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Matching-Based Virtual Network Function Embedding for SDN-Enabled Power Distribution IoT

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***Abstract*—The power distribution internet of things (PD-IoT) has the complex network architecture, various emerging services, and the enormous number of terminal devices, which poses rigid requirements on substrate network infrastructure. However, the traditional PD-IoT has the characteristics of single network function, management and maintenance difficulties, and poor service flexibility, which makes it hard to meet the differentiated quality of service (QoS) requirements of different services. In this paper, we propose the software-defined networking (SDN)-enabled PD-IoT framework to improve network compatibility and flexibility, and investigate the virtual network function (VNF) embedding problem of service orchestration in PD-IoT. To solve the preference conflicts among different VNFs towards the network function node (NFV) and provide differentiated service for services in various priorities, a matching-based priority-aware VNF embedding (MPVE) algorithm is proposed to reduce energy consumption while minimizing the total task processing delay. Simulation results demonstrate that MPVE significantly outperforms existing matching algorithm and random matching algorithm in terms of delay and energy consumption while ensuring the task processing requirements of high-priority services.**

***Keywords*—power distribution internet of things; software-defined networking; virtual service orchestration; virtual network function embedding; priority-aware; matching theory**

I. INTRODUCTION

THE power distribution internet of things (PD-IoT) is a novel paradigm which deeply integrates power distribution grid and internet of things (IoT). The comprehensive perception, data fusion, and intelligent application of power distribution grid can be achieved with the support of PD-IoT through the global identification as well as the interconnection, intercommunication, and interoperability of the devices [1]. In recent years, to realize rapid deployment, on-demand customization, and flexible orchestration, power distribution grid services have increased the requirements for the carrying capacity of the substrate network infrastructure resources [2]. In traditional power communications, dedicated devices, e.g., firewalls, network address converters, and traffic classifiers, are utilized to provide different network functions, which lead to high price, poor scalability, and difficult management. With the development of software-defined networking (SDN) and network function virtualization (NFV) technologies, an open, low-cost, and scalable solution has emerged to enable the flexible orchestration of PD-IoT services.

SDN can separate the data plane and the control plane of the network, and use SDN controller to centrally control the network devices, which reduces network complexity and realizes flexible deployment of network resources [3], [4]. By utilizing virtualization technology, the service request in PD-IoT can be abstracted into a service function chain (SFC) composed of multiple virtual network functions (VNFs) [5], [6]. NFV deploys network functions on standardized servers in the form of software, and enables infrastructures, e.g., NFV nodes, in the substrate network to provide network resources for VNFs through the NFV management and orchestration (MANO) system [7], [8]. The PD-IoT which integrates SDN and NFV can reasonably embed multiple VNFs on different NFV nodes according to service priorities and load conditions, so as to configure network resources for services on demand as well as realize convenient and flexible service orchestration [9], [10]. However, the studies on VNF embedding for PD-IoT are still in its infancy. Several research challenges are summarized below.

- VNF selection conflict: VNFs select NFV nodes according to their respective preference lists. When more than one VNF selects the same NFV node, the conflict occurs, i.e., the selections of NFV nodes among different VNFs are coupled with each other. Therefore, the VNF selection problem is NP-hard and cannot be solved by traditional convex optimization methods. How to resolve the selection conflicts among different VNFs and realize low-complexity, high-efficiency, and stable VNF embedding is an urgent challenge.
- Coupling between VNF embedding and NFV energy consumption minimization: The NFV node needs to provide network resources for VNFs to process task, and the choice of VNF embedding directly affects the transmission energy consumption of the NFV node, and vice versa. The satisfaction of NFV nodes with VNFs needs to be taken into consideration, i.e., delay and energy consumption minimization require joint optimiza-

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tion to improve the system performance. However, the coupling between VNF embedding decision-making and NFV node energy consumption minimization is difficult to be described with a linear method, which makes the problem more complicated.
- Service priority and orderliness of VNF embedding: Due to the service differences, the corresponding SFCs have their priorities, and the service requests with higher priority need to be preferentially satisfied. If the priority is ignored, it may cause low-priority service request to preempt high-priority service request resources and the degradation of quality of service (QoS). Meanwhile, the VNFs of the same SFC need to process tasks in order, and the selection of the previous VNF will affect the delay and energy consumption of the subsequent VNFs. How to optimize VNF embedding with the consideration of the service priority and orderliness is another challenge.

To solve the above-mentioned challenges, we firstly define the utility function to minimize the weighted sum of the delay and the energy consumption. Then, considering the priorities of different services, we model the preference lists of the VNFs and the NFV nodes as the total task processing delay and the transmission energy consumption, respectively. Finally, according to the preference lists constructed by VNFs and NFV nodes as well as the order of VNFs in SFC, we propose a matching-based priority-aware VNF embedding (MPVE) algorithm to solve the problem of VNF selection conflicts among different VNFs based on the two-sided matching theory. The main contributions of this work are summarized as follows:

- We propose a priority-aware VNF embedding algorithm to solve the problem of the VNF selection conflicts by leveraging the two-sided matching theory. We model the preference lists of the VNFs and the NFV nodes as the total task processing delay and the transmission energy consumption, respectively.
- Based on the service priority, we jointly optimize the delay of VNF embedding and the energy consumption of NFV nodes. The tradeoff between task processing delay and the energy consumption can be dynamically balanced by adjusting VNF embedding strategy.
- Compared with existing algorithms, simulation results demonstrate that the proposed MPVE algorithm can achieve higher service performance and maximize the weighted cumulative utility function in terms of the total task processing delay and transmission energy consumption.

The remainder of this paper is organized as follows. Section II presents a brief review of the related work. Section III describes the system model and problem formulation. The MPVE algorithm is introduced in Section IV. Section V provides simulation results. Finally, Section VI concludes the paper.

II. RELATED WORKS

In PD-IoT, service orchestration is an important research direction. Many researchers have explored service orchestration methods to achieve service management and resource allocation. In [11], You *et al.* proposed an intelligent service orchestration architecture for the integration of multi-source data and multi-mode data, which is utilized to coordinate ubiquitous objects, create interconnected data, and realize general intelligence service. In [12], Cheng *et al.* proposed a hybrid service orchestration platform for Internet telephone network to meet the asynchronous dynamic interaction between mixed services and achieve the purpose of rapid orchestration. In [13], Castellano *et al.* proposed a distributed service orchestration algorithm for the heterogeneity of applications, which solves the problem of optimal sharing of resource pools among multiple service data objects. Although the above methods can maximize resource utilization in the existing environment, the control plane and the data plane are not separated. A new network function requires dedicated hardware equipment due to the tight coupling between function and hardware, which leads to the increased costs in terms of deployment, operation, and energy consumption.

Applying SDN and NFV to service orchestration is a promising approach to reduce the operation and maintenance cost of PD-IoT. In recent years, the embedding of VNF has been widely studied in academia. In [14], Kar *et al.* proposed a M/M/C queuing model-based heuristic algorithm to solve the energy-aware VNF embedding problem. In [15], Tajiki *et al.* proposed an energy-aware heuristic algorithm to improve energy efficiency under the constraints of delay and link utilization in SDN. In [16], Ruiz *et al.* proposed a genetic algorithm that solves VNF placement and chaining in a metro 5G optical network equipped with mobile edge computing (MEC) resources. However, the above-mentioned works only analyze resources according to the arrival order of SFC, without considering the differentiated requirements of PD-IoT, thus failing to achieve higher resource utilization. Moreover, these schemes ignore the VNF selection conflicts, resulting in poor performance of the PD-IoT services.

Matching theory, as an effective method to solve the conflict of terminal selection, has been gradually applied to the VNF embedding. In [17], Ghaia *et al.* proposed a stable matching algorithm to reduce the delay generated by embedding VNF on the virtual machine. In [18], Pham *et al.* proposed a matching algorithm to solve the VNF embedding problem by constructing a preference list based on system delay. In [19], Pham *et al.* proposed a VNF embedding framework based on the combination of Markov approximation and matching theory to minimize the cost of VNF placement through selecting the NFV node with the most available resources. However, the above-mentioned works only opitimize single performance parameter without the joint optimization of delay and energy consumption. Moreover, the previous works have not considered the heterogeneity of PD-IoT services, and cannot effectively guarantee the QoS requirements of high-priority PD-IoT services.

III. SYSTEM MODEL

In this section, we firstly introduce the VNF embedding for SDN-enabled PD-IoT framework. Then, we define the weighted cumulative utility function and construct the joint

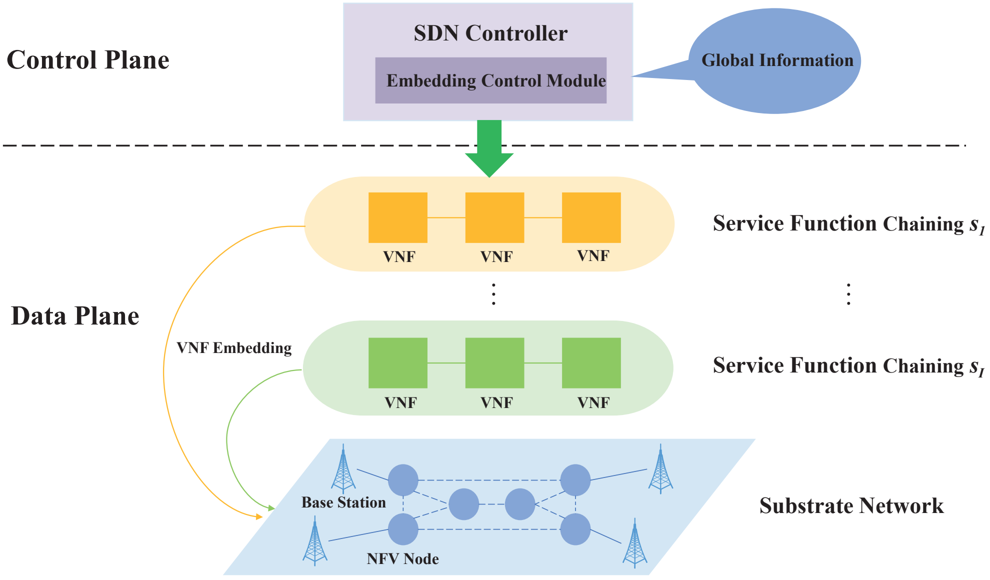

Fig. 1. VNF embedding for SDN-enabled PD-IoT framework.

optimization model of delay and energy consumption. Finally, the problem formulation is introduced.

A. Network Model of VNF Embedding for SDN-enabled PD-IoT

The considered VNF embedding for SDN-enabled PD-IoT framework is shown in Figure 1, which consists of two planes, i.e., the control plane and the data plane. In the control plane, the SDN controller can obtain the global information (including service function resource requirements and substrate network condition information, etc.) of PD-IoT, and achieve the management and control of the data plane. Moreover, the SDN controller is equipped with an embedding control module, which orchestrates the placement of VNFs from different SFCs and configures traffic routing among consecutive VNFs for load balancing. In the data plane, there exist several SFCs and a substrate network. Different SFCs that are constructed according to services requirements and application scenarios can support various types of PD-IoT services. PD-IoT service customization and isolation can be achieved by embedding different VNFs on multiple physical nodes in the substrate network.

In this paper, each service request can be represented by a SFC. The set of SFCs is denoted by $\mathcal{S} = \{s_1, \ldots, s_i, \ldots, s_I\}$. Assume that there exist J VNFs in s_i, the set of which is defined as $\mathcal{F}_i = \{f_{i,1}, \ldots, f_{i,j}, \ldots, f_{i,J}\}$. Let $f_{i,j}$ represent the j-th VNF in s_i, and the realization of SFC requires to process tasks in sequence according to the order of VNFs in the chain. The total number of VNFs of all SFCs is $F = IJ$, and the set is represented as $\mathcal{F} = \{\mathcal{F}_1, \ldots, \mathcal{F}_i, \ldots, \mathcal{F}_I\}$.

In addition, the substrate network is represented by an undirected graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$, where $\mathcal{N} = \{1, \ldots, n, \ldots, N\}$ denotes the set of physical nodes that can provide computing services and $\mathcal{L}$ represents the set of links connecting any pair of nodes in the network, denoted by $\mathcal{L} = \{(n, n') \mid n, n' \in \mathcal{N}\}$. (n, n'), n, and n' are physical link, initial node, and terminal node, respectively. We define $\mathcal{L}_i$ to represent the set of physical links successfully mapped by the virtual link in s_i. It is assumed that all the physical nodes in the substrate network can support VNF embedding, i.e., all physical nodes are considered to be NFV nodes. The binary variable $x_{i,j,n} \in \{0, 1\}$ is defined to indicate whether VNF $f_{i,j}$ of SFC s_i is embedded on NFV node n or not, which is given by

$$x_{i,j,n} = \begin{cases} 1, & \text{VNF } f_{i,j} \text{ of SFC } s_i \text{ is embedded on} \\ & \text{NFV node } n, \\ 0, & \text{otherwise.} \end{cases} \tag{1}$$

Similarly, we define the binary variable $y_{i,(j,j')}^{(n,n')}$ to denote whether the virtual link (j, j') of SFC s_i is mapped on the physical link (n, n') or not, which is given by

$$y_{i,(j,j')}^{(n,n')} = \begin{cases} 1, & \text{the virtual link } (j, j') \text{ of SFC } s_i \text{ is mapped on} \\ & \text{the physical link } (n, n'), \\ 0, & \text{otherwise,} \end{cases} \tag{2}$$

where $y_{i,(j,j')}^{(n,n')} = x_{i,j,n} x_{i,j',n'}$.

B. Models of Delay and Energy Consumption

In this paper, when the virtual link (j, j') is mapped on the physical link (n, n'), its transmission bandwidth is denoted as $B_{(j,j')}^{(n,n')}$. Thus, the transmission rate is given by

$$r_{(j,j')}^{(n,n')} = B_{(j,j')}^{(n,n')} \log_2(1 + \frac{p_n g_{(j,j')}^{(n,n')}}{N_0}), \tag{3}$$

where p_n is the transmission power of the NFV node n. $g_{(j,j')}^{(n,n')}$ and N_0 represent the channel gain and the noise power, respectively.

We assume that the task size in SFC s_i is a_i (Mbits). The unit complexity of the task data processed on VNF $f_{i,j}$ is $\lambda_{i,j}$ (CPU cycles/bit), and the computing capacity of NFV node n is represented as c_n (GHz). Therefore, the computing delay of the VNF $f_{i,j}$ embedded on the NFV node n, and the transmission delay of the virtual link (j,j') mapped on the physical link (n,n') can be expressed as

$$\tau_{i,j,n}^{c} = \frac{a_i \lambda_{i,j}}{c_n}, \tag{4}$$

$$\tau_{i,(j,j')}^{tra,(n,n')} = \frac{a_i}{r_{(j,j')}^{(n,n')}}. \tag{5}$$

For SFC s_i, the total delay for completing a task processing is the sum of computing delay and transmission delay, which is given by

$$\tau_i = \sum_{f_{i,j} \in \mathcal{F}_i} x_{i,j,n} \tau_{i,j,n}^{c} + \sum_{(n,n') \in \mathcal{L}_i} y_{i,(j,j')}^{(n,n')} \tau_{i,(j,j')}^{tra,(n,n')}. \tag{6}$$

In addition, the transmission energy consumption of the virtual link $(j, j‘)$ in SFC s_i mapped on the physical link (n,n') is given by

$$e_{i,(j,j')}^{(n,n')} = p_n \tau_{i,(j,j')}^{tra,(n,n')}. \tag{7}$$

The total transmission energy consumption for completing a task processing of s_i is given by

$$E_i = \sum_{(n,n') \in \mathcal{L}_i} y_{i,(j,j')}^{(n,n')} e_{i,(j,j')}^{(n,n')}. \tag{8}$$

In PD-IoT, service request delay and transmission energy consumption are key indicators for judging system performance. To further reduce the VNF task processing delay and energy consumption, we consider the priorities of different SFCs, and define the weighted cumulative utility function U as

$$U = \sum_{s_i \in \mathcal{S}} w_i [\alpha \exp(-\tau_i) + \beta \exp(-E_i)], \tag{9}$$

where α and β represent the weights corresponding to delay and energy consumption, respectively, and w_i is the priority of SFC s_i. A larger w_i indicates a higher service priority.

C. *Problem Formulation*

The objective of the VNF embedding optimization problem is to maximize the weighted cumulative utility function U by optimizing the embedding strategy for each VNF $f_{i,j}$ of the SFC s_i. The VNF embedding problem **P1** is formulated as

$$\begin{aligned} \mathbf{P1}: \ & \max_{\{x_{i,j,n}\}} U \\ \text{s.t.} \ & C_1: \sum_{n \in \mathcal{N}} x_{i,j,n} = 1, \ \forall f_{i,j} \in \mathcal{F}_i, \\ & C_2: \sum_{(n,n') \in \mathcal{L}_i} y_{i,(j,j')}^{(n,n')} = 1, \ \forall f_{i,j} \in \mathcal{F}_i. \end{aligned}$$

For any service request that is successfully served, the constraints C_1 and C_2 need to be satisfied. C_1 represents that each VNF $f_{i,j}$ should be embedded on one and only one NFV node n. C_2 represents that each virtual link (j,j') has one and only one successfully mapped physical link (n,n').

IV. MATCHING-BASED PRIORITY-AWARE VNF EMBEDDING ALGORITHM

In this section, we firstly introduce the relevant content of matching theory and transform the optimization problem into a two-sided matching problem between VNFs and NFV nodes. Then, we investigate the implementation process of the proposed MPVE algorithm. The detailed process is described as follows.

A. *Problem Transformation*

Based on the concepts of matching theory [20] , we have the definition as below:

Definition 1: A matching ϕ is a one-to-one correspondence from the set $\mathcal{F} \bigcup \mathcal{N}$ onto itself, which is denoted by $\phi : \mathcal{F} \bigcup \mathcal{N} \longrightarrow \mathcal{N} \bigcup \mathcal{F}$. For $f_{i,j} \in \mathcal{F}$, $\phi(f_{i,j}) \in \mathcal{N}$ and for $n \in \mathcal{N}$, $\phi(n) \in \mathcal{F}$. $\phi(f_{i,j}) = n$ if and only if $\phi(n) = f_{i,j}$, which means that VNF $f_{i,j}$ is embedded on NFV node n.

We transform **P1** into a two-sided matching problem, where VNFs represent one side and NFV nodes represent the other side.

The preference value of VNF $f_{i,j}$ for NFV node n, i.e., $\theta_{i,j}(n)$, is defined as the total weighted delay of VNF $f_{i,j}$ embedded on VNF node n, which is given by

$$\theta_{i,j}(n) = w_i \alpha \exp(-[\tau_{i,j,n}^{c} + \tau_{i,(j-1,j)}^{t,(\phi(f_{i,j-1}),n)}]). \tag{10}$$

When the first VNF of SFC s_i is embedded on the NFV node n, there is no link mapping, and the transmission delay is 0, i.e., if $j = 1$, $\tau_{i,(j-1,j)}^{t,(\phi(f_{i,j-1}),n)} = 0$. VNF $f_{i,1}$ selects NFV node n to be embedded based on the processing delay. $\phi(f_{i,j-1}) = n^*$ represents that the $(j-1)$-th VNF and NFV node n^* are successfully matched, which is equivalent to $x_{i,j-1,n^*} = 1$, i.e.,

$$\phi(f_{i,j-1}) = n^* \Longleftrightarrow x_{i,j-1,n^*} = 1. \tag{11}$$

The preference value of NFV node n for VNF $f_{i,j}$ is the weighted transmission energy consumption $\theta_n(f_{i,j})$ of VNF $f_{i,j}$ embedded on NFV node n, which is given by

$$\theta_n(f_{i,j}) = w_i \beta \exp(-e_{i,(j-1,j)}^{(\phi(f_{i,j-1}),n)}). \tag{12}$$

If $j = 1$, the transmission energy consumption $e_{i,(j-1,j)}^{(\phi(f_{i,j-1}),n)} = 0$, $\theta_n(f_{i,1}) = w_i \beta$, i.e., NFV node n selects the VNF to be embedded according to the value of w_i.

B. *The Proposed MPVE Algorithm*

After setting up the preference lists of NFV nodes and VNFs, the joint optimization of delay and energy consumption is carried out by leveraging the proposed MPVE algorithm.

The proposed MPVE algorithm is summarized in Algorithm 1, which consists of three phases, i.e., initialization (Line 3-4), preference list construction (Line 6-7), and iterative matching (Line 8-24).

Algorithm 1 The Proposed MPVE Algorithm

```
Input: $\mathcal{F}$, $\mathcal{N}$.
Output: $\phi$.
    Phase 1: Initialization
    Initialize $\mathcal{N}_j = \mathcal{N}$, $\phi = \emptyset$.
for $j = 1 : J$ do
    Phase 2: Preference List Construction
    The $j$-th VNFs calculate the preference values toward to NFV node $\forall n \in \mathcal{N}_j$ based on (10), and obtain the preference lists.
    NFV nodes $\forall n \in \mathcal{N}_j$ calculate the preference values toward to VNFs based on (12), and obtain the preference lists.
    Phase 3: Iterative Matching
    Define $\Omega$ as the set of $j$-th VNF.
    while $\Omega \neq \emptyset$ do
        for $j \in \Omega$ do
            $f_{i,j}$ proposes to its most preferred NFV node $n$ among who have not rejected it in its preference list.
        end for
        for $n \in \mathcal{N}_j$ do
            if $n$ receives a proposal from $f_{i,j}$, and prefers $f_{i,j}$ to its current partner $f_{k,j}$ then
                $n$ rejects $f_{k,j}$ and chooses $f_{i,j}$ to be its new candidate, i.e., $\phi(n) = f_{i,j}$.
                Remove $f_{i,j}$ from $\Omega$ and add $f_{k,j}$ into $\Omega$.
                $f_{k,j}$ updates its preference list by removing $n$.
            else
                $n$ rejects $f_{i,j}$ and hold $f_{k,j}$ as its candidate continually, i.e., $\phi(n) = f_{k,j}$.
                $f_{i,j}$ updates its preference list by removing $n$.
            end if
        end for
    end while
    $j = j + 1$.
end for
```

- Initialization phase: Initialize the sets of all available NFV nodes as $\mathcal{N}_j = \mathcal{N}$, $\phi = \emptyset$.
- Preference list construction phase: Calculate the preference values of all available NFV nodes and the j-th VNF in all SFCs based on (10) and (12), and sort the preference values in descending order to construct a preference list.
- Iterative matching phase: In the first iteration, every VNF $f_{i,j}$ would propose to its most preferred NFV node based on the established preference list. If any NFV node n receives proposal from only one VNF $f_{i,j}$, the requested NFV node n would hold the VNF $f_{i,j}$ as its candidate. Otherwise, any NFV node n that has received proposals from more than one VNF would choose the most preferred VNF based on its preference list and reject other VNFs. Next, any VNF $f_{i,j}$ that has been previously rejected would propose to its new choice n', which is the most preferred NFV node among those who have not rejected it. If NFV node n' has not held any candidate, the selection procedure of VNFs is the same as described before. Otherwise, NFV node n' will compare the held candidate with all newly received proposals and only accept the most preferred VNF based on its preference list. The matching iteration would end when every VNF has already been matched with a NFV node.

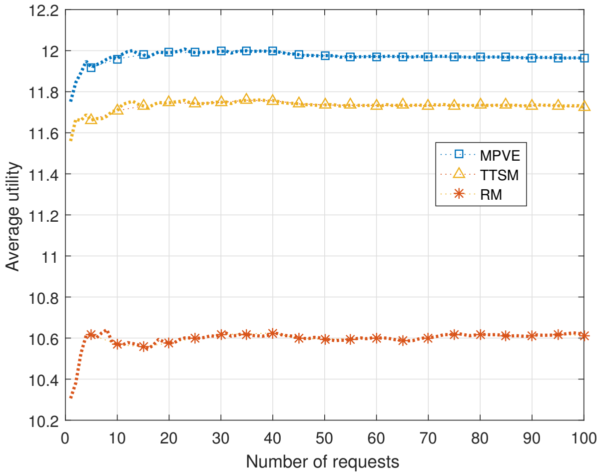

Fig. 2. Average utility versus the number of requests.

V. SIMULATION ANALYSIS

In this section, we evaluate the proposed MPVE algorithm through simulations. We consider a medium-scale network with 50 NFV nodes and 5 SFCs. The number of service requests is set as 100. The channel gain is defined as $g_{(j,j')}^{(n,n')}$=$A_0 l_{(n,n')}^{-2}$, where A_0= −17.8 dB [21] and $l_{(n,n')}$ is the distance between n and n'. The other detailed simulation parameters [22]–[25] are shown in Table I. We consider two existing algorithms for comparison. The first one is the traditional two-sided matching algorithm named TTSM [26], in which the priority of SFC is neglected. The second one is the random matching algorithm named RM [27], which allows the VNFs to be randomly embedded on different NFV nodes.

TABLE I
PARAMETER SETTING.

Parameter	**value**
Number of SFCs I	5
Number of VNFs J	10
Number of NFV nodes N	50
Transmission power p_n	100 W [22]
Task size a_i	$[3.9, 4.1]$ Mbits
Unit complexity$\lambda_{i,j}$	1000 CPU cycle/bit
Node computing capacity c_n	$[20, 40]$ GHz [25]
Bandwidth B	2 MHz
Noise power N_0	-114 dBm

Figure 2 shows the average utility versus the number of requests. Compared with TTSM and RM, simulation results demonstrate that MPVE improves the performance of average utility by 2.05% and 12.72%, respectively. The reason is that MPVE establishes the preference lists of VNF and NFV nodes by considering the service priorities, and therefore the optimal matching can be achieved. However, TTSM and RM have not taken into account the priority, which makes them difficult to realize utility maximization. Besides, it may cause low-priority services to preempt the resources of high-priority services, which degrades the performance degradation of delay and energy consumption. The details are shown in Figure 3 and Figure 4.

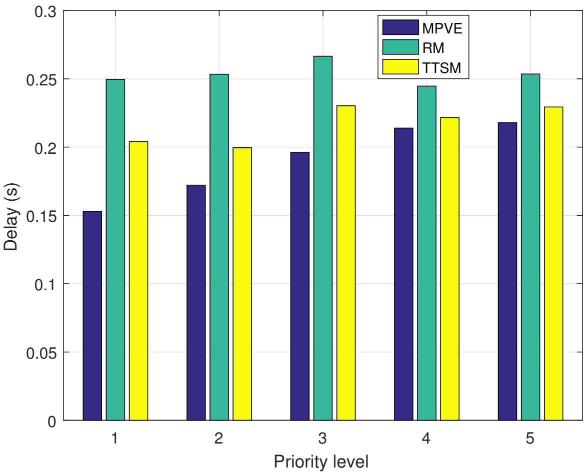

Fig. 3. Delay versus priority.

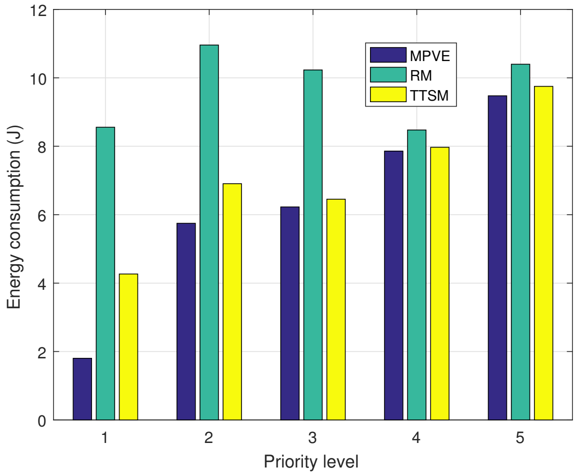

Fig. 4. Energy consumption versus priority.

Figure 3 and Figure 4 show the delay and energy consumption versus priority, respectively. We set 5 priority levels, in which priority level 1 indicates that the priority of the SFC is ranked first, i.e., the highest priority, and priority level 5 indicates that the priority of the SFC is ranked fifth, i.e., the lowest priority. Simulation results show that the performance of proposed MPVE decreases monotonously with the increase of priority. Specifically, the delay and energy consumption performance of high-priority services is better than that of low-priority services. By contrast, the performance of different services in TTSM and RM changes randomly due to the ignorance of priority. In addition, the proposed MPVE significantly outperforms comparison algorithms in terms of delay and energy consumption.

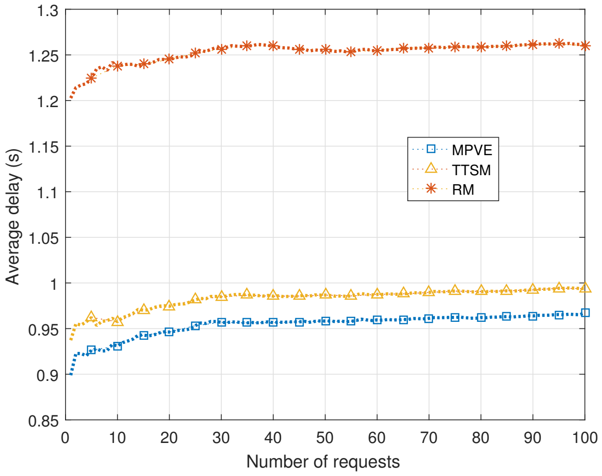

Fig. 5. Average delay versus the number of requests.

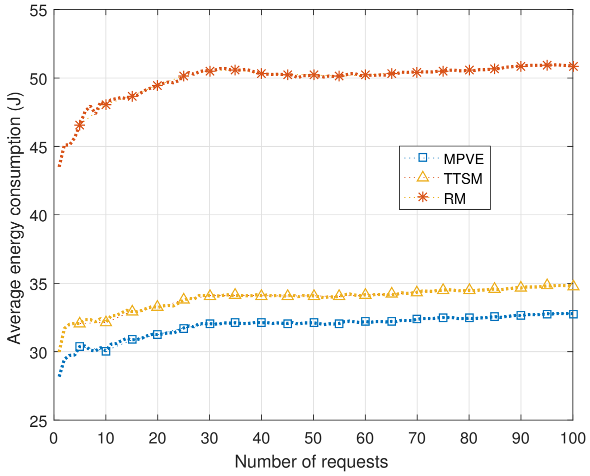

Fig. 6. Average energy consumption versus the number of requests.

Figure 5 and Figure 6 show the average delay and energy consumption versus the number of requests, respectively. The proposed MPVE outperforms TTSM and RM in terms of delay by 2.67% and 23.52%, respectively. Compared with the TTSM and RM, MPVE reduces the energy consumption by 5.83% and 35.59%, respectively. The reason is that MPVE improves the overall performance through jointly optimizing the delay and the energy consumption.

VI. CONCLUSION

In this paper, we proposed a novel VNF embedding algorithm named MPVE for SDN-enabled PD-IoT with different services. Simulation results demonstrate that MPVE can effectively improve the overall performance of utility, substantially reduce delay and energy consumption. The proposed MPVE outperforms TTSM and RM in terms of average utility by 2.05% and 12.72%, respectively. Compared with existing TTSM and RM algorithms, the average delay achieved by MPVE is reduced by 2.67% and 23.52%, respectively, while the energy consumption is reduced by 5.83% and 35.59%, respectively. Besides, the performance of high-priority services is better than that of low-priority services in the proposed MPVE algorithm. In the future work, we will consider the joint optimization of delay and energy consumption with incomplete information in VNF embedding problem.

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