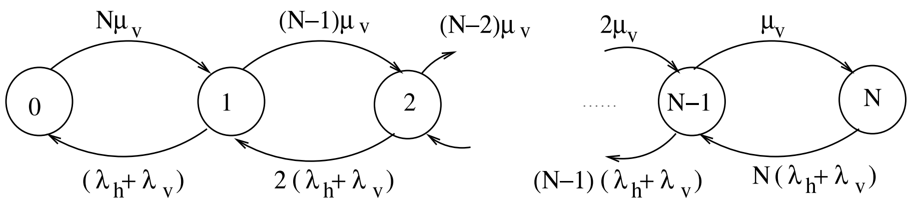

Fig. 5. Transition rate diagram of NS availability, with the placement of VNFs of an NS in different host nodes.

2) Case $\lambda_v = 0$: If we consider, the failure rate of VNF, $\lambda_v = 0$, then the transition rate diagram can be presented as in [30, Fig. 4].

The flow balance equations corresponding to Fig. 4 can be written as [30]:

$$\begin{aligned} N\mu_v\pi_0 &= \pi_1(\lambda_h + (N-1)\mu_v), \\ (N-1)\mu_v\pi_1 &= \pi_2(\lambda_h + (N-2)\mu_v), \\ (N-2)\mu_v\pi_2 &= \pi_3(\lambda_h + (N-3)\mu_v), \\ &\cdots \\ 2\mu_v\pi_{N-2} &= \pi_{N-1}(\lambda_h + \mu_v), \\ \mu_v\pi_{N-1} &= \pi_N\lambda_h. \end{aligned}$$

So the NS availability, $A_{ns}^{sc}(N, \lambda_h)$ can be further simplified from the previous equations as in equation (13).

$$A_{ns}^{sc}(N, \lambda_h) = \frac{\prod_{i=1}^{N} \frac{(N-i+1)\mu_v}{\lambda_h + (N-i)\mu_v}}{1 + \sum_{n=1}^{N}\left(\prod_{i=1}^{n} \frac{(N-i+1)\mu_v}{\lambda_h + (N-i)\mu_v}\right)}. \quad (13)$$

This equation (13), is same as derived in [30, eq. (5)].

B. Scenario-2: VNFs of an NS Are Placed in Different Host Nodes

In this case, we analyze the availability of NS considering the placement of all VNFs of NS in different host nodes. We analyze this system using CTMC. Here also like the previous section, we assume that the failure time of host node is distributed Exponentially with mean $\frac{1}{\lambda_h}$ and the failure time of VNF is distributed Exponentially with mean $\frac{1}{\lambda_v}$. The VNF creation time is distributed Exponentially with mean $\frac{1}{\mu_v}$ and there are N VNFs in an NS.

We consider the stochastic process $\{Z(t), t \geq 0\}$, where $Z(t)$ is used to identify the number of available VNFs of an NS. Initially, the system state is 0, i.e., no VNF is active. After the execution of the NS creation command, all the VNFs try to come up independently with rate μ_v. So with rate $N\mu_v$, the system state 0 changes into state 1. After creation of one VNF, the system state 1 changes into state 2, with rate $(N-1)\mu_v$. Similarly the system state changes in the forward direction. The state $(N-1)$, changes into state N with the rate μ_v. The host node where the VNFs are placed can fail. Also, the VNFs can be failed independently. Due to the failure of any VNF, the respective VNF has to be created again in the same host node or in different host node. If the host node fails, the respective VNF has to be created again in a different host node. So, the state N changes into state $(N-1)$, with rate $N(\lambda_v + \lambda_h)$. Similarly state $(N-1)$, changes into state $(N-2)$, with rate $(N-1)(\lambda_v + \lambda_h)$. In this way the system state 1, changes into state 0 with rate $(\lambda_v + \lambda_h)$. The transition rate diagram for this NS deployment is present in Fig. 5.

The flow balance equations corresponding to the transition rate diagram of Fig. 5, can be written as

$$\begin{aligned} N\mu_v\pi_0 &= (\lambda_v + \lambda_h)\pi_1, \\ (N-1)\mu_v\pi_1 &= 2(\lambda_v + \lambda_h)\pi_2, \\ (N-2)\mu_v\pi_2 &= 3(\lambda_v + \lambda_h)\pi_3, \\ &\cdots \\ 2\mu_v\pi_{(N-2)} &= (N-1)(\lambda_v + \lambda_h)\pi_{(N-1)}, \\ \mu_v\pi_{(N-1)} &= N(\lambda_v + \lambda_h)\pi_N. \end{aligned}$$

The previous equations can be simplified as

$$\begin{aligned} \pi_1 &= \left(\frac{N\mu_v}{(\lambda_v + \lambda_h)}\right)\pi_0, \\ \pi_2 &= \left(\frac{(N-1)\mu_v}{2(\lambda_v + \lambda_h)}\right)\pi_1, \end{aligned}$$

$$\pi_3 = \left(\frac{(N-2)\mu_v}{3(\lambda_v+\lambda_h)}\right)\pi_2,$$
$$\cdots$$
$$\pi_{(N-1)} = \left(\frac{2\mu_v}{(N-1)(\lambda_v+\lambda_h)}\right)\pi_{(N-2)},$$
$$\pi_N = \left(\frac{\mu_v}{N(\lambda_v+\lambda_h)}\right)\pi_{(N-1)}.$$

After simplification, we can write π_n as in equation (14).

$$\pi_n = \left(\prod_{i=1}^{n}\frac{(N-i+1)\mu_v}{i(\lambda_v+\lambda_h)}\right)\pi_0, n = 1, 2\cdots N. \quad (14)$$

Since $\sum_{n=0}^{N}\pi_n = 1$, with the use of equation (14), we can write as in equation (15).

$$\pi_0 = \left[1+\sum_{n=1}^{N}\left(\prod_{i=1}^{n}\frac{(N-i+1)\mu_v}{i(\lambda_v+\lambda_h)}\right)\right]^{-1} \quad (15)$$

So the NS availability, $A_{ns}^{mc}(N,\lambda_h,\lambda_v)$ $(=\pi_N)$ can be given by equation (16).

$$A_{ns}^{mc}(N,\lambda_h,\lambda_v) = \left(\prod_{i=1}^{N}\frac{(N-i+1)\mu_v}{i(\lambda_v+\lambda_h)}\right)\pi_0. \quad (16)$$

So the NS availability, $A_{ns}^{mc}(N,\lambda_h,\lambda_v)$ can be further simplified as in equation (17).

$$A_{ns}^{mc}(N,\lambda_h,\lambda_v) = \frac{\prod_{i=1}^{N}\frac{(N-i+1)\mu_v}{i(\lambda_v+\lambda_h)}}{1+\sum_{n=1}^{N}\left(\prod_{i=1}^{n}\frac{(N-i+1)\mu_v}{i(\lambda_v+\lambda_h)}\right)}. \quad (17)$$

In case there is no chance of host node failure (i.e., $\lambda_h = 0$), the NS availability considering multiple host nodes based placement of VNFs of NS can be written from equation (17), as in equation (18).

$$A_{ns}^{mc}(N,\lambda_v) = \frac{\prod_{i=1}^{N}\frac{(N-i+1)\mu_v}{i\lambda_v}}{1+\sum_{n=1}^{N}\left(\prod_{i=1}^{n}\frac{(N-i+1)\mu_v}{i\lambda_v}\right)}. \quad (18)$$

Note that, if there is no chance of host node failure, then the availability of NS, considering multiple host nodes based NS deployment and single host node based NS deployment are same (since equation (18) and equation (12) are same).

In case there is no chance of VNF node failure (i.e., $\lambda_v = 0$), the NS availability considering multiple host nodes based placement of NS can be written from equation (17), as in equation (19).

$$A_{ns}^{mc}(N,\lambda_h) = \frac{\prod_{i=1}^{N}\frac{(N-i+1)\mu_v}{i\lambda_h}}{1+\sum_{n=1}^{N}\left(\prod_{i=1}^{n}\frac{(N-i+1)\mu_v}{i\lambda_h}\right)}. \quad (19)$$

C. Scenario-3: Mixed-Mode Based Placement of VNFs of NS

There can be a situation, when some of the VNFs of an NS are placed in a host node and some of the VNFs of an NS are placed in different host nodes. Considering an NS with *N* VNFs. Out of these *N* VNFs, *m* VNFs are placed in different host nodes, n_i VNFs are placed in *i*-th host node. So the availability of NS considering the mixed-mode based placement of VNFs of NS can be defined as in equation (20).

$$A_{ns}^{md}(N,\lambda_h,\lambda_v) = A_{ns}^{mc}(m,\lambda_h,\lambda_v) \times \left(\prod_{i=1}^{n}A_{ns}^{sc}(n_i,\lambda_h,\lambda_v)\right), \quad (20)$$

where $N = m + \sum_{i=1}^{n} n_i$. The availability of *m* VNFs considering placement in *m* host nodes can be found using $A_{ns}^{mc}(m,\lambda_h,\lambda_v)$, which is defined as in equation (17). Also the availability of n_i VNFs which are placed in *i*-th host node can be found using $A_{ns}^{sc}(n_i,\lambda_h,\lambda_v)$, which is defined as in equation (10).

So with the availability expression of a single host node based placement and multiple host nodes based placement, it is possible to find the availability of NS considering mixed-mode based NS deployment.

III. Reliability Analysis of NS

In this section, we present the analysis of the reliability of NS considering the placement of all the VNFs of an NS with the use of multiple host nodes, single host node, and mixed-mode. Before we proceed, we define the reliability of NS.

Definition 2: The probability that an NS survives (i.e., all the VNFs of an NS survive) until some time *t* is defined as the reliability of NS.

A. Scenario-1: VNFs of NS Are Placed in a Single Host Node

Let the random variable X_c be the time to failure of a host node, and the random variable X_v be the time to failure of a VNF node. Here we have assumed, Exponential probability distribution function of X_c and X_v as in (21) and (22) respectively.

$$F_{X_c}(x) = \begin{cases} 1-\mathrm{e}^{-\lambda_h x} & x > 0, \\ 0 & \text{otherwise.} \end{cases} \quad (21)$$

$$F_{X_v}(x) = \begin{cases} 1-\mathrm{e}^{-\lambda_v x} & x > 0, \\ 0 & \text{otherwise.} \end{cases} \quad (22)$$

The probability that a host node survives until some time *t* is called the reliability of host node $R^c(t)$. So $R^c(t)$ can be defined as in equation (23).

$$R^c(t) = P(X_c > t) = e^{-\lambda_h t}. \quad (23)$$

The probability that a VNF node survives until some time *t* is called the reliability of VNF node $R^v(t)$. So $R^v(t)$ can be defined as in equation (24).

$$R^v(t) = P(X_v > t) = e^{-\lambda_v t}. \quad (24)$$

In case of single host node based NS deployment, the NS will be functioning properly, if the host node is functioning properly and all the VNFs of an NS are functioning properly.

So the reliability of single host node based NS deployment, $R_N^{sc}(t)$ can be defined as in equation (25).

$$\begin{aligned} R_N^{sc}(t) &= R^c(t) \times \left(\prod_{i=1}^{N} R_i^v(t)\right) \\ &= P(X_c > t) \times \left(\prod_{i=1}^{N} P(X_v > t)\right) \\ &= e^{-\lambda_h t} \times \left(\prod_{i=1}^{N} e^{-\lambda_v t}\right) \\ &= e^{-\lambda_h t} e^{-\lambda_v N t} \\ &= e^{-(\lambda_h + \lambda_v N)t}. \end{aligned} \tag{25}$$

The instantaneous failure rate, $h^{sc}(t)$ at time t can be defined as:

$$\begin{aligned} h^{sc}(t) &= \lim_{x\to 0}\left(\frac{R_N^{sc}(t) - R_N^{sc}(t+x)}{xR_N^{sc}(t)}\right) \\ &= \lim_{x\to 0}\left(\frac{e^{-(\lambda_h+N\lambda_v)t} - e^{-(\lambda_h+N\lambda_v)(t+x)}}{xe^{-(\lambda_h+N\lambda_v)t}}\right) \\ &= \lim_{x\to 0}\left(\frac{1 - e^{-(\lambda_h+N\lambda_v)x}}{x}\right) \\ &= \lambda_h + N\lambda_v. \end{aligned} \tag{26}$$

From equation (26), we can conclude that the instantaneous failure rate of a single host node based NS deployment is independent of time.

B. Scenario-2: VNFs of NS Are Placed in Multiple Host Nodes

In case of multiple host nodes based NS deployment, the NS will be functioning properly, if all the host nodes are functioning properly and all the VNFs of NS are functioning properly. So the reliability of NS deployment, $R_N^{mc}(t)$ based on multiple host nodes, can be defined as in equation (27).

$$\begin{aligned} R_N^{mc}(t) &= \prod_{i=1}^{N}[R_i^c(t)R_i^v(t)] \\ &= \prod_{i=1}^{N}[P(X_c > t)P(X_v > t)] \\ &= \prod_{i=1}^{N}\left[e^{-\lambda_h t} e^{-\lambda_v t}\right] \\ &= e^{-\lambda_h N t} e^{-\lambda_v N t} \\ &= e^{-(\lambda_h+\lambda_v)Nt}. \end{aligned} \tag{27}$$

The instantaneous failure rate, $h^{mc}(t)$ at time t can be defined as:

$$\begin{aligned} h^{mc}(t) &= \lim_{x\to 0}\left(\frac{R_N^{mc}(t) - R_N^{mc}(t+x)}{xR_N^{mc}(t)}\right) \\ &= \lim_{x\to 0}\left(\frac{e^{-N(\lambda_h+\lambda_v)t} - e^{-N(\lambda_h+\lambda_v)(t+x)}}{xe^{-(\lambda_h+\lambda_v)Nt}}\right) \\ &= \lim_{x\to 0}\left(\frac{1 - e^{-N(\lambda_h+\lambda_v)x}}{x}\right) \\ &= N(\lambda_h + \lambda_v). \end{aligned} \tag{28}$$

From equation (28), we can conclude that the instantaneous failure rate of multiple host nodes based NS deployment is independent of time.

C. Scenario-3: Mixed-Mode Based Placement of VNFs of NS

Considering an NS with *N* VNFs. Out of these *N* VNFs, *m* VNFs are placed in different host nodes, *n* VNFs are placed in a single host node. So the reliability of NS considering mixed-mode based placement of VNFs of NS can be defined as in equation (29)

$$\begin{aligned} R_{N=m+n}^{md}(t) &= R_m^{mc}(t) \times R_n^{sc}(t) \\ &= e^{-m(\lambda_h+\lambda_v)t} \times e^{-(\lambda_h+n\lambda_v)t} \\ &= e^{-(N(\lambda_h+\lambda_v)-(n-1)\lambda_h)t}, \end{aligned} \tag{29}$$

where $R_m^{mc}(t)$ is defined in equation (27), and $R_n^{sc}(t)$ is defined in equation (25). So it is possible to find the reliability of NS considering mixed-mode based placement of VNFs of an NS.

Similarly like equation (28), we can write instantaneous failure rate $h^{md}(t)$ for the mixed-mode based placement of VNFs of an NS as in equation (30), which is independent of time.

$$h^{md}(t) = N(\lambda_h + \lambda_v) - (n-1)\lambda_h. \tag{30}$$

1) Comparison of Reliability: It is known that, e^{-x} decreases with the increase of *x*. So $\forall \lambda, \lambda_h, N > n, t > 0$, $n \geq 1$,

$$\begin{aligned} &\because (\lambda_h + \lambda_v)Nt > (N(\lambda_h + \lambda_v) - (n-1)\lambda_h)t \\ &> (\lambda_h + \lambda_v N)t, \\ &\therefore -(\lambda_h + \lambda_v)Nt < -(N(\lambda_h + \lambda_v) - (n-1)\lambda_h)t \\ &< -(\lambda_h + \lambda_v N)t, \\ &\implies e^{-(\lambda_h+\lambda_v)Nt} < e^{-(N(\lambda_h+\lambda_v)-(n-1)\lambda_h)t} \\ &< e^{-(\lambda_h+\lambda_v N)t}, \\ &\implies e^{-(\lambda_h+\lambda_v N)t} > e^{-(N(\lambda_h+\lambda_v)-(n-1)\lambda_h)t} \\ &> e^{-(\lambda_h+\lambda_v)Nt}, \\ &\implies R_N^{sc}(t) > R_{m+n}^{md}(t) > R_N^{mc}(t). \end{aligned}$$

For extreme condition, reliability of mixed-mode based placement of VNFs of an NS is the same, like single host node based or multiple host nodes based placement of VNFs of an NS, i.e.,

$$\begin{aligned} n \to N \implies m \to 0 \implies R_{m+n}^{md}(t) \to R_N^{sc}(t); \\ n \to 0 \implies m \to N \implies R_{m+n}^{md}(t) \to R_N^{mc}(t); \end{aligned}$$

So $\forall n \geq 1$ and $m \geq 1$, the reliability of NS considering a single host node based placement is more than the reliability of NS considering mixed-mode based placement of VNFs of an NS. Also, the reliability of NS considering mixed-mode based placement of VNFs of an NS is higher than the reliability of NS considering multiple host nodes based placement of VNFs of an NS.

We can define the reliability gain, considering a single host node based NS deployment (Scenario-1) and multiple host nodes based NS deployment (Scenario-2) as in equation (31).

$$\begin{aligned} G^r(1,2) &= \left(\frac{R_N^{sc}(t) - R_N^{mc}(t)}{R_N^{mc}(t)}\right) \times 100\% \\ &= \left(\frac{e^{-(\lambda_h+\lambda_v N)t} - e^{-(\lambda_h+\lambda_v)Nt}}{e^{-(\lambda_h+\lambda_v)Nt}}\right) \times 100\% \\ &= \left(e^{\lambda_h(N-1)t} - 1\right) \times 100\%. \end{aligned} \tag{31}$$

The equation (31) is a function of λ_h, N, t and independent of λ_v. So the reliability gain is parameterized by the failure rate of host node, number of VNFs of an NS, and *t*, but not on the failure rate of VNF.

Since e^x is an increasing function of *x*, so $G^r(1,2)$ is also an increasing function of $\lambda_h, N, t, \forall N > 1$.

Similarly, we can define the reliability gain, considering a single host node based NS deployment (Scenario-1) and mixed-mode based NS deployment (Scenario-3) as in equation (32). Here for mixed-mode based deployment, out of *N* VNFs, *n* VNFs are placed in a single host node and ($N - n$) VNFs are placed in different host nodes.

$$\begin{aligned} G^r(1,3) &= \left(\frac{R_N^{sc}(t) - R_N^{md}(t)}{R_N^{mc}(t)}\right) \times 100\% \\ &= \left(e^{\lambda_h(N-n)t} - 1\right) \times 100\%. \end{aligned} \tag{32}$$

IV. Results and Discussions

We compare the availability as well as the reliability results of NS, considering Scenario-1: when all the VNFs of an NS are placed in a single host node, Scenario-2: when all the VNFs of an NS are placed in different host nodes, and Scenario-3: when all the VNFs of an NS are placed with the use of mixed-mode. Also for mixed-mode based NS deployment, we consider, out of *N* VNFs of an NS, 2 VNFs are placed in different host nodes and the rest of the VNFs, i.e., ($N - 2$) VNFs out of *N* VNFs are placed in a single host node. We have used Scilab to generate results from the derived equations. Also, we have written Python code to simulate the NS availability. Further, we have used Gnuplot to create figures from results. To quantify the advantage of Scenario-1 with respect to Scenario-2 from availability perspective, we define $G^a(1,2)$, as

$$G^a(1,2) = \frac{A_{ns}^{sc}(N,\lambda_h,\lambda_v) - A_{ns}^{mc}(N,\lambda_h,\lambda_v)}{A_{ns}^{mc}(N,\lambda_h,\lambda_v)} \times 100\%. \tag{33}$$

Similarly, we can define $G^a(1,3)$, to quantify the advantage of Scenario-1 with respect to Scenario-3 from availability perspective as

$$G^a(1,3) = \frac{A_{ns}^{sc}(N,\lambda_h,\lambda_v) - A_{ns}^{md}(N,\lambda_h,\lambda_v)}{A_{ns}^{md}(N,\lambda_h,\lambda_v)} \times 100\%. \tag{34}$$

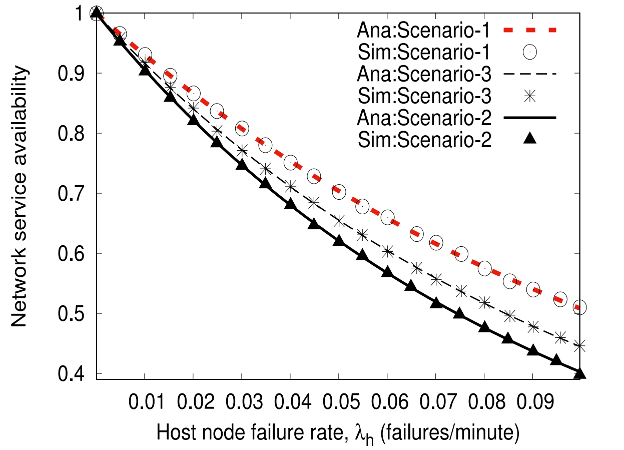

Fig. 6. Analysis and simulation of NS availability corresponding to the host node failure rate per minute (λ_h) with $\mu_v = 1$ VNF/minute, $N = 5$ VNFs per NS, and the failure rate of VNF, $\lambda_v = \lambda_h$.

A. Analysis Verification

Due to unavailability of any standard simulator to simulate the analytical study of this present work, we have used our own Python code to simulate the availability study. Corresponding to each state, we have one or more transition rates as defined in the transition rate diagram of Fig. 2 and Fig. 5. So corresponding to transition rates of any state, we generate Exponentially distributed transition times. After that minimum value of transition time is selected from the generated transition times and accordingly the transition state is changed. Again for the new state, the same procedure is followed to change state. This simulation process continued for 70000 minutes. During the simulation, the number of times any particular state-visit is noted. After that, we find the steady state probability of any state. Then we find the availability, when all the VNFs of an NS are active. In Fig. 6, we show that the availability considering analysis and simulation are matching. We see the availability is decreasing in all three cases. But availability considering Scenario-1 is more than the availability considering Scenario-2. Because Scenario-1 considers a single host node for the placement of all the VNFs of an NS, as a result, the failure rate is less compared to multiple host nodes based placement of all VNFs of an NS.

B. Availability Comparison of NS

In this section, we compare the availability of NS with respect to the failure rate of VNF, the failure rate of a host node, the creation rate of VNF, and the number of VNFs per NS.

1) Comparison of Availability With Respect to Failure Rate of Host Node: In Fig. 7(a), Fig. 7(b), Fig. 7(c) and Fig. 7(d), we plot the availability of NS for various values of host node failure rate, λ_h. The NS availability with Scenario-1 is higher than the availability of NS with Scenario-3. Also, the NS availability with Scenario-3 is higher than the availability of NS with Scenario-2. Since with the use of multiple host nodes (e.g., Scenario-2 and Scenario-3), the total failure rate is more than the use of a single host node (e.g., Scenario-1).

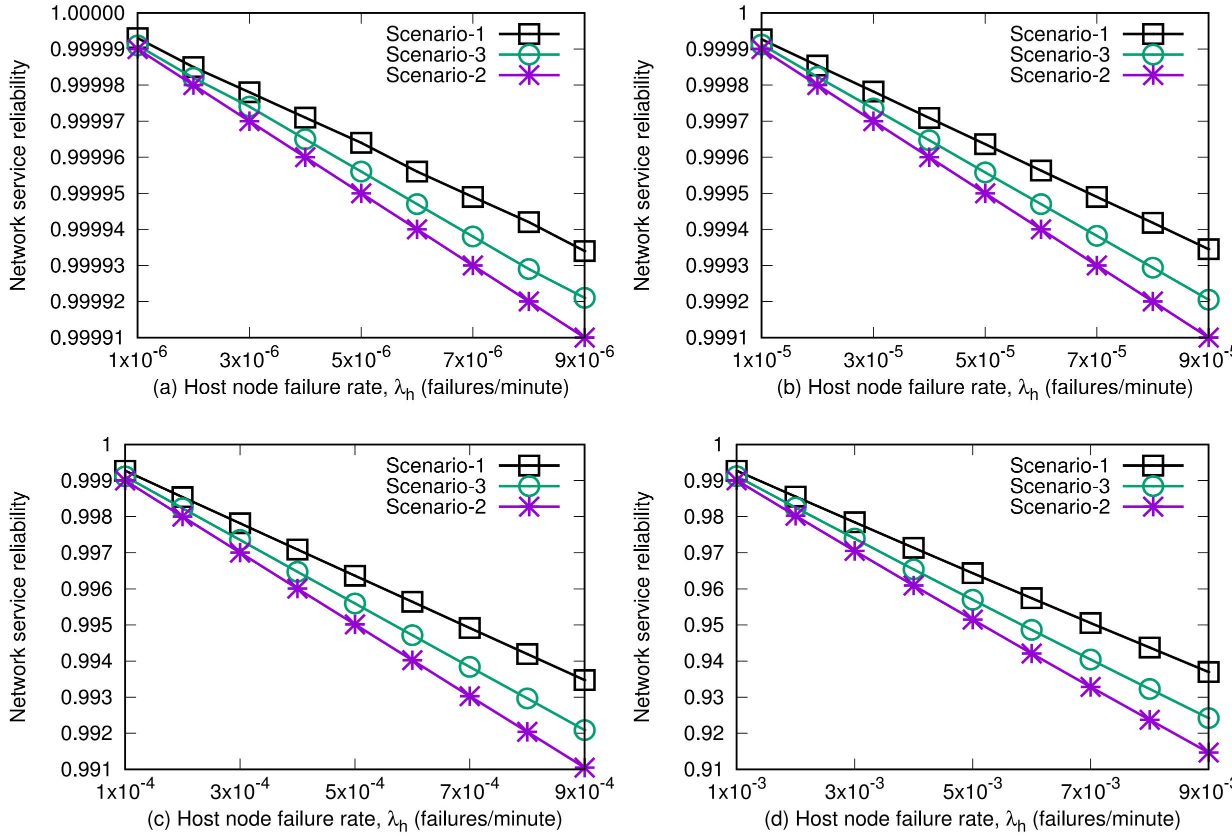

Fig. 7. Availability of NS with respect to the failure rate of host node per minute (λ_h) with $\mu_v = 1$ VNF/minute, $N = 5$ VNFs per NS, and failure rate of VNF, $\lambda_v = \lambda_h$, (a) $\lambda_h \in \{1 \times 10^{-6}, \ldots, 9 \times 10^{-6}\}$ failures/minute (b) $\lambda_h \in \{1 \times 10^{-5}, \ldots, 9 \times 10^{-5}\}$ failures/minute (c) $\lambda_h \in \{1 \times 10^{-4}, \ldots, 9 \times 10^{-4}\}$ failures/minute (d) $\lambda_h \in \{1 \times 10^{-3}, \ldots, 9 \times 10^{-3}\}$ failures/minute.

TABLE II
AVAILABILITY OF NS WITH RESPECT TO λ_h (FAILURES/MINUTE), WITH $\lambda_h = \lambda_v$ AND $N = 5$

λ_h	Scenario-1	Scenario-3	Scenario-2	$G^a(1,2)$	$G^a(1,3)$
9×10^{-3}	0.936967	0.924171	0.914663	2.4%	1.38%
10^{-3}	0.992749	0.991213	0.990060	0.27%	0.15%
10^{-4}	0.999272	0.999117	0.999001	0.027%	0.02%
10^{-5}	0.999927	0.999912	0.999900	0.0027%	0.002%
10^{-6}	0.999993	0.999991	0.999990	0.0003%	0.0002%

If we increase the host node failure rate, then the NS spends more time for the creation of VNFs, so the availability of NS decreases with the increase of the failure rate of host node in all scenarios.

Further, in Table II, we compare the availability of NS for few other values of host node failure rate, λ_h. Here also we can see the availability of NS decreases with the increase of host node failure rate, λ_h and the availability of NS is higher with Scenario-1. The availability gain of Scenario-1 with respect to Scenario-2 for $\lambda_h = 9 \times 10^{-3}$ failures/minute is 2.4%.

2) Comparison of Availability With Respect to VNF Creation Rate: In Fig. 8, we compare NS availability for various values of creation rate of VNF, μ_v. Here, with the large value of the VNF creation rate, any VNF takes a very short time to come up. As a result, the NS availability is more for a large value of the VNF creation rate. The NS availability with a single host node (Scenario-1) is higher than the availability of NS with multiple host nodes (e.g., Scenario-2 and Scenario-3). The NS availability considering a single host node in the case of Scenario-1 is higher than the NS availability considering multiple host nodes with Scenario-2 and Scenario-3, because with more number of host nodes the total failure rate increases. Further in Table III, we compare the availability of NS for few other values of μ_v and λ_h. Here also we see the availability of NS with Scenario-1 is higher than other schemes of NS deployment and with the decrease of failure rate (host node and VNF) the availability increases.

3) Comparison of Availability With Respect to Number of VNFs Per NS: We show the availability of NS for various values of the number of VNFs per NS in Fig. 9.

In case of multiple host nodes (e.g., Scenario-2 and Scenario-3), with a large number of VNFs per NS, the total failure rate is higher than the failure rate of Scenario-1, so the availability of NS with Scenario-2 and Scenario-3 are less compare to the availability of NS with Scenario-1. With more number of VNFs, NS takes a long time to come up due to the failure of VNFs. As a result, the availability of NS increases with the decrease of the number of VNFs per NS in all cases

TABLE III
AVAILABILITY OF NS WITH RESPECT TO μ_v (VNFS/MINUTE), WITH $\lambda_h = \lambda_v$ (FAILURES/MINUTE) AND $N = 5$

μ_v	λ_h	Scenario-1	Scenario-3	Scenario-2	$G^a(1,2)$	$G^a(1,3)$
0.95	10^{-4}	0.999234	0.999071	0.998948	$2.8 \times 10^{-2}\%$	$1.6 \times 10^{-2}\%$
0.95	10^{-5}	0.999923	0.999907	0.999895	$2.8 \times 10^{-3}\%$	$1.6 \times 10^{-3}\%$
0.95	10^{-6}	0.999992	0.999991	0.999989	$3.0 \times 10^{-4}\%$	$1.0 \times 10^{-4}\%$
1.95	10^{-4}	0.999627	0.999547	0.999487	$1.4 \times 10^{-2}\%$	$0.8 \times 10^{-2}\%$
1.95	10^{-5}	0.999963	0.999955	0.999949	$1.4 \times 10^{-3}\%$	$0.8 \times 10^{-3}\%$
1.95	10^{-6}	0.999996	0.999995	0.999995	$1.0 \times 10^{-4}\%$	$1.0 \times 10^{-4}\%$

TABLE IV
AVAILABILITY OF NS WITH RESPECT TO N, WITH $\lambda_h = \lambda_v$ (FAILURES/MINUTE) AND $\mu_v = 1$ VNF/MINUTE

N	λ_h	Scenario-1	Scenario-3	Scenario-2	$G^a(1,2)$	$G^a(1,3)$
4	10^{-4}	0.999392	0.999250	0.999200	$1.9 \times 10^{-2}\%$	$1.4 \times 10^{-2}\%$
4	10^{-5}	0.999939	0.999925	0.999920	$1.9 \times 10^{-3}\%$	$1.4 \times 10^{-3}\%$
4	10^{-6}	0.999994	0.999993	0.999992	$1.9 \times 10^{-4}\%$	$1.0 \times 10^{-4}\%$
10	10^{-4}	0.998708	0.998529	0.998002	$7.0 \times 10^{-2}\%$	$1.8 \times 10^{-2}\%$
10	10^{-5}	0.999871	0.999853	0.999800	$7.0 \times 10^{-3}\%$	$1.8 \times 10^{-3}\%$
10	10^{-6}	0.999987	0.999985	0.999980	$7.0 \times 10^{-4}\%$	$2.0 \times 10^{-4}\%$

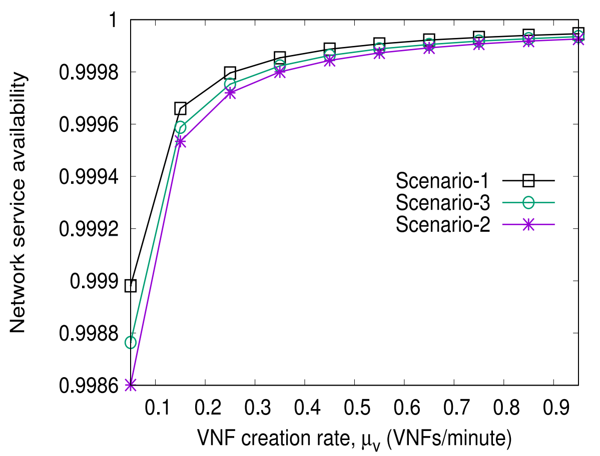

Fig. 8. Availability of NS with respect to the VNF creation rate per minute (μ_v) with $\lambda_v = \lambda_h = 7 \times 10^{-6}$ failures/minute, and $N = 5$ VNFs per NS.

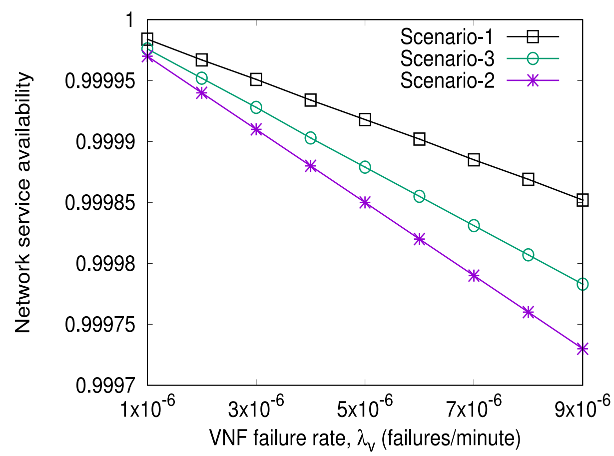

Fig. 10. Availability of NS for various values of VNF failure rate, with $\lambda_h = 5\lambda_v$, $\mu_v = 1$ VNF/minute, and number of VNFs per NS, $N = 5$.

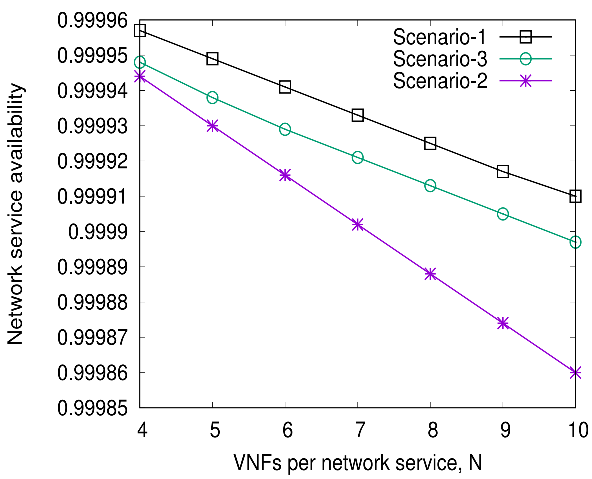

Fig. 9. Availability of NS with respect to the number of VNFs per NS with $\lambda_v = \lambda_h = 7 \times 10^{-6}$ failures/minute and $\mu_v = 1$ VNF/minute.

of placement scenarios. Further, in Table IV, we compare the availability of NS for few other values of N and λ_h. Here also we can see the availability is higher with Scenario-1.

4) Comparison of Availability With $\lambda_v > \lambda_h$ and $\lambda_v < \lambda_h$: We consider the host node failure rate (λ_h) as five times the VNF failure rate (λ_v), and generate the NS availability as in Fig. 10. Here, with the decrease of the VNF failure rate, the NS availability increases in all cases (Scenario-1, Scenario-2, and Scenario-3). Although the rate of decrease of NS availability is more for multiple host nodes (Scenario-2, Scenario-3), than the NS availability considering a single host node (Scenario-1). Since with the increase of λ_h, the total failure rate of multiple host nodes based placement of VNFs of NS increases more than the single host node based placement of VNFs of NS. Further, in Table V we show the availability of NS for $\lambda_v = \{10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}\}$ failures/minute. Here also we can see that the availability of NS increases with the decrease of failure rate of VNF (λ_v).

We consider the failure rate of VNF (λ_v) as five times the host node failure rate (λ_h) and compare the NS availability as in Fig. 11. Here, the NS availability decreases at almost the same rate considering a single host node (Scenario-1) and multiple host nodes (Scenario-2, Scenario-3). Since the failure rate of VNF is more, with the consideration of a single host

TABLE V
AVAILABILITY OF NS WITH RESPECT TO λ_v WITH $\lambda_h = 5 \times \lambda_v$, $\mu_v = 1$ VNF/MINUTE AND $N = 5$

λ_v	λ_h	Scenario-1	Scenario-3	Scenario-2	$G^a(1,2)$	$G^a(1,3)$
10^{-3}	5×10^{-3}	0.983749	0.976185	0.970533	$1.4 \times 10^{0}\%$	$0.8 \times 10^{0}\%$
10^{-4}	5×10^{-4}	0.998360	0.997587	0.997005	$1.4 \times 10^{-1}\%$	$0.8 \times 10^{-1}\%$
10^{-5}	5×10^{-5}	0.999836	0.999758	0.999700	$1.4 \times 10^{-2}\%$	$0.8 \times 10^{-2}\%$
10^{-6}	5×10^{-6}	0.999984	0.999976	0.999970	$1.4 \times 10^{-3}\%$	$0.8 \times 10^{-3}\%$

TABLE VI
AVAILABILITY OF NS WITH RESPECT TO λ_h, WITH $\lambda_v = 5 \times \lambda_h$, $\mu_v = 1$ VNF/MINUTE AND $N = 5$

λ_h	λ_v	Scenario-1	Scenario-3	Scenario-2	$G^a(1,2)$	$G^a(1,3)$
10^{-3}	5×10^{-3}	0.973158	0.971659	0.970533	$2.7 \times 10^{-1}\%$	$1.5 \times 10^{-1}\%$
10^{-4}	5×10^{-4}	0.997276	0.997122	0.997005	$2.7 \times 10^{-2}\%$	$1.5 \times 10^{-2}\%$
10^{-5}	5×10^{-5}	0.999727	0.999712	0.999700	$2.7 \times 10^{-3}\%$	$1.5 \times 10^{-3}\%$
10^{-6}	5×10^{-6}	0.999973	0.999971	0.999970	$3.0 \times 10^{-4}\%$	$2.0 \times 10^{-4}\%$

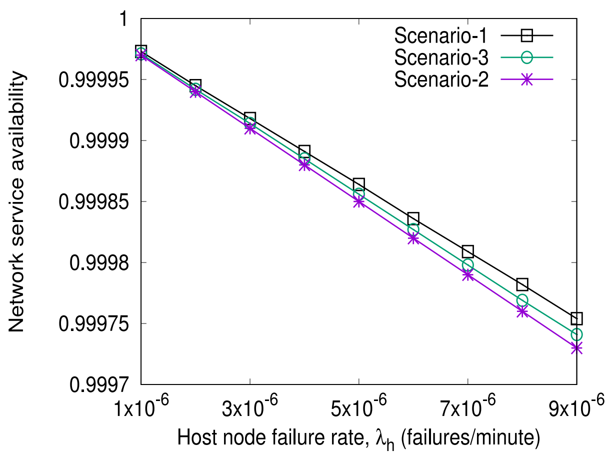

Fig. 11. Availability of NS for various values of host node failure rate, with $\lambda_v = 5\lambda_h$, $\mu_v = 1$ VNF/minute, and number of VNFs per NS, $N = 5$.

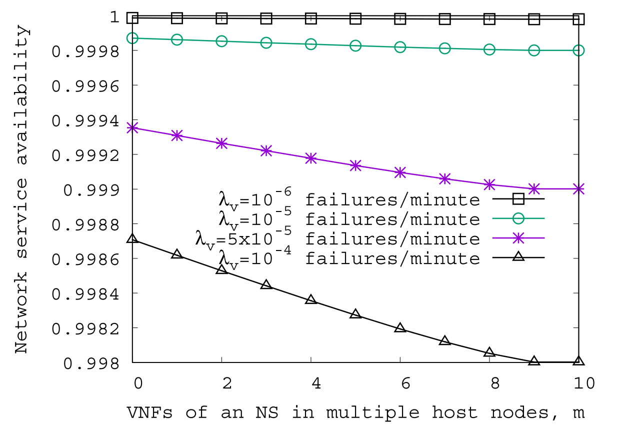

Fig. 12. Availability of NS with mixed mode based deployment with $N = 10$, $\lambda_h = \lambda_v$ and out of N VNFs of an NS, $(N - m)$ VNFs are in a single host node and m VNFs are in different host nodes.

TABLE VII
COMPARISON OF NS AVAILABILITY BETWEEN SCENARIO-1 AND SCENARIO-2 WITH $N = 5$

λ_v	λ_h	A_{ns}^{sc}	A_{ns}^{mc}	$G^a(1,2)$
0.0007	0.0007	0.995	0.993	0.2%
0.0007	0.00014	0.9962	0.9958	0.03%
0.0007	0.0035	0.9886	0.9793	0.95%

node the rate of decrease of NS availability is more and very close to the NS availability considering the deployment of NS based on multiple host nodes. Further, in Table VI we show the availability of NS for $\lambda_h = \{10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}\}$ $\mathrm{failures/minute}$. Here also we can see that the availability of NS increases with the decrease of failure rate of host node (λ_h).

To see the comparison results in a tabular form for a particular value of λ_v and λ_h, we show the NS availability in Table VII. In this table, we denote A_{ns}^{sc} to identify the availability considering NS deployment based in a single host node (i.e., Scenario-1) and A_{ns}^{mc} to identify the availability considering deployment based on multiple host nodes (i.e., Scenario-2). It can be seen from the table that, with the failure rate of the host node as 0.0035 $\mathrm{failures/minute}$, and the failure rate of VNF as 7×10^{-4} $\mathrm{failures/minute}$, the availability of single host node based deployment (Scenario-1) can provide 0.95% more availability than the availability of NS deployment based on multiple host nodes (Scenario-2).

5) Optimization of Availability of Mixed-Mode Based NS Deployment: In Fig. 12, we show the availability of mixed-mode based NS deployment for various values of VNF failure rate, λ_v. Also, we consider the host node failure rate (λ_h) is same as the VNF failure rate (λ_v), i.e., $\lambda_h = \lambda_v$. With the increase of VNF failure rate, λ_v most of the time VNF creation restarts, as a result, the availability of NS decreases. Here, out of N VNFs of an NS, m VNFs are placed in different host nodes, and $(N - m)$ VNFs are placed in a single host node. If we increase the value of m then the availability decreases, since the total failure rate increases with the increase of more host nodes. At $m = N$, i.e., when all the VNFs are placed in different host nodes, then the availability of mixed-mode based NS deployment is minimum and same as the availability of NS deployment based on multiple host nodes. Further, with $m = 0$, all the VNFs of an NS are deployed in a single host node. As a result, the availability will be maximum and same as the availability of NS with single host node based NS deployment. This is captured in Table VIII.

TABLE VIII
AVAILABILITY OF NS WITH $\lambda_h = \lambda_v = 10^{-5}$ FAILURES/MINUTE AND $N = 10$

$(m, (N-m))$	Scenario-1	Scenario-3	Scenario-2	$G^a(1,2)$	$G^a(1,3)$
$(0, 10)$	**0.999871**	**0.999871**	0.999800	0%	0.007%
$(2, 8)$	0.999871	0.999853	0.999800	0.002%	0.007%
$(5, 5)$	0.999871	0.999827	0.999800	0.004%	0.007%
$(8, 2)$	0.999871	0.999805	0.999800	0.0066%	0.007%
$(10, 0)$	0.999871	**0.999800**	**0.999800**	0.007%	0.007%

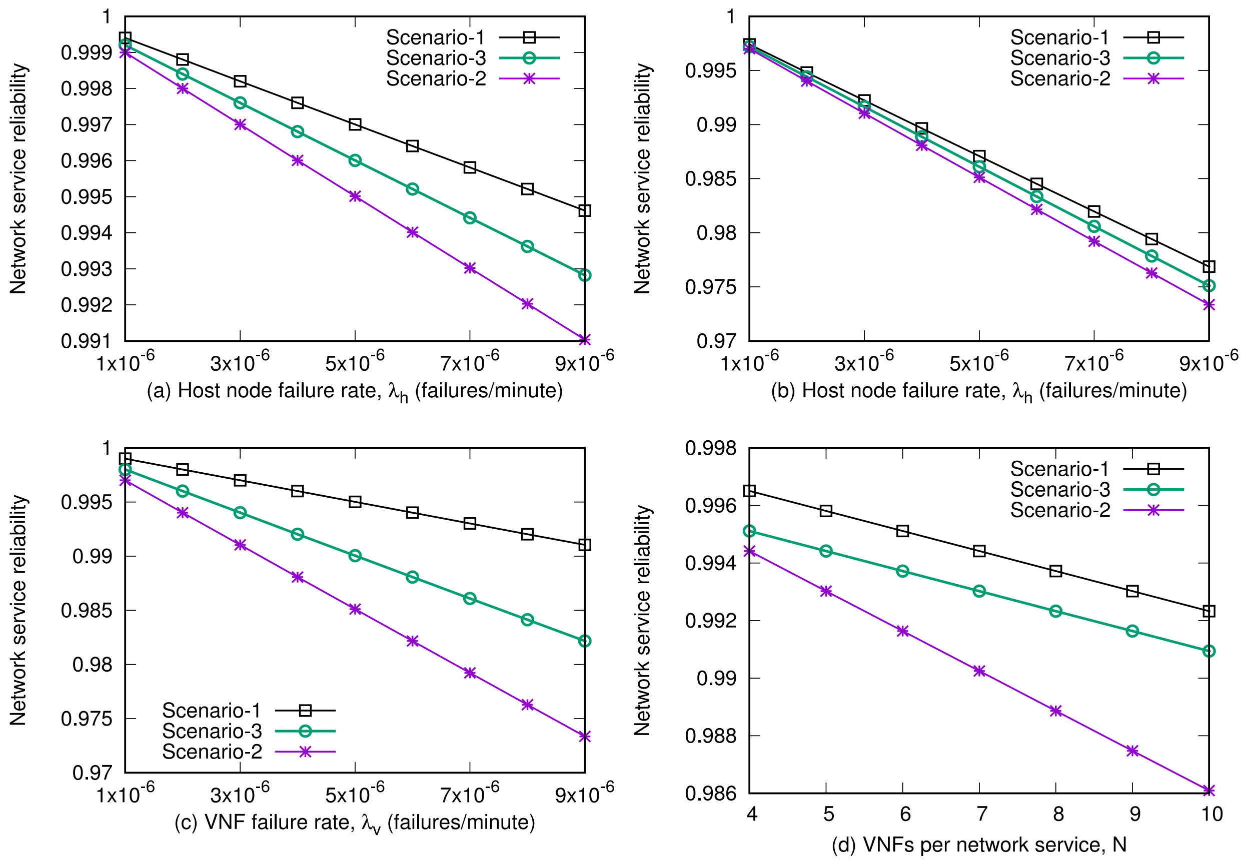

Fig. 13. Reliability of NS considering t = 100 minutes and (a) $\lambda_v = \lambda_h$, $N = 5$ (b) $\lambda_v = 5\lambda_h$, $N = 5$ (c) $\lambda_h = 5\lambda_v$ $N = 5$ (d) $\lambda_v = \lambda_h = 7 \times 10^{-6}$ failures/minute.

C. Reliability Comparison of NS

In Fig. 13, we compare the reliability of NS considering the placement of VNFs of NS based on multiple host nodes, single host node, and mixed-mode.

In all cases of reliability comparison, we see the reliability of NS considering deployment based on Scenario-1 is more than the reliability of NS based on Scenario-2 and Scenario-3. In case of a single host node based deployment, the only host node needs to be up, but in the case of multiple host nodes based deployment, all the host nodes need to be up for the VNFs to be operational. So the reliability of NS considering Scenario-1 is higher than the reliability of NS considering deployment based on Scenario-2 and Scenario-3. This is true for all cases of comparison with $\lambda_h = \lambda_v$, $\lambda_h < \lambda_v$, and $\lambda_h > \lambda_v$. In all cases of comparison, we have considered $t = 100$ minutes.

In Fig. 13(a), the difference in reliability between Scenario-1 and Scenario-2, considering $N = 5$, $t = 100$ minutes, can be expressed as, $(e^{-600\lambda_h} - e^{-1000\lambda_h})$, which is an increasing function of λ_h, when $\lambda_h \leq 10^{-3}$ failures/minute. So the difference in reliability is increasing in this case.

In Fig. 13(b), the difference in reliability between Scenario-1 and Scenario-2, considering $N = 5$, $t = 100$ minutes, can be expressed as, $(e^{-2600\lambda_h} - e^{-3000\lambda_h})$, which is an increasing function of λ_h, when $\lambda_h \leq 3 \times 10^{-4}$ failures/minute. So the difference in reliability is increasing here.

In Fig. 13(c), the difference in reliability between Scenario-1 and Scenario-2, considering $N = 5$, $t = 100$ minutes, can be expressed as, $(e^{-1000\lambda_v} - e^{-3000\lambda_v})$, which is an increasing function of λ_v, when $\lambda_v \leq 7 \times 10^{-4}$ failures/minute. So the difference in reliability is increasing in Fig. 13(c).

In Fig. 13(d), $(e^{-0.0007(N+1)} - e^{-0.0014N})$ is the difference in reliability between Scenario-1 and Scenario-2, considering $\lambda_v = 7 \times 10^{-6}$ failures/minute, $t = 100$ minutes. This difference is an increasing function of N, when $N \leq 10$. So the difference in reliability is increasing with the increase of N.

In Table IX, we compare the reliability of NS for few other values of host node failure rate, λ_h =

TABLE IX
COMPARISON OF NS RELIABILITY

λ_h	Scenario-1	Scenario-3	Scenario-2	$G^r(1,2)$	$G^r(1,3)$
10^{-3}	0.548812	0.449329	0.367879	49.18%	22.14%
10^{-4}	0.941765	0.923116	0.904837	4.08%	2.02%
10^{-5}	0.994018	0.992032	0.990050	0.4%	0.2%
10^{-6}	0.999400	0.999200	0.999000	0.04%	0.02%

TABLE X
RELIABILITY OF NS WITH $\lambda_h = \lambda_v = 10^{-5}$ FAILURES/MINUTE AND $N = 10$

$(m,(N-m))$	Scenario-1	Scenario-3	Scenario-2	$G^r(1,2)$	$G^r(1,3)$
$(0,10)$	**0.989060**	**0.989060**	0.980199	0%	0.9%
$(2,8)$	0.989060	0.987084	0.980199	0.2%	0.9%
$(5,5)$	0.989060	0.984127	0.980199	0.5%	0.9%
$(8,2)$	0.989060	0.981179	0.980199	0.8%	0.9%
$(10,0)$	0.989060	**0.980199**	**0.980199**	0.9%	0.9%

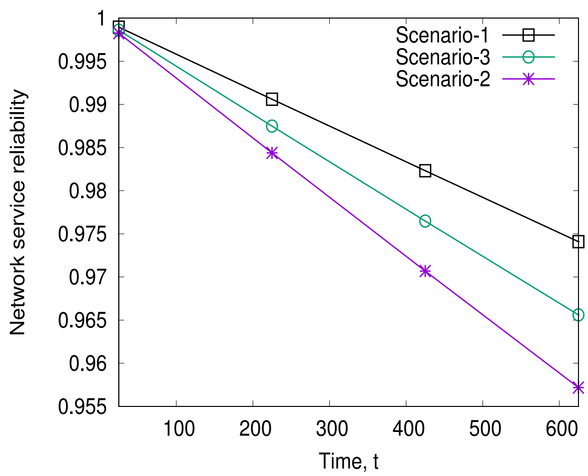

Fig. 14. Reliability of NS with respect to the time and $N = 5, \lambda_v = \lambda_h = 7 \times 10^{-6}$ failures/minute.

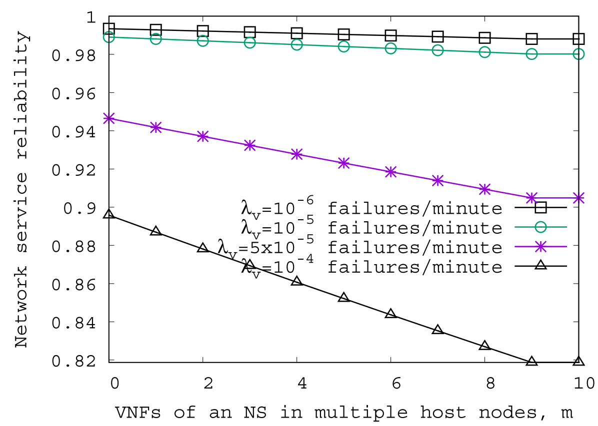

Fig. 15. Reliability of NS with mixed-mode based deployment with $N = 10$, $\lambda_h = \lambda_v$ and out of N VNFs of an NS, $(N - m)$ VNFs are in a single host node and m VNFs are in different host nodes.

$\{10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}\}$ failures/minute. Here also the reliability increases with the decrease of host node failure rate.

Further, in Fig. 14, we compare the NS reliability with respect to time. Here, the reliability of NS considering Scenario-1 is higher than the NS reliability of Scenario-3.

Also, the NS reliability of Scenario-3 is higher than the NS reliability of Scenario-2. Further, here with the increase of time, t the NS reliability decreases in all cases.

1) Optimization of Reliability of Mixed-Mode Based NS Deployment: In Fig. 15, we show the reliability of mixed-mode based NS deployment for various values of VNF failure rate, λ_v. Also, we consider the host node failure rate (λ_h) is same as the VNF failure rate (λ_v), i.e., $\lambda_h = \lambda_v$. With the increase of VNF failure rate, λ_v most of the time VNF creation restarts, as a result, the reliability of NS decreases. Here, out of N VNFs of an NS, m VNFs are placed in different host nodes, and $(N - m)$ VNFs are placed in a single host node. If we increase the value of m then the reliability decreases, since the total failure rate increases with the increase of more host nodes. At $m = N$, i.e., when all the VNFs are placed in different host nodes, then the reliability of mixed-mode based NS deployment is minimum and same as the reliability of NS deployment based on multiple host nodes. Further, with $m = 0$, all the VNFs of an NS are deployed in a single host node. As a result, the reliability will be maximum and same as the reliability of NS with single host node based NS deployment. This is captured in Table X.

V. CONCLUSION

We have presented an analysis of NS availability in the presence of host node failure and VNF failure. Since the VNFs of an NS can be placed in a single host node, and multiple host nodes, we compare the NS availability considering the placement of VNFs of NS based in a single host node, multiple host nodes, and mixed-mode. We have compared the NS availability with respect to the failure rate of host node, failure rate of VNF, creation rate of VNFs, and number of VNFs of an NS. Via analysis, supported by simulation, we have demonstrated that, the single host node based NS has higher availability than the availability of NS with multiple host nodes.

Further, we have analyzed and compared the reliability of NS considering the placement of VNFs of an NS based on multiple host nodes, single host node, and mixed-mode. We have proved that the reliability of single host node based placement of VNFs of NS like Scenario-1 is better than the reliability of NS considering the placement of VNFs based on multiple host nodes like Scenario-2 and Scenario-3.

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