2011 IEEE International Conference on High Performance Computing and Communications

Dependability Modeling and Analysis for the Virtual Data Center of Cloud Computing

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***Abstract*—Virtual data center is becoming increasingly popular as the infrastructure of Cloud computing. In order to provide efficient and uninterrupted service, the dependability of the Cloud infrastructure has received extensive attention. But modeling and analysis of dependability of the virtual data center is challenging for the particular characteristics and mechanisms of virtualization. In this paper, we use hierarchical method and develop the hybrid models combining reliability block diagrams and general stochastic Petri nets. Focusing on the two attributes reliability and availability, we give the computation expressions by solving the models. The impact of the characteristics and mechanisms of virtualization such as consolidation backup and live migration on dependability is studied. We analyze the relation between reliability and consolidation ratio, as well as the relation between availability and the workload. In addition, some useful rules are summarized and discussed, which are believed to be helpful to the design and construction of more dependable virtual data center.**

***Keywords*-Dependability; general stochastic Petri net; reliability block diagram; virtual data centers; Cloud Computing**

I. INTRODUCTION

A data center can be viewed as a massive server farm that runs many of today's Internet and business applications [1]. In recent years, data centers have rapidly grown to become an integral part of the Internet fabric and become increasingly popular as the IT infrastructure in large enterprises, banks, portal sites, etc., especially in the context of Cloud computing and IaaS (Infrastructure as a service) [2, 3, 4].

As data centers are inexorably growing more complex and large-scale, it brings many challenges for deployment, management and dependability [5], etc. Virtualization is viewed as an effective weapon against these challenges. Data centers which are built using virtualization technology with virtual machines as the basic processing elements are called virtual data centers (VDCs) [6, 7]. Comparing with the traditional data centers, VDCs could provide some significant merits such as server consolidation, high availability and live migration, and provide flexible resource management mechanisms. Therefore, VDCs are widely used as the infrastructure of existing Cloud computing systems [8, 9].

Achieving required level of dependability is one of the most challenging issues in implementing the VDCs. In this paper, we focus on two attributes of dependability, availability and reliability. With the sharp increase of server nodes and the aggrandizement scale of the systems, node failure is thought to be normality instead of abnormality. The threat to the dependability of infrastructure may seriously affect the Quality of Service (QoS) for the business in Cloud computing, even resulting in paralysis of the whole system. For example, due to a database server failure, Google's Cloud computing service Google App Engine suffered an outage lasting over several hours [10].

In order to provide continual services through graceful degradation despite these node failures, it is important to evaluate and improve the dependability of the underlying infrastructure. For the VDC, some novel mechanisms of virtualization such as consolidated backup [11] and live migration [12, 13] are deemed as powerful tools for enhancing dependability. Evaluating the practical impacts brought by these virtualization mechanisms on dependability is also a concern. However, as we known, all existed works about dependability evaluation of virtualization research on one or two virtual servers system, and there are not quantifiable dependability evaluation models and methods for VDCs which contain thousands of physical servers yet. In this paper, we use hierarchical method and develop the hybrid models for VDCs of cloud computing combining the Reliability Block Diagrams (RBD) and General Stochastic Petri Nets (GSPN). By solving the models, we analyze the dependability of VDCs and the impacts brought by virtualization mechanisms including consolidated backup and live migration. According to the dependability analysis result of the hybrid models, some useful rules are summarized and discussed, which are believed to be helpful to the design and construction of more dependable VDCs.

The rest of paper is organized as follows. In Section II, some background and related work are introduced. In Section III, we establish the comprehensive dependability models for VDCs which combine RBD model and GSPN model together using a hierarchical method. In Section IV, by solving the hybrid models, dependability of VDCs is analyzed including reliability and availability. In Section V, we give some numerical results and discuss them. Finally we give our conclusions and future work in Section VI.

978-0-7695-4538-7/11 $26.00 © 2011 IEEE
DOI 10.1109/HPCC.2011.111

II. BACKGROUND AND RELATED WORK

A. Virtualization and Virtual Data Center

Virtualization adds a hardware abstraction layer called the virtual machine monitor (VMM) or hypervisor. It provides an interface that is functionally equivalent to the actual hardware of a number of virtual machines [14]. Using the VMM, multiple virtual machines can run on a physical server.

Virtual data center can be viewed as a massive server farm which is composed of several groups of physical servers (see Figure 1). Each server has many virtual machines running on the VMM layer. The VM which contains an operating system and specific application works as the basic processing element. These servers and VMs are under unified management. Many novel characteristics and mechanisms of virtualization have brought numerous advantages to VDC. Server consolidation [14] make one physical server can hold many active operating systems at the same time, while keeping a good isolation each other. It increases the utilization of hardware resources. Consolidated backup [11] makes it easier and low-cost to backup system and service. Live migration [12, 13] enables active VM to move between different physical servers without interrupting the application service. It helps to dynamic load-balance and fault-avoidance, and makes the management and maintenance of data center more flexible and efficient.

VDC is becoming increasingly popular as the infrastructure of Cloud computing. Amazon EC2 [15] uses tens of thousands of servers and Xen virtualization technique to build the VDC, and provides service in the form of IaaS. VMware provides a series of VDC solutions, based on which they publish their own Cloud computing platform vCloud [8].

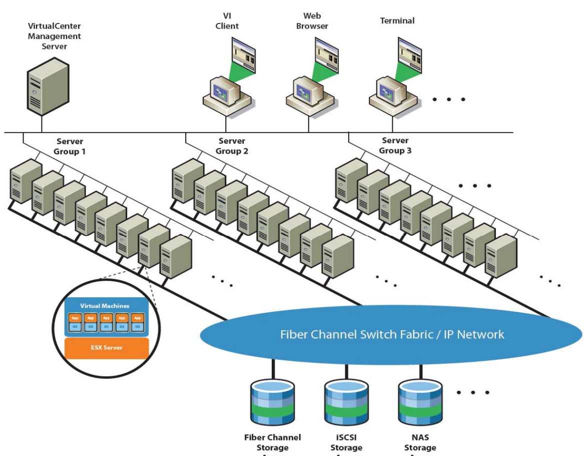

Fig. 1. Typical architecture of a virtual data center [16]

B. Dependability Modeling of Virtualization Systems

Dependability is a global concept that subsumes the attributes of reliability, availability, safety, etc[17]. This paper focuses on two common attributes for VDC, which are reliability and availability. As virtualization systems are used extensively, their dependability becomes a concern. HariGovind et al. studied how virtualization can affect system dependability. They analyzed the reliability of multiple design choices when a single physical server is used to host multiple virtual machines using combinatorial modeling [18]. But their work was limited to single virtual server. In addition, the combinatorial model was difficult to describe the dynamic mechanisms such as live migration. Ref. [19] and [20] used stochastic reward nets to represent two servers virtualized system, to capture failures, reactive recovery and proactive recovery by software rejuvenation. D. S. Kim and F. Machida [21] used two level hierarchical modeling which uses fault tree in the upper layer and Markov sub-models in the lower layer. In our previous work [22], we used Markov model to describe virtualization systems and gave the solving methods to quantitatively analyze their dependability. These existing works focus on the single virtual server or two virtual servers, which contain only one or two physical machines, one or two VMMs and several virtual machines. But in VDC, there can be up to thousands of servers and tens of thousands of virtual machines. Moreover, some characteristics and mechanisms such as dynamic migration of VM and consolidated backup bring more challenges to dependability modeling and analysis of VDC. As we known, there is no comprehensive study of the dependability model of VDC yet.

III. DEPENDABILITY MODEL

There are two major categories of dependability models: combinatorial models and state-based stochastic models [23]. The former are easier and have more obvious physical meaning, but their descriptive power for dynamic characteristic is limited. The latter can describe more complex systems, but they are usually hard to solve and analyze. In [18], a reliability block diagram (RBD) is used to evaluate the reliability of virtualized system with only one server, which is too simple to analyze the complex behavior of the hardware and software component and their interdependencies. In [20], continues time Markov chains (CTMC) is used to modeling the behavior of a virtualized system, but all these works focus on modeling system with few physical servers and therefore their analyses are simplified. Our objective is to solve modeling and analysis of VDC which contains thousands of servers. RBD model is easy to express relations between different clusters, and concerning about the virtualization mechanism such as consolidation backup and live migration, we use GSPN model to express complex behavior in VDC. Hence, in this paper, we combine the advantages of the two types of models (RBD model and GSPN model), and use a hierarchical method to simplify the model and relieve state space explosion.

We first build a top-level model for VDC using reliability block diagrams (see Figure 2), which describes the whole structure intuitively. Several servers mutually backup and form a cluster. Many clusters are connected by network modules, and cooperate with each other to implement the function of VDC. Without loss of generality, it is assumed that a VDC has l clusters, and $Cluster_i$ ($1 \le i \le l$) contains m_i servers and a network module C_i. Because servers in the same cluster are often connected by the backplane or else high-speed link that seldom break down, we omit the inner connection of cluster in our dependability study.

Then we study the inner model of a server. W. l. o. g., it is assumed that $Server_{ij}$ ($1 \le i \le l, 1 \le j \le m_i$) contains n_{ij} virtual machines (VMs), a virtual Machine monitor (VMM) and a hardware machine (HW). So the RBD model of a server can be depicted in Figure 3.

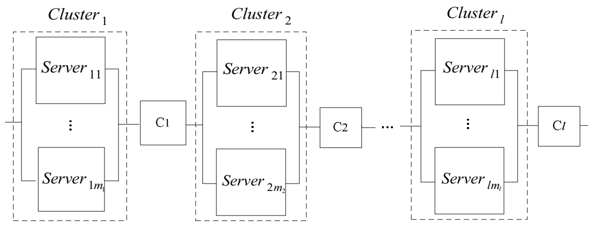

Fig. 2. The top-level RBD model

In order to study the dynamic mechanisms such as live migration of VDC, we turn to the state-based stochastic models. As a powerful model tool, GSPN is an effective tool for dependability modeling [24]. Figure 4 describes the GSPN model of a component with failure and repair. The timed transition $t_{arrival}$ represents the tasks arrival. The places p_{up} and p_{down} represent the normal state and failure state of the component. When a task arrives, it can be normally processed if the token is in the p_{up} place, or else it has to wait until the component is repaired. The two timed transitions $t_{failure}$ and t_{repair} represent the failure and repair process, the firing rate of those are the failure rate λ and the repair rate μ .

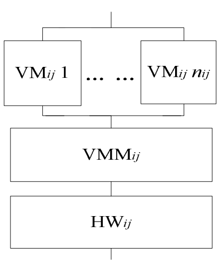

Fig. 3. RBD model of $Server_{ij}$

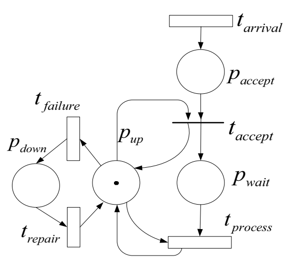

Fig. 4. GSPN model of a component

Taking the GSPN model in Figure 4 (here a component implies one component of a physical server, i.e. VMM, HW or VM) as the basic unit, we build the dependability model for a cluster in the VDC. Figure 5 shows the GSPN dependability model of the $Cluster_i$. Coincide with Figure 2, there are m_i servers in the $Cluster_i$. $Server_{ij}$ ($1 \le i \le l, 1 \le j \le m_i$) is composed of n_{ij} VMs, a VMM and a HW. Each of these components can be depicted by the GSPN model similar to Figure 4. But two points should be paid attention to in the partial model of the VMs of Figure 5.

The first one is the description of the mechanism of live migration. When a token in $Server_{i\alpha}$ is in the place $p_{vm\_decision\ 1}$, system will make a decision whether to trigger the process of live migration. When the migration transition $t_{\text{Migration}\,\alpha}$ is triggered, the token entries the place p_M. Then the aim server $Server_{i\beta}$ is selected according to some strategy and the corresponding transition $t_{M\beta}$ is triggered. It expresses the process of an active VM moves form $Server_{i\alpha}$ to $Server_{i\beta}$ through live migration.

The other one is to distinguish between the privileged and non-privileged instruction. When a task can be processed by non-privileged instructions, it needn't invoke the system calls of the practical machines. Otherwise, the transition $t_{privileged}$ is triggered, and the underlying system calls are invoked and VMM does the instruction conversion.

Figure 5 only depicts one cluster in VDC, taking the GSPN model in Figure 5 as the basic unit, we can easily build the whole dependability models for VDCs.

In this section, we take RBD model as a top-level model and GSPN model as each inner-level model to build the comprehensive models for VDCs, RBD model can easily models the whole performance of VDCs while GSPN model as a powerful tool handles complex behaviors such as live migration. With this hierarchical method we simplify the combined model, hence it can be easier solved in the next section.

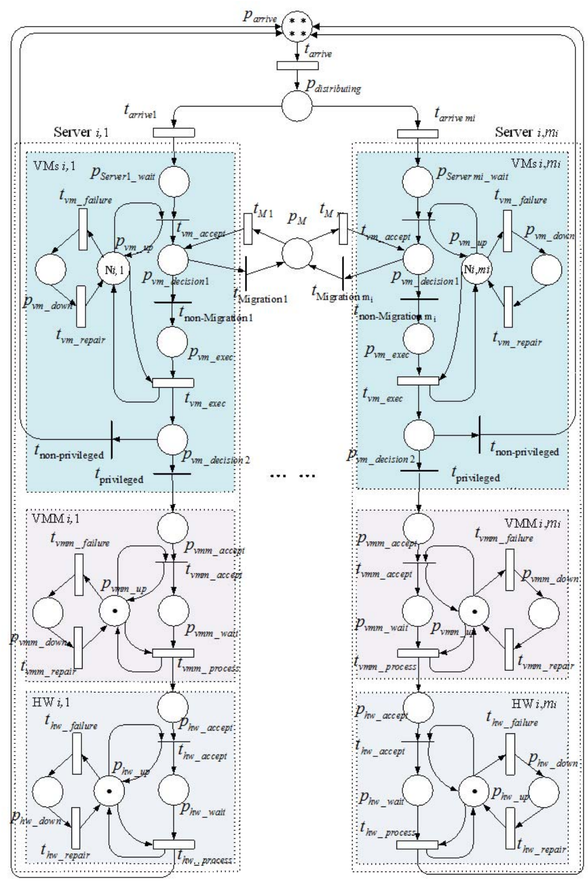

Fig. 5. The GSPN model of the $Cluster_i$

IV. Dependability Analysis

A. Reliability Analysis

1) Solving the Models for Reliability

Reliability [25-27] is expressed by the probability that the system will perform its required function under given conditions for a stated time interval.

Reliability can be calculated by $R(t) = Prob\{T > t\}$, where T denotes the lifetime of the component (the cumulative time until it fails) and $R(t)$ denotes the reliability at time t [27]. The existing study of reliability usually ignores the repair process. In engineering, the lifetime is often assumed to conform to the exponential distribution. So the reliability can be expressed as follows:

$$R(t) = 1 - Prob\{T \le t\} = e^{-\lambda t} \tag{1}$$

Where λ is the average failure rate, and $0 \le R(t) \le 1$. According to (1), we can get the reliability of each component of $Server_{ij}$:

$$R_{HW_{ij}}(t) = e^{-\lambda_{HWij} t},\ R_{VMM_{ij}}(t) = e^{-\lambda_{VMMij} t},\ R_{VM_{ij}}(t) = e^{-\lambda_{VMij} t}.$$

The virtual machines on the same server usually have the near average failure rate. Here we denote the failure rate of the VM on $Server_{ij}$ as λ_{VMij}. According to the RBD model in Figure 3, the reliability of $Server_{ij}$ is

$$R_{Server_{ij}} = \left(1 - \left(1 - R_{VM_{ij}}\right)^{n_{ij}}\right) R_{VMM_{ij}} R_{HW_{ij}} \tag{2}$$

There are m_i servers that mutually backup in $Cluster_i$, and these servers may be heterogeneous. Then l sites and network modules make up the VDC. Therefore the reliability of the VDC R_{VDC} can be expressed by

$$R_{VDC} = \prod_{i=1}^{l} \left\{ \left(1 - \prod_{j=1}^{m_i} \left(1 - R_{Server_{ij}}\right)\right) \cdot R_{C_i} \right\} \tag{3}$$

From the expressions (2) and (3), we can see that the number of virtual machines on each server n_{ij} is an important factor which affects the reliability of VDC. The average number of virtual machines on each server are called *consolidation ratio*, which is an important parameter and will be study later.

2) Relation between Reliability and Consolidation Ratio

We assume that the average number of virtual machines on each server, i.e. consolidation ratio is N. For a simpler presentation, we assume the average reliability of virtual machines is R_{VM}. In fact, the practical VDC usually employs virtualization products and services from the same vendor for the convenience of deployment and management. The reliability of virtual machines in a VDC has little difference. Then we can get the following theorem.

Theorem 1: *The reliability of virtual data center is positive correlated with the consolidation ratio, and there is a definite upper bound of reliability no matter how the consolidation ratio increases. The upper bound can be expressed as*

$$\lceil R_{VDC} \rceil = \prod_{i=1}^{l} \left\{ \left(1 - \prod_{j=1}^{m_i} \left(1 - R_{VMM_{ij}} R_{HW_{ij}}\right)\right) \cdot R_{C_i} \right\} \tag{4}$$

Proof: From the formula (2), we have

$$R_{Server_{ij}}(N) = \left(1 - \left(1 - R_{VM}\right)^{N}\right) R_{VMM_{ij}} R_{HW_{ij}}$$

Then, $R_{Server_{ij}}(N+1) - R_{Server_{ij}}(N)$

$$= R_{VM}\left(1 - R_{VM}\right)^{N} R_{VMM_{ij}} R_{HW_{ij}} \ge 0$$

According to the formula (3),

$$R_{VDC}(N) = \prod_{i=1}^{l} \left\{ \left(1 - \prod_{j=1}^{m_i} \left(1 - R_{Server_{ij}}(N)\right)\right) \cdot R_{C_i} \right\}$$

Since $0 \le R_{Server_{ij}}(N) \le R_{Server_{ij}}(N+1) \le 1$, we obtain

$$R_{VDC}(N+1) - R_{VDC}(N) > 0.$$

Hence, $R_{VDC}(N)$ is positive correlated with N.

And then, $\lceil R_{Server_{ij}} \rceil = \lim_{N\to\infty} R_{Server_{ij}}(N) = R_{VMM_{ij}} R_{HW_{ij}}$

Substituting it to the formula (3), we have the upper bound of the reliability of VDC as

$$\lceil R_{VDC} \rceil = \prod_{i=1}^{l} \left\{ \left(1 - \prod_{j=1}^{m_i} \left(1 - R_{VMM_{ij}} R_{HW_{ij}}\right)\right) \cdot R_{C_i} \right\} \quad \square$$

Raising the consolidation ratio contributes to the reliability of the VDC. But consolidating too many virtual machines on a server will bring the sacrifice of performance and increase the cost. So to get an optimal consolidation ration needs to consider the various factors comprehensively.

B. Availability Analysis

1) Solving the Models for Availability

Availability is expressed by the probability that the system can perform its required function under given conditions at a stated instant of time t.

Assuming $Y(t)$ is the normal operating state of the system at time t and S_N is the normal working state set, the *point availability* [28] at time t can be defined as

$$PA(t) = Prob\{\, Y(t) \in S_N \,\} \tag{5}$$

In engineering, *intrinsic availability* [27] is widely used, which can be expressed by

$$IA = MTBF / (MTBF + MTTR) \tag{6}$$

Where $MTBF$ is the mean time between failures and $MTTR$ is the mean time to repair. For a VDC, providing normal services needs the collaboration and interaction among different clusters. Let $A_{Cluster_i}$ and A_{C_i} represent the availability of the server cluster $Cluster_i$ and the network module C_i (see Figure 2). Then the availability of VDC can be expressed by

$$A_{VDC} = \prod_{i=1}^{l} \left(A_{Cluster_i} \cdot A_{C_i} \right) \tag{7}$$

For the network module C_i, let λ_{C_i} be the failure rate and μ_{C_i} be the repair rate. Under the assumption of exponential life distribution, the expectation value of the time between failures $MTBF = 1/\lambda_{C_i}$ and the expectation value of the time to repair $MTTR = 1/\mu_{C_i}$.

According to (6), we have

$$A_{C_i} = \mu_{C_i} / (\lambda_{C_i} + \mu_{C_i}) \tag{8}$$

For the $Cluster_i$, because the complex characteristics and dynamic mechanisms such as live migration, the availability can't be directly computed by such an easy method. Figure 5 gives the GSPN model of *Cluster$_i$*. In order to solve the model, the parameters should be assigned, including mainly the failure rate and repair rate of each component, which correspond to the firing rates of the failure and repair transitions. By solving the model, we can get the transient and steady-state probability of all the states of the system. Then, the point availability or intrinsic availability of the cluster can be obtained.

2) Relation between Availability and Workload

Except for the failure rate and repair rate, workload is also a potential factor to system availability. In one extreme case, when the workload exceeds the system process capacity, the system is too busy to be unavailable to any new application requests, even though the system is fault free. In VDC, live migration is usually used to avoid the unavailability caused by overload. The relation between availability and workload should be studied. We define the average workload as the average number of tasks processing in each server of the VDC. Let T denote the average workload. In section 5, we will study the impact of T on the availability of VDC, after solving the GSPN model and obtain the availability.

V. Numerical Results and Discussions

In this section, we parameterize the models described, and solve the models for some numerical results. Then some rules are summarized and discussed based on the numerical results.

The failure rate λ and repair rate μ of different component should be set as model parameters. We set the failure rates of the virtual machine, VMM and hardware components according to their typical values of failure frequency. The repair rates are set depending on the difficulty level of repair process after failure. The parameters are shown in table 1. In practical VDC, the parameters can be obtained by measurement and estimation.

Table I. The model parameters

Parameters	Values (times/day)	Parameters	Values (times/day)
λ_{VM}	1/7	μ_{VM}	3
λ_{VMM}	1/30	μ_{VMM}	3
λ_{HW}	1/365	μ_{HW}	1
λ_{C}	1/365	μ_{C}	1

According to the formula (1-3), we can get the reliability of VDC. We study the reliability in unit time, i.e. $t=1$. In Figure 6, we plot the different reliability of the VDC when the consolidation ratio increases from 1 to 8. We can see from the figure that the reliability increases as the consolidation ratio, until it reaches an upper bound. We can see it agrees with the theorem 1.

There is another point worthy of special remark. We can see from the figure that certain consolidation ratio which is not very large is required to approach the upper bound of reliability. The reliability increases little after n=5 or 6. This is a useful rule. It indicates that, after the consolidation ratio exceeds a certain value, the action to improve the reliability by keeping increasing the consolidation ratio produces very little effect. Instead, it could lower the performance and increase the cost. Different colors in Figure 6 stand for the reliability curves of different VDC with 1, 10, 100 clusters. The curves reflect the decrease of reliability caused by the increase of system scale and complexity.

We solve the GSPN models shown in Figure 5 by substituting the parameters in table 1. The stochastic Petri net package (SPNP) [23] is used in our work. Using the formulas (7) and (8), the availability of the VDC can be obtained. Figure 7 shows the availability curves of the VDC with different average workload and different consolidation ratios. From the figure we can see that the availability of VDC decreases when increasing average workload. Moreover, when the average workload doesn't exceed the given consolidation ratio ($T \le N$), the availability maintains a fairly high value, approaching 0.9685. But when T>N, the availability decreases rapidly. This unavailability is caused by the overload at this point.

In addition, we can see that the availability is also positive correlated with the consolidation ratio. It is because that, when the consolidation ratio increases, there are more virtual machines to process the arrival tasks. In our current models, the degradation of performance caused by the increase of consolidation ratio has not been taken into account. It is one issue of our future work.

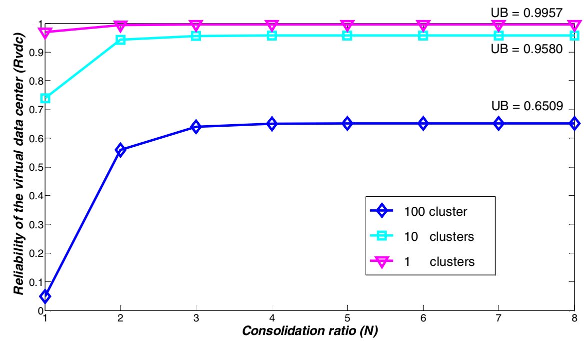

Fig. 6. Reliability of virtual data center

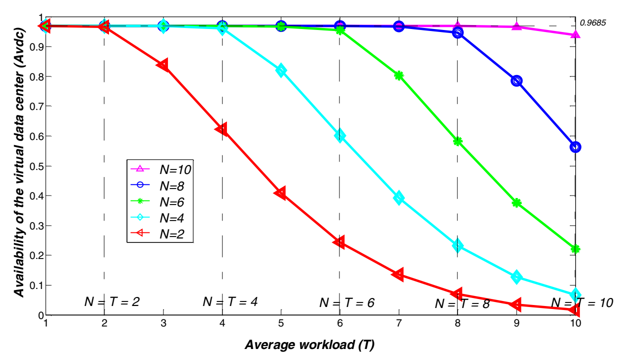

Fig. 7. Availability of the virtual data center

So to design more dependable VDCs, some rules should be pay attention to. The consolidation ratio, i.e. the average number of virtual machines on each server has a certain value to achieve leverage of the reliability and the cost, after exceeding the certain value, reliability has little space to increase but the cost increases a lot. To achieve high availability, the average workload should keep within certain value of consolidation ratio, after exceeding the certain value, availability decreases rapidly. In addition, the availability also has a positive correlation with the consolidation ratio. We can see from this section that the consolidation ratio is an important parameter to design more dependable VDCs.

VI. CONCLUSIONS

Virtual Data Center's significant merits such as server consolidation and live migration lead to its popularity in Cloud Computing and Internet services. With the sharp increase of server nodes, the evaluation of dependability becomes a challenge.

In spite of widespread interest in data center's network, few work researches on the modeling of VDCs, and as we know, all existed researches only analyze virtualization system with only few servers. In this paper, we make first attempt to model and evaluate the dependability of VDC as a whole. We propose the hybrid dependability models combining RBD and GSPN models using hierarchical method, which both simplifies solving the problems and takes advantages of both models. Then we give the calculation expressions of dependability attributes, including reliability and availability. Moreover, we study the impact on dependability brought by the characteristics and mechanisms of virtualization such as consolidation backup and live migration. In addition, we discuss the relation between reliability and consolidation ratio, and the relation between availability and the workload in our work. And some useful rules are summarized and discussed, which can provide references for the design and construction of more dependable VDCs.

From the evaluation expressions and the numerical results above, we can see that the hybrid models of VDCs can powerfully express the complex characteristics and mechanism of virtualization, which combine the advantages of two types of models. The expressions given in section IV can generally evaluate the dependability of VDCs, and according to the numerical results, we find that the reliability is positive correlated to consolidation ratio as well as the availability positive correlated to consolidation ratio. In addition, to design more dependable VDCs, the consolidation ratio, i.e. the average virtual machine number on a physical server is concerned to be a key parameter.

Our work gives a preliminary analysis of dependability including availability and reliability, the maintainability or safety aren't discussed in this paper, Future work will include the evaluation of maintainability or of issues such as the performance degradation caused by the increase of consolidation ratio.

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