Cost-efficient Deployment Scheme for User and Control Plane Functions in Non-public Networks

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***Abstract*—Non-public networks (NPNs) have been considered as a promising technology to provide secure and customized services. There are several deployment options for NPNs according to the placement of network functions (NFs). To enhance the network performance, it is required to deploy more control plane NFs (CPFs) and user plane NFs (UPFs) in NPN. However, deploying more NFs can increase operating expenditure (OPEX) for the NPN operator. To assess this problem, this paper formulates a Markov decision process (MDP) and uses the policy iteration method to find the optimal policy. The simulation results show that the proposed scheme outperforms the comparison schemes in terms of the total reward.**

***Index Terms*—Non-public networks (NPNs), network function (NF) deployment, Markov decision process (MDP)**

I. Introduction

Non-public networks (NPNs) have been considered as a promising technology to provide secure and customized services. There are several deployment options for NPNs according to the placement of network functions (NFs). NPNs can be deployed as either 1) a stand-alone NPN (SNPN) or 2) a public network integrated NPN (PNI-NPN) [1]. In the case of SNPN, since it is a fully isolated network, all of the required NFs should be deployed within SNPN. On the other hand, PNI-NPN shares NFs with public networks, which can reduce OPEX. Specifically, as shown in Figure 1, there are three different models for PNI-NPN: 1) shared radio access network (S-RAN), 2) shared RAN and control plane NFs (CPFs) (S-CP), and 3) shared RAN, CPFs, and user plane NFs (UPFs) (S-CUP) [2]. In S-RAN, RAN is shared by the public network and CPFs are deployed in NPN. In S-CP, UPFs are only deployed in NPN, and CPFs are operated by the public network. In S-CUP, both UPFs and CPFs are operated by the public network and then logically decoupled using a data network name (DNN) or a network slice. As more NFs are deployed in NPN, network performance could be improved while operating expenditure (OPEX) for the NPN operator could be increased. To assess this problem, this paper formulates a Markov decision process (MDP) and uses the policy iteration method to find the optimal policy.

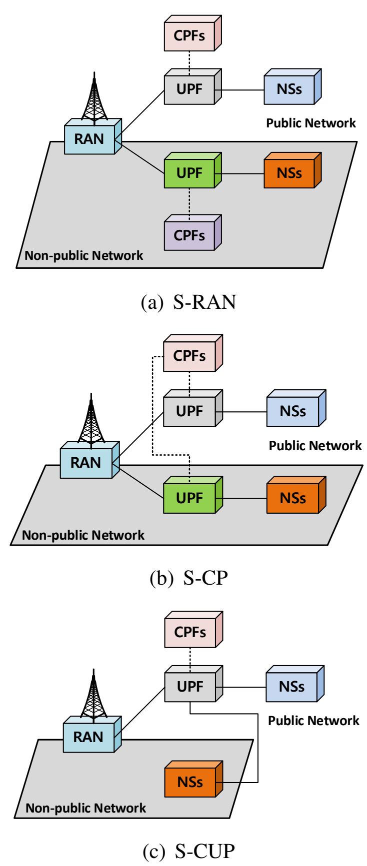

Fig. 1. Three different models for PNI-NPN

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II. System model

As shown in Figure 1, according to the operator's policy, CPFs and UPFs can be deployed in NPN or shared from public networks. Since CPFs and UPFs can be implemented as software instances, the NPN operator can allocate a certain amount of resources to each CPF or UPF instance during operation periods. If the NPN operator deactivates UPFs, it can reduce OPEX but the amount of packet processing (i.e., user plane performance) within NPN also can be reduced. This means that to guarantee the user plane performance even when there are lots of requests for packet data unit (PDU) sessions in NPN, more UPF instances should be activated. Compared to UPFs which are responsible for the user plane performance, CPFs are in charge of the control plane performance. The completion time is one of the important metrics of the control plane performance because the data transmission of the user plane can be performed after the completion of the control plane. If the NPN operator allocates more CPF instances, the completion time for the control plane procedure can be reduced. However, it can increase OPEX. Therefore, from the operator's perspective, it is important to determine the optimal policy considering both network performance in terms of user and control planes and OPEX simultaneously.

III. Markov decision process

In this paper, we assume that the NPN operator shares RAN with the public operator and determines the number of operating CPFs and UPFs at the time epochs of $\mathbf{T} = \{1, 2, 3, ...\}$ to minimize the cost function.

A. State

The state set $\mathbf{S}$ can be defined as

$$\mathbf{S} = \mathbf{C} \times \mathbf{U} \times \mathbf{S} \tag{1}$$

where $\mathbf{C}, \mathbf{U}$, and $\mathbf{S}$ denote the number of CPFs, UPFs, and PDU session requests in NPN, respectively.

First, $\mathbf{C}$ can be defined as

$$\mathbf{C} = \{0, ..., C_m\} \tag{2}$$

where c ($\in \mathbf{C}$) represents the number of CPFs and C_m is the maximum number of CPFs in the system model.

Moreover, $\mathbf{U}$ can be defined as

$$\mathbf{U} = \{0, ..., U_m\} \tag{3}$$

where u ($\in \mathbf{U}$) denotes the number of UPFs and U_m is the maximum number of UPFs in the system model.

In addition, $\mathbf{S}$ is represented by

$$\mathbf{S} = \{0, ..., S_m\} \tag{4}$$

where s ($\in \mathbf{S}$) is the number of PDU session requests and S_m is the maximum number of PDU session requests in the system model.

B. Action

Based on the current state, the action set can be defined as

$$\mathbf{A} = \{A_C, A_U\} \tag{5}$$

where A_C and A_U are the action sets for CPF and UPF instance scheduling, respectively. A_C can be defined as

$$\mathbf{A_C} = \{0, ..., C_m\} \tag{6}$$

where a_c ($\in \mathbf{A_C}$) denotes the number of CPF instances that the NPN operator operates during the next time epoch. A_U can be defined as

$$\mathbf{A_U} = \{0, ..., U_m\} \tag{7}$$

where a_u ($\in \mathbf{A_U}$) denotes the number of UPF instances that the NPN operator operates during the next time epoch.

C. Transition probability

Since all states are not dependent on the other states, the transition probability from the current state $S = [C, U, S]$ to the next state $S' = [C', U', S']$ can be described as

$$P[S'|S, A] = P[C'|C, A_C] \times P[U'|U, A_U] \times P[S'|S]. \tag{8}$$

We assume that the delays to initialize CPF and UPF instances follow exponential distributions and they are immediately terminated [3]. In addition, the transition probability of S can be determined based on the Poisson process [4].

D. Reward and Cost Functions

For the reward and cost functions, we consider the performance gain and OPEX. OPEX can be reduced when UPFs and CPFs are deactivated. In addition, the performance gain includes both user and control plane performance gains that can be achieved by activating UPFs and CPFs. Consequently, the total reward function, $r(s, a)$, is defined as

$$r(s, a) = w_0 g(s, a) - (1 - w_0) f(s, a) \tag{9}$$

where $g(s, a)$ is the reward function of performance gain and $f(s, a)$ is the cost function of OPEX. w_0 ($0 \leq w_0 \leq 1$) is a weight factor to balance $g(s, a)$ and $f(s, a)$.

When CPFs are activated, the completion time of the control plane procedures can be reduced. [1] In addition, when UPFs are activated, the amount of packet processing can be improved. Therefore, $g(s, a)$ can be represented as

$$g(s, a) = \begin{cases} m a_c, & \text{if } a = a_c \\ n a_u, & \text{if } a = a_u \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

where m and n are the weight factors for the amount of packet processing at each UPF and for the reduced completion time at each CPF.

[1] Although each CPF (e.g., SMF, AMF, PCF, etc.) has its own role in the control plane procedure, we just assume that more CPFs lead to reduced completion time. Specific control plane procedures according to each CPF activation will be analyzed in our future work.

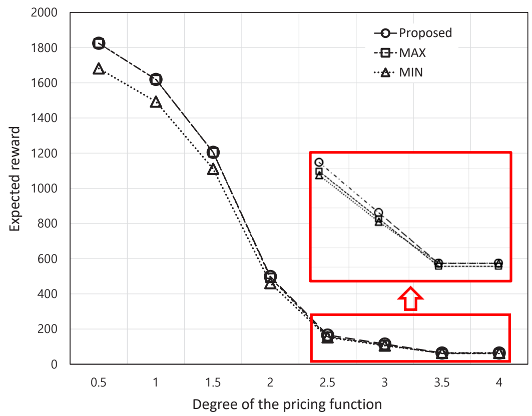

Fig. 2. Expected reward according to the degree of the pricing function.

On the other hand, $f(s,a)$ can be defined by

$$f(s,a) = \begin{cases} M(a_c), & \text{if } a = a_c \\ N(a_u), & \text{if } a = a_u \\ 0, & \text{otherwise} \end{cases} \tag{11}$$

where $M(x)$ and $N(y)$ mean the functions of OPEX according to the number of CPF and UPF instances (i.e., x and y), respectively. The function can be dependent on the pricing policy (e.g., linear, quadric, etc.). This means that according to the degree of the pricing function, the effect of the number of CPF and UPF instances can be changed.

Based on the above equations, to find the optimal policy, this paper utilizes a policy iteration algorithm.

IV. Simulation Results

To evaluate the performance, we conduct extensive simulations and compare the proposed scheme with the following two schemes: 1) MAX where the maximum number of CPFs and UPFs are activated, and 2) MIN where only one CPF and one UPF are activated. The default parameter settings are as follows. The maximum number of CPFs and UPFs is set to 5. In addition, the maximum number of PDU session requests is 10. Both λ_C and λ_U are set to 0.75. A weight factor w_0 is assumed to be 0.5.

Figure 2 shows the expected reward according to the degree of the pricing function. As shown in Figure 2, the expected reward becomes reduced as the degree of the pricing function increases because the cost function of OPEX increases in the total reward function. This means that the small number of CPFs and UPFs is only allowed due to the cost. When the degree of the pricing function has small values, the expected reward of MAX is higher than that of MIN because the performance gain is relatively more important in the total cost function. On the other hand, when the degree of the pricing function has large values, MIN has lower expected rewards due to the importance of OPEX. Compared to MAX and MIN schemes, the proposed scheme has the highest expected reward because it always finds the optimal policy to maximize the total reward function.

V. Conclusion

In this paper, a cost-efficient deployment scheme for control plane and user plane NFs in NPNs is introduced. To find an optimal policy, we formulate an MDP problem considering the network performance gain and OPEX for NPN operators. In our future work, specific operations of CPFs and UPFs and the detailed pricing policy of PNI-NPN scenarios will be considered for optimal deployment.

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