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Energy consumption optimization-based joint route selection and flow allocation algorithm for software-defined networking

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Abstract Software-defined networking (SDN) is expected to dramatically simplify network control processes, enable the convenient deployment of sophisticated networking functions, and support user applications with guaranteed quality of service (QoS). To achieve data packet transmission between two non-adjacent switches in SDN, an efficient route selection algorithm should be designed. In this paper, we consider the data transmission of multiple user flows over SDN. Under the assumption that flow splits at intermediate switches are allowed, we jointly study the route selection and flow allocation problem. To stress the problem of resource competition among various user flows, we apply network virtualization technology and propose a virtual network architecture based on the design of an optimal joint route selection and flow allocation algorithm. Jointly considering the transmission performance of multiple user flows and stressing the importance of energy consumption at transmission links and switches, we formulate the total energy consumption of user flows and design an optimization problem that minimizes the energy consumption, subject to data transmission and service requirement constraints of the flows. Because the formulated optimization problem is an NP-complete problem that cannot be conveniently solved, we transform it into a minimum-cost commodity flow problem and solve the problem by using an N-algorithm. Numerical results demonstrate the effectiveness of the proposed algorithm.

Keywords software-defined networking, virtualization, route selection, flow allocation, energy consumption

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1 Introduction

The rapid development of broadband data services poses challenges to network architecture and management mechanisms. Traditional Internet architecture and technologies can hardly meet increasing service requirements due to the tightly coupled control and date plane, inflexible network architecture, and complicated network and service management mechanisms [1]. To overcome the drawbacks of traditional Internet technologies and offer user services in a more efficient and effective manner, software-defined networking (SDN) technology has been proposed [2, 3].

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In SDN, the control plane is separated from the data plane. One or multiple controllers are introduced in the control plane to conduct the control and management of data forwarding devices in the data plane, such as routers and switches, in a centralized manner. On the other hand, data forwarding devices in SDN are merely required to execute the network strategies received from the controllers and are no longer involved in network control. Benefitting from the centralized and efficient management of controllers and the relatively simple function requirement of forwarding devices, SDN is expected to dramatically simplify network control processes, enable the convenient deployment of sophisticated networking functions, and support user applications with guaranteed quality of service (QoS) [4].

To enhance the data transmission performance of networks and improve the utilization of network resources, network virtualization technology is proposed [5]. By abstracting and mapping physical network infrastructures into logically isolated virtual networks, network virtualization technology enables a more flexible allocation of network resources as well as the integration of heterogeneous network architectures and services. The integration of network virtualization and SDN promises to facilitate network innovation by providing an efficient framework to enable cooperative control and scheduling of network resources [6].

To achieve data packet transmission between two non-adjacent switches, referred to as the source switch and destination switch, one or multiple suitable routes consisting of intermediate switches should be selected. Because various intermediate switches and the transmission links connecting adjacent switches may offer different transmission characteristics, designing optimal route selection algorithms is of particular importance; in particular, it may significantly affect user QoS and network performance [7]. Furthermore, we assume that a flow split at intermediate switches is allowed, i.e., the data packets belonging to one user flow are allowed to be partitioned into multiple sub-flows and transmitted from a source switch to destination switch via various paths through the network. Under this assumption, routing and flow allocation strategies can be jointly designed in order to improve the performance of data transmission.

In this paper, we consider the data transmission problem of multiple user flows in SDN and stress the joint route selection and flow allocation problem under the assumption that flow splits are allowed. To achieve flexible resource management of multiple user flows in the network, we propose a virtual network architecture based on the design of a joint route selection and flow allocation algorithm. Jointly considering the transmission performance of multiple user flows and stressing the importance of energy consumption at transmission links and switches, we formulate the total energy consumption of user flows and design an optimization problem that minimizes the energy consumption subject to data transmission and service requirement constraints of the flows. The formulated optimization problem is transformed into the class of minimum-cost commodity flow problems and is solved by using an N-algorithm.

The major contributions of this paper are summarized as follows:

• Route selection schemes have already been designed for single user flow in SDN [8–10]. In this paper, we study the joint route selection and flow allocation problem of both a single flow and multiple flows. To tackle the resource competition problem among multiple flows, we design a virtual network architecture in which each virtual network is designed for each user flow; then, a network slice of each user flow can be created by applying the proposed joint route selection and flow allocation algorithm.

• The route selection problem and resource allocation problem of user flows in SDN have already been studied in [11–17]. In this paper, under the assumption that flow splits at intermediate switches are allowed, we jointly consider the route selection and flow allocation problem of user flows in SDN and design a joint optimal strategy for all the flows.

• To characterize the transmission performance of multiple user flows and achieve energy efficient transmissions, we examine the energy consumption of all user flows and formulate the joint route selection and flow allocation problem in SDN as an energy consumption minimization problem. Because the optimization problem formulated is an NP-complete problem, which cannot be conveniently solved, we transform the problem into a minimum-cost commodity flow problem that can then be solved by using an N-algorithm.

The remainder of this paper is organized as follows. Section 2 presents an overview of related works. Section 3 describes the system model considered in this paper and the proposed virtual network architecture. In Section 4, the energy consumption optimization problem is formulated. In Section 5, we consider the case of a single flow and design the optimal joint route selection and flow allocation strategy by solving the formulated optimization problem. In Section 6, we extend the case of single flows (considered in Section 5) to multiple user flows and design the corresponding optimal joint route selection and flow allocation strategy. Simulation results are presented in Section 7. Finally, we conclude this paper in Section 8.

2 Related work

In recent years, the problem of route selection in SDN has been studied, and several routing algorithms have been proposed. In [8], the authors propose a probabilistic QoS routing mechanism for SDN. By making use of Bayes' theorem and the Bayesian network model, the link probability is examined, and the route with high link probability is selected under the given bandwidth constraints. The authors of [9] propose a hybrid hierarchical architecture, which contains both an intra-area control layer and inter-area control layer with each layer having its own area controllers. Based on the architecture, a fast reroute mechanism is presented in which the area controller of the intra-area control layer employs Dijkstra's algorithm to select the main path, while the controller in the inter-area control layer is responsible for route selection across various areas. In [10], the authors consider an SDN scenario that realizes policy-aware network functions such as intrusion detection, access control, and load balancing via specified middlebox devices and propose a joint middlebox selection and routing scheme that maximizes the throughput of a specified set of sessions.

While previous research [8–10] mainly focuses on route selection for a single user flow in a practical SDN, a number of user flows may transmit simultaneously between various switches; hence, the problem of route selection for multiple user flows should be considered. The authors of [11] consider resource requirements of multiple user flows in SDN. By defining transmission bandwidth and flow tables as resource requirements of user flows, the analytic hierarchy process (AHP) is applied to quantize the resource preferences of different user flows, and a resource preference-aware routing algorithm is proposed that matches each flow to the path with the largest preference degree. In [12], a multi-flow oriented packets scheduling problem is formulated with the objective of minimizing the total cost of content addressable memory occupation and remote packet processing, and an online distributed algorithm is proposed to obtain the optimal packet forwarding strategy.

The multicast route selection problem is also considered for SDN. The authors of [13] propose a new reliable multicast tree for SDN, named recover-aware Steiner tree (RST), which aims at minimizing both tree and recovery costs. Since finding an RST is highly challenging, the authors design an approximate algorithm, i.e., the recover-aware edge education algorithm, to solve the problem. In [14], to deal with the traffic engineering and flow table scalability problem, the authors propose a branch-aware Steiner tree (BST) for SDN, which jointly minimizes the bandwidth consumption and number of forwarding entries. In [15], the authors consider the transmission of a set of unicast sessions from a source to a destination, with each session having a QoS requirement on transmission throughput. Under the assumption that each session is associated with a collection of packet forwarding rules, a rule multiplexing scheme is proposed that allows the same set of rules to be deployed on the common nodes of multiple paths. Based on the proposed scheme, a joint route selection and rule placement strategy is designed to minimize the rule space occupation of all the sessions under QoS constraints.

Network virtualization technology and network function virtualization (NFV) technology can be applied in SDN to achieve efficient route selection and resource management. In [16], a multi-tenancy routing problem is studied. By applying network virtualization technology, a subnet is created for each tenant, and a QoS-aware routing scheme is proposed to maximize the minimum residue bandwidth of links. The authors of [17] study the multicast transmission mechanism of real-time video streaming services over SDN. Based on NFV technology, a transcoding function is deployed on a set of servers, switches, or routers, referred to as NFV nodes, and a multicast routing algorithm is proposed that minimizes the total routing cost and ensures each multicast flow traverses through the NFV nodes before reaching the destination.

While transmission throughput has been stressed by previous works, energy consumption is also an important factor affecting the transmission performance of user flows; in fact, recent research stresses energy consumption and energy saving issues in SDN. The authors of [18] present a survey of approaches reducing energy consumption of core networks and provide a taxonomy to classify different energy-aware approaches. The authors of [19] address the problem of optimizing power consumption in SDN and propose an energy-aware traffic engineering approach that minimizes the number of transmission links. In [20], the authors propose a shortest path algorithm for energy-aware routing in SDN with the goal of minimizing the energy consumption of the selected routes by turning off switches and links with a relatively low load.

In many previous research works, it was assumed that user flows cannot be split during the transmission process through source switches to destination switches. More specifically, for a certain switch, only one output link can be assigned to one user flow; however, when multiple output links of one switch are available, limiting flow transmission on one link may result in inefficient resource utilization, which is highly undesired. While Refs. [19, 20] stress energy consumption in SDN, they mainly tend to minimize the number of links and switches and fail to extensively examine the energy characterization on switches. In this paper, we assume that data packets of one flow are allowed to transmit from source switches to destination switches via multiple paths and jointly design a route selection and flow allocation scheme for multiple user flows in SDN.

3 System model and proposed virtualized network architecture

In this paper, we consider an SDN model consisting of one controller and a number of switches, also referred to as physical switches, and stress the data transmission scenario that user flows with a fixed traffic volume are required to transmit from source switches to destination switches. We denote the number of user flows by K, the source switch and destination switch of the kth user flow by S^k and D^k, respectively, and the traffic volume of the kth flow by F^k, where $1 \leqslant k \leqslant K$. When no direct transmission link between S^k and D^k exists, an optimal route selection algorithm should be designed. Furthermore, assuming that a flow split is allowed at intermediate physical switches, the route selection scheme should be jointly designed with a flow allocation algorithm to improve the transmission performance of user flows. Figure 1 shows the system model considered in this paper.

In the considered SDN scenario, we assume that the number of intermediate physical switches is N. For simplicity, we assume that the source switches and destination switches are not allowed to forward data packets for other user flows. To characterize the connection status between switches, we introduce binary connection identifiers. Let $\alpha_{\mathrm{s},i}^k$ denote the connection identifier between S^k and the ith physical switch denoted by S_i^{p}; we set $\alpha_{\mathrm{s},i}^k = 1$ if S_i^{p} is the adjacent node of S^k, otherwise, $\alpha_{\mathrm{s},i}^k = 0$, where $1 \leqslant i \leqslant N$, $1 \leqslant k \leqslant K$. Let $\alpha_{j,\mathrm{d}}^k$ denote the connection identifier between S_j^{p} and D^k; we set $\alpha_{j,\mathrm{d}}^k = 1$ if S_j^{p} is the adjacent node of D^k, otherwise, $\alpha_{j,\mathrm{d}}^k = 0$, where $1 \leqslant j \leqslant N$, $1 \leqslant k \leqslant K$. Similarly, let $\alpha_{i,j}$ denote the connection identifier between S_i^{p} and S_j^{p}; we define $\alpha_{i,j} = 1$ if S_i^{p} is the adjacent node of S_j^{p}, otherwise, $\alpha_{i,j} = 0$, where $1 \leqslant i, j \leqslant N$, $i \neq j$. In this paper, we assume that the network topology of SDN is given, i.e., $\alpha_{\mathrm{s},i}^k$, $\alpha_{j,\mathrm{d}}^k$, and $\alpha_{i,j}$ are known constants.

To achieve route selection and flow allocation of multiple user flows, we apply network virtualization technology and propose a virtual network architecture by mapping the given physical network into multiple virtual networks with each virtual network corresponding to one user flow. More specifically, the physical switches in the network are mapped into one or multiple virtual switches, and the physical links of the network are mapped into one or multiple virtual links that logically connect virtual switches. The virtual switches and virtual links, which are responsible for transmitting one user flow, constitute the virtual network of the particular user flow. We further apply multi-dimensional network slicing technology [21] where the resources of the virtual networks, i.e., virtual switches and virtual links, are segmented into numerous network slices with each slice offering a data transmission service for one particular user

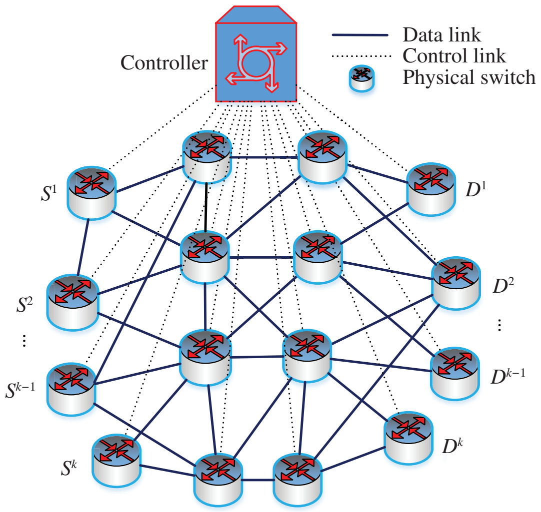

Figure 1 (Color online) System model.

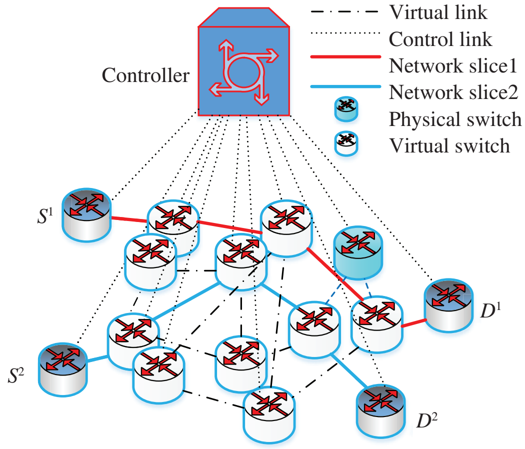

Figure 2 (Color online) Proposed virtual network architecture.

flow. For convenience, we refer to the network slice assigned to the kth flow as the kth network slice, which is denoted by NS^k. Figure 2 shows the proposed virtual network architecture.

To map the physical network into virtual networks, the physical resource constraints should be considered. For instance, since the virtual switches corresponding to one physical switch share the transmission resources of the physical switch, they should be subject to the capacity constraint of the physical switch. Similarly, the virtual links corresponding to one physical link should also be subject to the capacity constraint of the physical link. In addition, when different user flows pose various data rate requirements, only the physical links satisfying the rate constraints are qualified to transmit the corresponding user flows; thus, only the corresponding virtual links and the associated virtual switches can be selected to form the virtual network of the particular user flows.

It is important to mention that the problem of resource mapping from a physical network to a virtual network is of particular importance since it may significantly affect resource utilization and network performance. In this paper, we assume that the virtual network architecture is available for offering data transmission of multiple user flows and focus on the optimal design of route selection and flow allocation strategies of user flows.

4 Energy consumption optimization problem formulation

In this section, we formulate the joint route selection and flow allocation problem of SDN as an energy consumption minimization problem.

4.1 Energy consumption formulation

In this paper, the physical switches in the network are mapped into one or multiple virtual switches, and the physical links in the network can be mapped into their corresponding virtual links. For convenience, we denote $L_{i,j}^{\mathrm{v},k}$ as the virtual link of the kth user flow, which corresponds to the physical link connecting S_i^{P} and S_j^{P}, denoted by $L_{i,j}^{\mathrm{P}}$, and $x_{i,j}^k \in \{0,1\}$ as the route selection and flow allocation variable of the kth user flow on $L_{i,j}^{\mathrm{P}}$; $x_{i,j}^k = 1$ if the data packets of the kth user flow transmit through $L_{i,j}^{\mathrm{P}}$, i.e., NS^k contains $L_{i,j}^{\mathrm{v},k}$, otherwise, $x_{i,j}^k = 0$. Let $f_{i,j}^k$ denote the amount of traffic belonging to the kth flow transmitting on $L_{i,j}^{\mathrm{P}}$, where $1 \leqslant i,j \leqslant N$, $i \neq j$, $1 \leqslant k \leqslant K$. Similarly, let $x_{\mathrm{s},i}^k \in \{0,1\}$ denote the route selection and flow allocation variable at S^k, i.e., $x_{\mathrm{s},i}^k = 1$ if the data packets of the kth user flow directly transmit from S^k to S_i^{P}. Let $f_{\mathrm{s},i}^k$ denote the amount of traffic belonging to the kth flow transmitting from S^k to S_i^{P}, where $1 \leqslant i \leqslant N$, $1 \leqslant k \leqslant K$. Let $x_{j,\mathrm{d}}^k \in \{0,1\}$ denote the route selection and flow allocation variable at S_j^{P}, which is the one-hop adjacent node of D^k, i.e., $x^k_{j,\mathrm{d}} = 1$ if the data packets of the kth user flow transmit directly from S^{p}_j to D^k, and let $f^k_{j,\mathrm{d}}$ denote the amount of traffic belonging to the kth flow transmitting from S^{p}_j to D^k. For convenience, let $L^{\mathrm{p},k}_{\mathrm{s},i}$ and $L^{\mathrm{p},k}_{j,\mathrm{d}}$ denote the link between S^k and S^{p}_i and the link between S^{p}_j and D^k, respectively.

Since virtual switches and virtual links are logical concepts, the energy consumption of virtual switches and virtual links indeed occur on the corresponding physical switches and links. When K user flows transmit from source switches to destination switches via multiple virtual switches, the total energy consumption required to transmit the user flows can be expressed by

$$E^{\mathrm{tot}} = \sum_{k=1}^{K} \left(\sum_{i=1}^{N} \sum_{j=1, j\neq i}^{N} x^k_{i,j} f^k_{i,j} E_{i,j} + \sum_{i=1}^{N} x^k_{\mathrm{s},i} f^k_{\mathrm{s},i} E_{\mathrm{s},i} + \sum_{j=1}^{N} x^k_{j,\mathrm{d}} f^k_{j,\mathrm{d}} E_{j,\mathrm{d}} \right), \tag{1}$$

where $E_{i,j}$ denotes the energy consumption for transmitting one bit through S^{p}_i to S^{p}_j via $L^{\mathrm{p}}_{i,j}$, where $1 \leqslant i, j \leqslant N$, $i \neq j$. $E_{i,j}$ can be expressed by [22]

$$E_{i,j} = E^{\mathrm{out}}_i + E^{\mathrm{in}}_j + E^{\mathrm{proc}}_j, \tag{2}$$

where E^{out}_i denotes the energy consumption for storing and transmitting one bit through the outport of S^{p}_i, E^{in}_j represents the energy consumption for receiving and storing one bit on the import of S^{p}_j, and E^{proc}_j denotes the energy consumption of processing one bit at S^{p}_j. E^{out}_i can be expressed by

$$E^{\mathrm{out}}_i = f^{\mathrm{rp}}(R^{\mathrm{out}}_i) E^{\mathrm{out,max}}_i, \tag{3}$$

where $E^{\mathrm{out,max}}_i$ denotes the maximum energy consumption at the outport of S^{p}_i, which is defined as the energy consumption for storing and transmitting data packets at the maximum rate of the outport. Without loss of generality, we assume that the maximum rate and maximum energy consumption of switch imports and outports are given by constants in this paper. Moreover, R^{out}_i in (3) denotes the rate on the outport of S^{p}_i, and $f^{\mathrm{rp}}(R^{\mathrm{out}}_i)$ represents a function of R^{out}_i, characterizing the energy consumption at the outport of S^{p}_i when the outport rate is R^{out}_i. By referring to [22], the function $f(x)$ can be defined as

$$f(x) = 0.00062x + 0.38. \tag{4}$$

Similarly, E^{in}_j in (2) can be expressed by

$$E^{\mathrm{in}}_j = f^{\mathrm{rp}}(R^{\mathrm{in}}_j) E^{\mathrm{in,max}}_j, \tag{5}$$

where $E^{\mathrm{in,max}}_j$ denotes the maximum energy consumption at the import of S^{p}_j, which is obtained when the transmission rate of the import reaches the maximum rate; R^{in}_j denotes the import rate of S^{p}_j. E^{proc}_j in (2) and can be formulated as

$$E^{\mathrm{proc}}_j = \frac{N_j}{2} E^{\mathrm{m}}_j + E^{\mathrm{a}}_j, \tag{6}$$

where N_j denotes the flow table size of S^{p}_j, E^{m}_j and E^{a}_j denote the unit energy consumption per bit for matching data packets with flow table items and taking actions at S^{p}_j, respectively. $E_{\mathrm{s},i}$ in (1) denotes the energy consumption for transmitting one bit through one source switch to S^{p}_i, which can be expressed as

$$E_{\mathrm{s},i} = E^{\mathrm{in}}_i + E^{\mathrm{proc}}_i. \tag{7}$$

Note that $E_{j,\mathrm{d}}$ in (1) denotes the energy consumption for transmitting one bit through S^{p}_j to one destination switch and can be expressed by

$$E_{j,\mathrm{d}} = E^{\mathrm{out}}_j. \tag{8}$$

It should be noted that when transmitting data packets from source switches and destination switches, energy consumption also occurs at both the source switches and destination switches; however, since this amount of energy consumption is fixed and is independent on both route selection and flow allocation, for simplicity, it is omitted in the energy consumption analysis conducted in this paper.

4.2 Optimization constraints

The optimal design of the joint route selection and flow allocation strategy should be subject to a number of constraints including flow conservation constraints at switches, capacity constraint of links, and route selection constraints.

1) Flow conservation constraints: While the data packets of user flows may transmit via various virtual switches and virtual links, flow conservation should be guaranteed at source switches, destination switches, and intermediate physical switches. More specifically, the amount of the output data packets at the source switch S^k should be equal to F^k, i.e.,

$$\sum_{i=1}^{N} x_{\mathrm{s},i}^{k} f_{\mathrm{s},i}^{k} = F^k,\ 1 \leqslant k \leqslant K. \tag{9}$$

At destination switch D^k, the amount of the input data packets should be equal to F^k, i.e.,

$$\sum_{j=1}^{N} x_{j,\mathrm{d}}^{k} f_{j,\mathrm{d}}^{k} = F^k,\ 1 \leqslant k \leqslant K. \tag{10}$$

At the intermediate switches, there is no traffic volume being created or destroyed; hence, the amount of traffic flows into the nodes should be equal to the amount of traffic flows that flows out, i.e.,

$$\sum_{i=1}^{N} x_{i,j}^{k} f_{i,j}^{k} = \sum_{i=1}^{N} x_{j,i}^{k} f_{j,i}^{k},\ 1 \leqslant j \leqslant N,\ 1 \leqslant k \leqslant K. \tag{11}$$

2) Capacity constraint: In this paper, we assume that each physical link has a capacity, representing the maximum amount of traffic that can be transmitted; hence, the traffic volume transmitting on various virtual links belonging to one physical link should not be greater than the capacity of the physical link, which can be expressed by

$$f_{\mathrm{s},i}^{k} \leqslant f_{\mathrm{s},i}^{k,\max},\ 1 \leqslant i \leqslant N,\ 1 \leqslant k \leqslant K, \tag{12}$$

$$f_{j,\mathrm{d}}^{k} \leqslant f_{j,\mathrm{d}}^{k,\max},\ 1 \leqslant i \leqslant N,\ 1 \leqslant k \leqslant K, \tag{13}$$

$$\sum_{k=1}^{K} x_{i,j}^{k} f_{i,j}^{k} \leqslant f_{i,j}^{\max},\ 1 \leqslant i,j \leqslant N,\ i \neq j,\ 1 \leqslant k \leqslant K, \tag{14}$$

where $f_{\mathrm{s},i}^{k,\max}$, $f_{j,\mathrm{d}}^{k,\max}$, and $f_{i,j}^{\max}$ denote the capacity of links $L_{\mathrm{s},i}^{\mathrm{p},k}$, $L_{j,\mathrm{d}}^{\mathrm{p},k}$, and $L_{i,j}^{\mathrm{p}}$, respectively.

3) Route selection and flow allocation constraints: Since virtual links are logical mappings of physical links, any virtual link can only be selected to transmit data packets if the corresponding physical link exists; hence, we can obtain the following route selection and flow allocation constraints:

$$x_{\mathrm{s},i}^{k} = 0,\ \text{if}\ \alpha_{\mathrm{s},i}^{k} = 0,\ 1 \leqslant i \leqslant N, 1 \leqslant k \leqslant K, \tag{15}$$

$$x_{j,\mathrm{d}}^{k} = 0,\ \text{if}\ \alpha_{j,\mathrm{d}}^{k} = 0,\ 1 \leqslant j \leqslant N, 1 \leqslant k \leqslant K, \tag{16}$$

$$x_{i,j}^{k} = 0,\ \text{if}\ \alpha_{i,j} = 0,\ 1 \leqslant i,j \leqslant N, i \neq j,\ 1 \leqslant k \leqslant K. \tag{17}$$

4.3 Optimization problem formulation

The energy consumption minimization-based joint route selection and flow allocation problem can be formulated as the following optimization model:

$$\min\ E^{\mathrm{tot}}(x_{\mathrm{s},i}^{k}, x_{i,j}^{k}, x_{j,\mathrm{d}}^{k}, f_{\mathrm{s},i}^{k}, f_{i,j}^{k}, f_{j,\mathrm{d}}^{k})\ \ \text{s.t.}\ \ \begin{aligned}[t] &\sum_{i=1}^{N} x_{\mathrm{s},i}^{k} f_{\mathrm{s},i}^{k} = F^k,\ 1 \leqslant k \leqslant K, \\ &\sum_{j=1}^{N} x_{j,\mathrm{d}}^{k} f_{j,\mathrm{d}}^{k} = F^k,\ 1 \leqslant k \leqslant K, \end{aligned}$$

$$\sum_{i=1}^{N} x_{i,j}^k f_{i,j}^k = \sum_{i=1}^{N} x_{j,i}^k f_{j,i}^k,\ 1 \leqslant j \leqslant N,\ 1 \leqslant k \leqslant K,$$
$$f_{\mathrm{s},i}^k \leqslant f_{\mathrm{s},i}^{k,\max},\ 1 \leqslant i \leqslant N,\ 1 \leqslant k \leqslant K,$$
$$f_{j,\mathrm{d}}^k \leqslant f_{j,\mathrm{d}}^{k,\max},\ 1 \leqslant j \leqslant N,\ 1 \leqslant k \leqslant K,$$
$$\sum_{k=1}^{K} x_{i,j}^k f_{i,j}^k \leqslant f_{i,j}^{\max},\ 1 \leqslant i,j \leqslant N,\ i \neq j,\ 1 \leqslant k \leqslant K,$$
$$x_{\mathrm{s},i}^k = 0,\ \text{if } \alpha_{\mathrm{s},i}^k = 0,\ 1 \leqslant i \leqslant N, 1 \leqslant k \leqslant K,$$
$$x_{j,\mathrm{d}}^k = 0,\ \text{if } \alpha_{j,\mathrm{d}}^k = 0,\ 1 \leqslant j \leqslant N, 1 \leqslant k \leqslant K,$$
$$x_{i,j}^k = 0,\ \text{if } \alpha_{i,j} = 0,\ 1 \leqslant i,j \leqslant N, i \neq j,\ 1 \leqslant k \leqslant K. \tag{18}$$

5 Solution to the proposed joint optimization problem: single user flow case

The optimization problem formulated in (18) is an NP-complete problem, which is difficult to solve using traditional optimization tools. In this section, we consider a relatively simple case; that is, a single user flow is transmitted from one source switch to its destination switch, and an optimal joint route selection and flow allocation scheme is designed. For convenience, we set $K = 1$ in the formulas derived in the previous sections. When transmitting a single user flow, since resource competition among user flows does not exist, the virtualization on switches and network links may not contribute extra performance enhancement. Hence, for simplicity, we assume that the mapping from a physical switch to a virtual switch is one-to-one.

To solve the route selection and flow allocation problem of single user flows, we transform the problem into the class of minimum-cost commodity flow problems and leverage graph theory [23]. A typical application of this problem involves reasonably assigning the commodity and obtaining the best delivery route from a factory to a warehouse, where the routes are subject to capacity and cost constraints. The minimum-cost commodity flow problem can be solved efficiently using an N-algorithm in a directed graph [24]. In the following subsections, a brief introduction to N-algorithms is presented, then the optimal route selection and flow allocation strategy is obtained by applying an N-algorithm.

5.1 Introduction to minimum-cost commodity flow problem

Let $G = (V, B)$ denote a directed road network consisting of a set of nodes $V = \{V_i\}$ and a set of edges $B = \{B_{i,j}\}$. The node V_i represents a mid-hub-city, and the edge $B_{i,j}$ represents the road connecting cities V_i and V_j. For edge $B_{i,j}$, we associate a capacity $C_{i,j}$, which denotes the maximum weight of commodities that can be transported on the road and a cost $b_{i,j}$, which denotes the transport cost of a unit weight commodity on the road.

Assume a batch of commodities with a total weight of $W_{\mathrm{s,d}}$ is required to be transported from V_{s} to V_{d}, where V_{s} and V_{d} denote the source and destination places of the commodities, respectively, e.g., one factory and a certain warehouse; moreover, assume that the commodities are allowed to be transported via different routes. We can formulate the minimum-cost commodity flow problem as follows:

$$\min_{w_{i,j}} \sum_{V_i, V_j \in V} w_{i,j} b_{i,j} \quad \text{s.t.}\ \ 0 \leqslant w_{i,j} \leqslant C_{i,j}$$
$$\sum_{V_j \in V} w_{i,j} - \sum_{V_j \in V} w_{j,i} = W_{\mathrm{s,d}},\ \text{if } V_i = V_{\mathrm{s}},$$
$$\sum_{V_j \in V} w_{i,j} - \sum_{V_j \in V} w_{j,i} = -W_{\mathrm{s,d}},\ \text{if } V_i = V_{\mathrm{d}},$$
$$\sum_{V_j \in V} w_{i,j} - \sum_{V_j \in V} w_{j,i} = 0,\ \text{if } V_i \neq V_{\mathrm{s}}, V_i \neq V_{\mathrm{d}}, \tag{19}$$

Table 1 Variable notations and description

The minimum-cost commodity flow problems		Proposed energy consumption optimization algorithm	
Variables	Description	Variables	Description
V_s	Factory	S^1	Source switch
V_d	Warehouse	D^1	Destination switch
$W_{\mathrm{s,d}}$	Total weight of commodities	F^1	Traffic volume
$C_{i,j}$	The maximum tolerable weight on road $B_{i,j}$	$f_{i,j}^{\max}$	Capacity of link $L_{i,j}^{\mathrm{p}}$
$b_{i,j}$	Transmission cost per unit weight on road $B_{i,j}$	$E_{i,j}$	Energy consumption of transmitting per bit on link $L_{i,j}^{\mathrm{p}}$
$w_{i,j}$	Commodity weight on road $B_{i,j}$	$f_{i,j}$	Amount of traffic transmitting on link $L_{i,j}^{\mathrm{p}}$

where $w_{i,j}$ denotes the weight of the commodity required to be transported from V_i to V_j. An N-algorithm can be applied to solve the above optimization problem. In an N-algorithm, we define the negative cost cycle C_0 as a circle, where the sum of the edge cost is negative.

The steps of the N-algorithm can be summarized as follows:

1. Find a feasible route in G: Find a feasible route for the commodities in G under the constraints described in (19), and characterize the route by the commodity weight of the edge $B_{i,j}$, i.e., $w_{i,j}$, and set $w = \{w_{i,j}\}$.

2. Create a complementary graph of G for a feasible route w: Given a feasible route w, create a complementary graph $G^{'}$ of G. Specifically, for any B_{ij}, if $C_{i,j} > w_{i,j}$, an edge $B'_{i,j}$ can be created with the capacity and cost being set as $C^{'}_{i,j} = C_{i,j} - w_{i,j}$ and $b'_{i,j} = b_{i,j}$, respectively. If $w_{i,j} > 0$, another edge $B^{'}_{j,i}$ is created whose capacity and cost are set as $C^{'}_{j,i} = w_{i,j}$ and $b'_{j,i} = -b_{i,j}$, respectively.

3. Search a negative cost cycle C_0 in $G^{'}$: Search whether there exists any negative cost cycle C_0 in G; if one exists, divide the edges of C_0 into two categories, i.e., C_0^+ and C_0^-. If the direction of the edge $B_{i,j}$ in $G^{'}$ is the same as that in G, set the edge in C_0^+, i.e., $B_{i,j} \in C_0^+$, otherwise, set $B_{i,j} \in C_0^-$, and increase the weight of the commodities along the direction of the negative cost cycle so that the total cost of transporting commodities can be reduced. If there is no other negative cost cycle, the algorithm terminates.

4. Modify the commodity weight assignment in the feasible route: Define

$$\delta = \min\left\{\min_{B_{i,j}\in C_0^+}(C_{i,j} - w_{i,j}), \min_{B_{i,j}\in C_0^-}(w_{i,j})\right\}.$$

The new weight is set as $w' = \{w'_{i,j}\}$, where $w'_{i,j}$ is given by

$$w'_{i,j} = \begin{cases} w_{i,j} + \delta, & B_{i,j} \in C_0^+, \\ w_{i,j} - \delta, & B_{i,j} \in C_0^-, \\ w_{i,j}, & B_{i,j} \notin C_0. \end{cases} \tag{20}$$

5. Set $w = w'$. Return to Step 2.

5.2 N-algorithm-based optimization solution

Applying an N-algorithm to solve the optimal route selection and flow allocation strategy of a single flow transmitting from S^1 to D^1, we map the considered SDN topology into a capacity-cost network $G = (V, B, C, b)$. The nodes in V represent physical switches, and the edges in B represent the physical links between adjacent physical switches; C denotes the maximum traffic volume that the physical links can transmit, and b represents the energy consumption when transmitting each bit on the physical links. The detailed matching relationship is described in Table 1. Applying an N-algorithm, we solve the joint route selection and flow allocation problem for a single flow. The pseudo-code of the proposed algorithm is shown in Algorithm 1.

Algorithm 1 Solving the energy consumption minimization problem of a single user flow

Create a network topology graph $G = (V, B)$;
Select a feasible route with $f = \{f_{i,j}\}$;
Repeat main loop;
Create a complementary graph G' of G based on f;
for each $B_{i,j} \in G$
$f'^{\max}_{i,j} = f^{\max}_{i,j} - f_{i,j}$;
$E'_{i,j} = E_{i,j}$;
$f'^{\max}_{j,i} = f_{i,j}$;
$E'_{j,i} = -E_{i,j}$;
end
if hasCycle (G')=false **then**
  return $f^* = \{f_{i,j}\}$, the algorithm terminates;
else
  if $E'_{i,j} > 0$ **then**
    $B_{i,j} \in C_0^+$;
  else
    $B_{i,j} \in C_0^-$;
  end if
  $\delta = \min\{\min\limits_{B_{i,j} \in C_0^+} (f^{\max}_{i,j} - f_{i,j}), \min\limits_{B_{i,j} \in C_0^-} (f_{i,j})\}$;
  if $E'_{i,j} > 0$ **then**
    $f'_{i,j} = f_{i,j} + \delta$;
  else
    $f'_{i,j} = f_{i,j} - \delta$;
  end if
  $f = f'$;
end if

6 Solution to the proposed joint optimization problem: multiple user flows case

In this section, we extend the route selection and flow allocation strategy for single user flows to multiple user flows and consider two special multiple user flow cases. In particular, for Case 1, we assume that various user flows have different priorities in occupying network resources; thus, user flows with relatively low priorities have to wait until the route selection and flow allocation for high priority flows have been conducted. For Case 2, we assume that no priority difference exists between different user flows, and the contents of various user flows are indistinguishable, i.e., there is no difference among the data packets being transmitted through different source switches to the destination switches. This assumption may characterize a common content transmission scenario when multiple users tend to access the same content from various source switches in the network. In the following subsections, we address these two cases individually.

6.1 Multiple user flows with different priorities

In this subsection, we assume that user flows have different priorities. For simplicity, we assume that the first user flow has the highest priority, the second user flow has the second highest priority, and so on. Let P^k denote the priority of the kth user flow and $P^1 \geqslant P^2 \cdots \geqslant P^k$. To guarantee the priorities of user flows, we conduct our proposed joint route selection and flow allocation algorithm successively according to the priority order of user flows, i.e., from the first user flow to the Kth user flow. To stress resource sharing and competition among various user flows, we create virtual networks and design corresponding network slices for each user flow.

The steps for solving the optimal joint route selection and flow allocation problem for multiple user flows with different priorities can be described as follows.

1. Given network topology $G = (V, B, C)$ and the transmission request of the user flows, i.e., the transmitting flow volume F^k from S^k to D^k, set $k = 1$ and $\mathrm{NS}^0 = \Psi$, where Ψ denotes the empty set.

2. Solve the optimal joint route selection and flow allocation strategy problem for the kth user flow:

(a) Create a virtual network for the kth user flow in G: $G' = G - \mathrm{NS}^{k-1}$.

(b) Update the virtual network topology $G = G'$.

(c) Given network topology G and the transmission request of the kth user flow, apply an N-algorithm to calculate the optimal route selection and flow allocation solution, i.e., the optimal solution of $(x^k_{\mathrm{s},i}, x^k_{i,j}, x^k_{j,\mathrm{d}}, f^k_{\mathrm{s},i}, f^k_{i,j}, f^k_{j,\mathrm{d}})$. Denote the obtained optimal strategy by $(x^{k,*}_{\mathrm{s},i}, x^{k,*}_{i,j}, x^{k,*}_{j,\mathrm{d}}, f^{k,*}_{\mathrm{s},i}, f^{k,*}_{i,j}, f^{k,*}_{j,\mathrm{d}})$.

(d) Create a network slice for the kth flow. Define

$$
\begin{aligned}
V^k_0 &= \{V_i, \text{if } x^{k,*}_{\mathrm{s},i} \neq 0 \text{ or } x^{k,*}_{i,j} \neq 0 \text{ or } x^{k,*}_{j,\mathrm{d}} \neq 0, 1 \leqslant i,j \leqslant N, i \neq j\},\\
B^k_0 &= \{B_{i,j}, \text{if } x^{k,*}_{\mathrm{s},i} \neq 0 \text{ or } x^{k,*}_{i,j} \neq 0 \text{ or } x^{k,*}_{j,\mathrm{d}} \neq 0, 1 \leqslant i,j \leqslant N, i \neq j\},\\
F^k_0 &= \{f^{k,*}_{\mathrm{s},i}, \text{if } x^{k,*}_{\mathrm{s},i} \neq 0, 1 \leqslant i \leqslant N\} \bigcup \{f^{k,*}_{i,j}, \text{if } x^{k,*}_{i,j} \neq 0, 1 \leqslant i,j \leqslant N, i \neq j\}\\
&\quad \bigcup \{f^{k,*}_{j,\mathrm{d}}, \text{if } x^{k,*}_{j,\mathrm{d}} \neq 0, 1 \leqslant j \leqslant N\}.
\end{aligned}
$$

3. Define $\mathrm{NS}^k = (V^k_0, B^k_0, F^k_0)$ as the network slice of the kth user flow, which characterizes the optimal route selection and flow allocation strategy of the kth user flow.

4. $k = k + 1$.

5. **if** $k \leqslant K$, return to Step 2.

6. **else** the algorithm terminates.

7. **endif**.

The pseudo-code of the proposed algorithm is shown in Algorithm 2.

Algorithm 2 Solving the energy consumption minimization problem with multiple user flows with priority

```
Create a network topology graph G = (V, B, C);
Initialize NS^0 = Ψ;
for k = 1 : K
G' = G − NS^{k−1};
G = G';
Run an N-algorithm over graph G;
get (x^{k,*}_{s,i}, x^{k,*}_{i,j}, x^{k,*}_{j,d}, f^{k,*}_{s,i}, f^{k,*}_{i,j}, f^{k,*}_{j,d});
if x^{k,*}_{s,i} ≠ 0 or x^{k,*}_{i,j} ≠ 0 or x^{k,*}_{j,d} ≠ 0 then
    V^k_0 = {V_i, V_j};
    B^k_0 = {B_{i,j}};
end if
if x^{k,*}_{s,i} ≠ 0 then
    F^k_0 = {f^{k,*}_{s,i}};
end if
if x^{k,*}_{i,j} ≠ 0 then
    F^k_0 = F^k_0 ⋃ {f^{k,*}_{i,j}};
end if
if x^{k,*}_{j,d} ≠ 0 then
    F^k_0 = F^k_0 ⋃ {f^{k,*}_{j,d}};
end if
NS^k = (V^k_0, B^k_0, F^k_0);
end
```

6.2 Multiple user flows with indistinguishable contents

In this subsection, we consider the scenario when indistinguishable contents are required simultaneously by multiple users; more specifically, flow volume $F = F^1 = \cdots = F^K$ needs to be transmitted from S^k to D^k, where $1 \leqslant k \leqslant K$. Since the general N-algorithm is only applicable for flow transmissions from a single source node to a single destination node, to apply the N-algorithm to the scenario of transmitting multiple user flows simultaneously, we introduce a virtual super source switch S^0 and a virtual destination switch D^0. We assume that S^0 is the adjacent node of all the source switches of K user flows, and we denote the virtual link between S^0 and S^k by $L^{\mathrm{v}}_{0,k}$; we set the capacity and flow allocation variables of

Table 2 System parameters

Parameter	Minimal value	Maximal value
Capacity of links	0	100 Mb
Port rate of switches	$10a$ Mbps	$10a+10$ Mb, $a=1,2,\ldots,12$
Maximum import energy consumption	1.529 mJ	2.359 mJ
Maximum outport energy consumption	5.175 mJ	10.103 mJ
Energy consumption for processing packets	5.838 nJ/B	10.974 nJ/B
Energy consumption for matching packets	3.982 nJ/B	7.286 nJ/B

$L^{\rm v}_{0,k}$ as F, where $1 \leqslant k \leqslant K$. Similarly, we assume that D^0 is the adjacent node of all the destination switches of K user flows and denote the virtual link between D^k and D^0 by $L^{\rm v}_{k,0}$; we set the capacity and flow allocation variables of $L^{\rm v}_{k,0}$ as F, where $1 \leqslant k \leqslant K$.

By introducing S^0 and D^0, the problem of designing a route selection and flow allocation strategy for K user flows transmitting from S^k to D^k, where $1 \leqslant k \leqslant K$, can be equivalently transformed into the problem of designing a route selection and flow allocation strategy for single user flows transmitting from S^0 to D^0 under the capacity and flow allocation constraints on $L^{\rm v}_{0,k}$ and $L^{\rm v}_{k,0}$, for $1 \leqslant k \leqslant K$, as well as the constraints summarized in (18). By applying an algorithm similar to the algorithm described in Algorithm 1, we can solve the joint route selection and flow allocation problem for multiple user flows with indistinguishable contents and obtain the corresponding optimal strategy.

7 Simulation results

In this section, we examine the performance of the proposed joint route selection and flow allocation algorithm via simulation. In the simulation, we consider an SDN scenario of an 100 m $\times$ 100 m square area with 12 intermediate switches randomly deployed in the area. We assume that there exists a direct connection between any two switches that are less than 30 m apart. Parameters including the capacity of links, port rate of switches, maximum import and outport energy consumption of switches, and the unit energy consumption for processing packets and matching packets at switches are all randomly chosen between a minimum value and a maximum value, as summarized in Table 2. It is assumed that there are multiple user flows being transmitted through the network. The simulation results are averaged over 1000 independent simulation processes.

Figure 3 shows the energy consumption versus the number of iterations for transmitting a single user flow through the network. The traffic volume is chosen as 10, 15, and 20 Mb. Notice from the figure that the proposed algorithm converges within a small number of iterations, demonstrating the effectiveness of the proposed algorithm. As can be expected, the energy consumption of the switches increases when the traffic volume of the user flow increases.

In Figure 4, we consider the transmission of multiple user flows with different priorities and examine the energy consumption of the intermediate switches versus the traffic volume of user flows. In the simulation, we consider three and five user flows; for comparison, we also plot the simulation results when transmitting a single user flow. The results are obtained based on our proposed algorithm and the other two algorithms proposed in [19, 20]. Notice from the figure that the energy consumption increases with the increase of traffic volume and the number of user flows for the three algorithms. Comparing the results obtained from our proposed scheme and those proposed in [19, 20], we can see that our proposed algorithm consumes less energy. This is because the algorithms proposed in [19, 20] fail to consider flow splitting at intermediate switches as well as the exact energy consumption characterization of switches.

In Figure 5, we fix the port rate of other switches and vary the port rate of one switch, i.e., Switch 4. The energy consumption is examined when transmitting different amounts of user flows with different priorities. To plot the curves, we assume $F^k = 10$ Mb for all user flows. Notice from the figure that the energy consumption increases as the port rate of the switch increases. Compared to the schemes

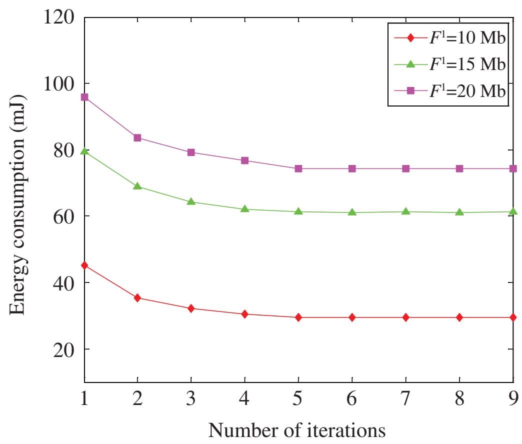

Figure 3 (Color online) Energy consumption versus the number of iterations.

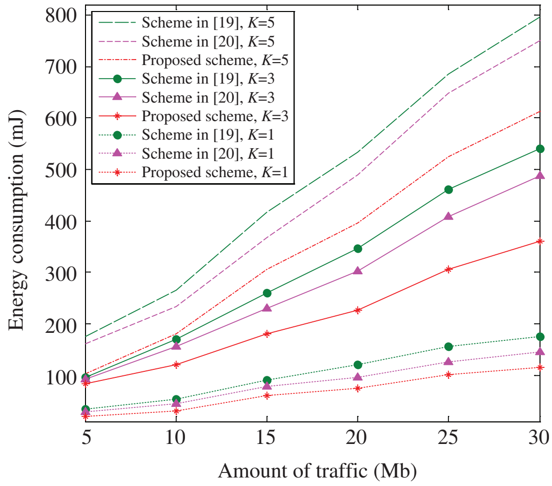

Figure 4 (Color online) Energy consumption versus the amount of traffic.

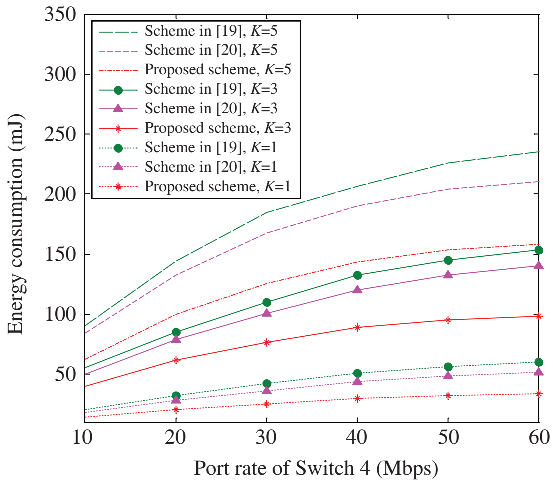

Figure 5 (Color online) Energy consumption versus the outport rate of Switch 4 (multiple user flows with different priorities).

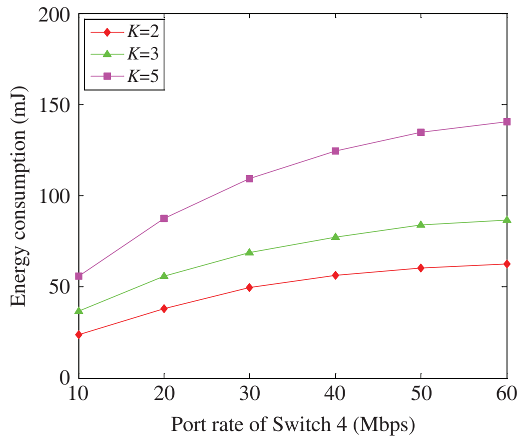

Figure 6 (Color online) Energy consumption versus the outport rate of Switch 4 (multiple user flows with indistinguishable contents).

proposed in [19, 20], our proposed scheme consumes less energy.

In Figure 6, we consider transmitting a different number of user flows with indistinguishable data packets where the amount of traffic is 10 Mb. Similar to Figure 5, we plot energy consumption versus the port rate of Switch 4. Notice from the figure that the energy consumption increases as the port rate of the switch and the number of user flows increases.

8 Conclusion

In this paper, we studied the joint route selection and flow allocation problem of SDN. To manage multiple user flows in a more efficient manner, we proposed a virtual network architecture, which consisted of multiple virtual networks with each network being created for one particular user flow. Based on the proposed virtual network architecture, we designed an optimal joint route selection and flow allocation algorithm. We formulated the total energy consumption of user flows and designed an optimization problem that minimizes the energy consumption subject to data transmission and service requirement constraints. The formulated optimization problem was equivalently transformed into the minimum-cost commodity flow problem and then solved using an N-algorithm. Numerical results demonstrated the effectiveness of the proposed algorithm.

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Conflict of interest The authors declare that they have no conflict of interest.

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