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Modélisation d'un réseau 5G par des réseaux de Pétri pour estimer sa résilience

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Avec l'évolution des technologies des télécommunications, les réseaux 5G sont censés, par rapport aux générations précédentes, répondre d'une part à des besoins d'échange de données plus importants des utilisateurs finaux, d'autre part à des nouveaux besoins liés au développement de services exigeants en termes de latence et de fiabilité ou au large déploiement d'objets connectés. Cependant, cette évolution de réseau entraîne davantage de risques potentiels pour le réseau 5G et elle entraîne également une complexité croissante de la gestion du réseau. De ce fait, la fiabilité et la résilience sont essentielles pour les opérateurs afin d'assurer le lancement des services. Pour évaluer la résilience, il est nécessaire de comprendre la structure de la 5G et de construire un modèle basé sur celle-ci. Cet article aborde ce problème en proposant un modèle basé sur un réseau de Pétri, un outil bien connu pour la modélisation des systèmes. Nous introduisons un réseau de Pétri étendu pour modéliser l'infrastructure physique, l'infrastructure virtuelle, les services de réseau, leurs comportements et leurs dépendances. Ce modèle pourrait être appliqué à l'analyse de la disponibilité des services de communication, à l'estimation de la fiabilité des services de communication et à la résilience. Nous présentons dans un premier temps le résultat sur l'estimation de la disponibilité du réseau vis-à-vis de la défaillance des éléments du réseau. Ce résultat montre le potentiel du modèle à être appliqué à l'évaluation de la résilience d'un système de télécommunication.

Mots-clés : Petri Net, 5G networks, resilience, availability, modeling, simulation

1 Introduction

Telecommunication networks are becoming indispensable for modern production and living. Facing the diverse and high requirements from a broad vertical industry, 5G and beyond networks are expected to be both efficient and reliable. Keeping such systems at good performance during their whole life cycle is essential for service providers and operators. To meet the different requirements and high demand, Network Function Virtualization (NFV) should be introduced for both RAN (Radio Access Network) and CN (Core Network) to better adjust the network configuration to the requirements. Thus, the resilience of the telecommunication networks is no longer an issue only for physical infrastructure but also for virtual elements and service delivery [ASVW17]. This study builds a Petri Net-based model to describe 5G networks. This model could be applied to communication service availability analysis, service reliability estimation, and network resilience evaluation [Say20], and it will be helpful for operators to deploy vertical 5G services.

2 Petri Net-based network model

2.1 Timed Stochastic Colored Petri Net

Petri Net is a widely used technique for tracking systems' states, dynamics, and constraints. It can also be used to describe a complex system like 5G. As defined in [Mur89], Petri Net is a 5-tuple $\mathcal{N} = \langle P, T, F, W, M_0 \rangle$. P is a finite set of places representing different states of a system. Places are graphically presented in circles. T is a finite set of transitions representing the state-changing process. Transitions are presented in rectangles. F is a finite set of arcs with $F \subseteq (P \times T) \cup (T \times P)$. W is a multi-set of arcs $F \rightarrow \mathbb{N}$

assigning the weight to inputs and outputs of a transition. $M_0 = P \rightarrow \{m_1, m_2, \dots, m_{|P|}\}$ assigns the initial marking of the graph. Tokens of the graph describe the dynamic and concurrent activities of systems.

The classical Petri Net is not directly applicable to telecommunication systems. We need to introduce some extensions. A Stochastic Petri Net includes a new set $R = \{r_1, r_2, \dots, r_{|T|}\}$, representing the firing rate of each transition. This extension could be applied to describe a failure process. In order to describe a time-dependent process, for instance, the packet transmission, Timed Petri Nets are introduced. A new set $D : T \rightarrow \mathbb{Q}_0^+$ associates each transition with a specific non-negative number to represent the time factor. Colored Petri Net [Jen92] attaches a value to tokens to distinguish them. This extension adds the following items: Σ , a finite color set; C , a function defining the type of tokens allowed in a place; G : a function associating a transition with a Boolean expression; E , an arc expression; I , an initialization function.

Combining the extensions above, we use a Timed Stochastic Colored Petri Net (TSCPNet) to describe the 5G system. Such a TSCPNet is a multi-tuple: $TSCPNet = \langle \Sigma, P, T, F, W, m_0, C, G, E, I, R, D \rangle$.

2.2 Composition of the telecommunication network system

We divide a 5G network into three layers (network service, virtualization, and physical infrastructure).

Network service: We consider an End-to-End service with an ordered Service Function Chain (SFC). In this system, the user equipment sends service request packets to the SFC. We assume every packet conveys the same data size, and its SFC always follows the same order of VNFs. An SFC defines a series of VNFs connected by links. The transport network is considered a perfectly reliable system (with redundant paths).

VNF and virtualization: A VNF is an application consisting of several microservices. Each microservice is considered a sub-function. In this paper, we adopt container-based virtualization. We assume that Kubernetes is used to automate deployment and manage containerized applications in 5G NFV. Pods are the smallest deployable units. One pod is composed of one container, and it corresponds to one replica of the microservice. Pods are running on Kubernetes nodes in the form of physical machines.

Infrastructure and resources: The infrastructures used to deliver an end-to-end function are physical links and physical nodes. Each node (physical machine) has a certain amount of CPU, storage, and network resources. Pods can only be hosted on a node with enough resources.

In this virtualized network, Kubernetes is an enabler for the orchestration and management to keep its normal operation. To evaluate the system resilience under failure, we consider self-healing operation [Chu20]. Kubernetes can regularly detect the healthiness of the pods or nodes. In case of failure, they will be terminated, and new ones will be created. Other operations such as auto-scaling, in which Kubernetes detects particular indicators and changes the deployment manners accordingly, will be studied in future work.

2.3 Telecommunication network modeling

The top layer Petri Net, as presented in Fig. 1 depicts the packet processing in an SFC with m VNFs.

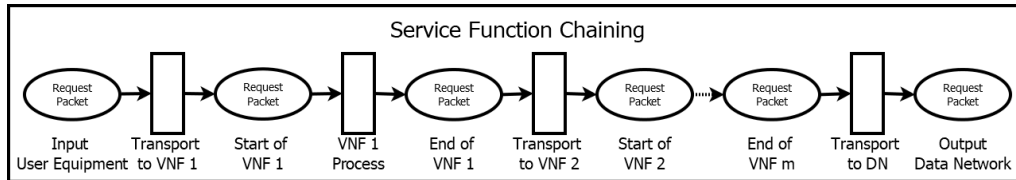


FIGURE 1: Petri Net of SFC example.

The VNF i process transition $t_{VNF\ i\ process}$ is expanded in Fig. 2a. Inside a VNF i , there are n microservices embedded in containers. When a packet gets into this i -th VNF, an immediate transition $t_{service\ selection}$ routes them to the microservice k it looks for. Then this packet is inserted into a packet list at the place $p_{MS\ queue\ k}$ waiting to be processed. Microservice k transition $t_{MS\ k-transition}$ is enabled as long as there is at least one microservice pod with enough capacity. After finishing the task, the packet will be processed at next microservice in the current VNF or in the next VNF.

Microservices level Petri Net explains the transition $t_{MS\ k-transition}$ in detail, as shown in Fig. 2b. The transition $t_{MS\ bounding}$ couples the first packet of the packet list with an available pod. To complete the task,

the packet borrows certain computation resources. An output packet token will be sent to p_{bounded} packets after a certain processing duration. Finally, the transition $t_{\text{MS process}}$ verifies the completion of the service.

Failures can also be described by a Petri Net. In this paper, we explain a pod failure process. This is one of the most common failures that affect the virtualized system's performance. As shown in Fig. 2c, a stochastic transition $t_{\text{Stochastic pod failing process}}$ connects the state change of a pod token. Kubernetes launches a liveness probe once in a while to detect the healthiness of pods. This time interval is called periodsecond of the probe. If a pod is unhealthy, Kubernetes starts self-healing. The transition $t_{\text{Pods termination}}$ consumes the failed token after a graceful termination time. Transition $t_{\text{Pods creation}}$ will create a pod containing the same microservice on an available node with enough resources.

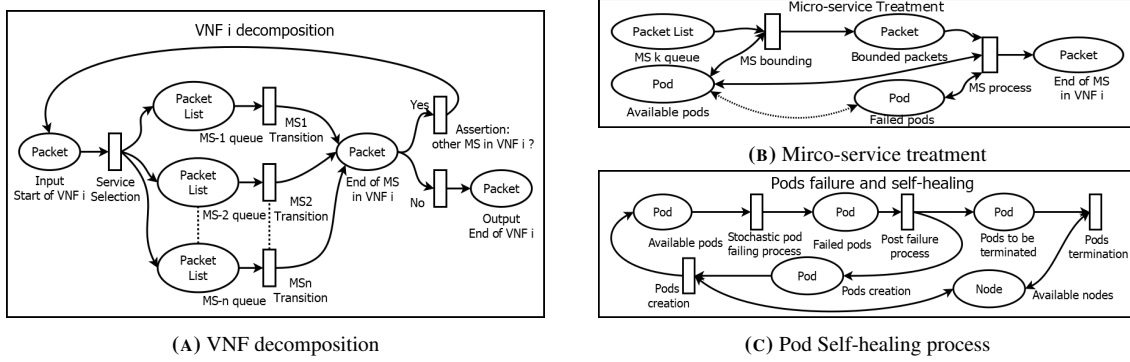


FIGURE 2: Different levels of Petri Net-based model

3 Network availability estimation

The first step of our work is to apply the model to estimate the system resilience by looking at the virtualization and infrastructure layer without mapping them to telecommunication services. By doing so, the availability of the network to provide services is estimated. The failures of nodes and pods are identified as the main risks to the system. When a failure occurs, Kubernetes will launch self-healing. We consider a system with one VNF that consists of two microservices. We assume that these microservices container pods are deployed on the same Data Center with four physical nodes (servers). For load-balancing reasons, each microservice initially has three identical pod replicas. Other parameters are given in Table 1.

TABLE 1: VNF parameters

| Parameter | Value |
|------------------------------------|--------------------------|
| Pod failure rate | MTTF = 1258 hours |
| Pod termination time | 30 seconds (fixed value) |
| Average time for pod instantiating | 5 seconds |
| Node(server) failure rate | MTTF = 8760 hours |
| Node(server) repair rate | MTTR = 0.5 hours |
| Average time for node creation | 1 second |
| Node(server) capacity | 3 pods per node seconds |

A microservice is considered available at time t if the number of pods is greater than the desired replica quantity. The uptime of a microservice is the duration of time that a microservice is available. Then the average availability of a microservice i can be calculated as:

$$A_i = \frac{\text{microservice } i \text{ uptime}}{\text{total simulation time}}$$

In the first situation, we assume the self-healing detection is immediate, i.e., a failure on a pod or node can be detected without delay. We assume that the two microservices are from the same VNF supplier and

are managed by the same Kubernetes Master. We simulate the microservice behavior over 50 years to get a high probability of failure in each iteration. It takes about two hours to run 20000 simulations (to get a higher confidence level) with CPN Tools. We take the average value of microservices' uptime as the final result. The results in Fig. 3a show that if the desired replica quantity is three pods, then the availability of a single microservice is 99.9996712% (5 nines). If the desired replica quantity is one pod (one pod is enough, but three initial pods only for redundancy reason), then the availability of this microservice achieves 9 nines (some URLLC services may require up to 8 nines according to 3GPP Release 16). The overall availability for the VNF (at least three available replicas for both microservice 1 and 2) is 99.9993523%.

In the second situation, the effect of self-healing probe frequency t_p on system availability is studied. The result is shown in Fig. 3b. We compare the overall VNF availability for t_p varying from 0 to 10 seconds. The longer the probe periodsecond, the lower the overall availability. The availability drops from 99.9993523% (5 nines) to 99.9987198% (4 nines) by changing immediate detection to 10 seconds. Thus, according to this result, the telecommunication network can consume less energy while satisfying the availability requirement by wisely optimizing the periodsecond if allowed.

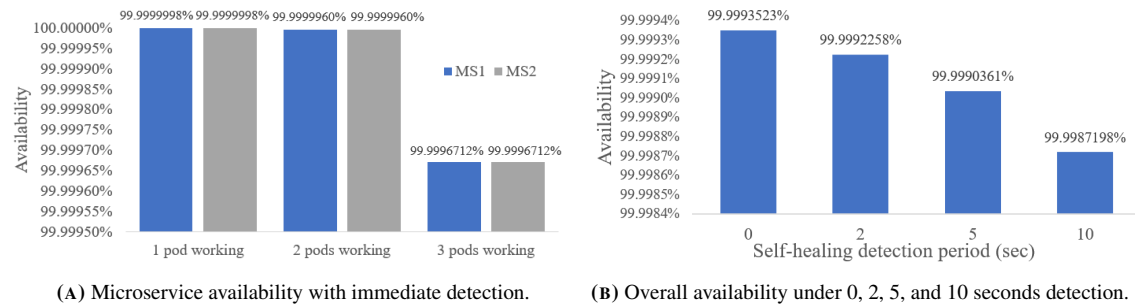


FIGURE 3: Simulation results

4 Conclusion

This paper presents a Petri Net-based model to analyze the performance and resilience of 5G networks. This model divides a 5G system into multiple layers and proves its ability to describe new features of 5G. The simulation results on self-healing show the prospects of this model on telecommunication network availability analysis. The results remain optimistic since other risks, such as network failure or maintenance are not fully considered. In addition, more precise parameters need to be collected from experts. For the next step, the auto-scaling use case will be carried out to complete the service-level reliability and resilience analysis and see how networks adapt to different traffic changes. We also intend to expand the use case from one single VNF to an SFC and apply the model to simulate a real use case from the verticals.

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