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Utility-Optimized Flow-Level Bandwidth Allocation in Hybrid SDNs

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ABSTRACT The software-defined network (SDN) is a new networking paradigm to improve network performance via logically centralized control and open standardized interfaces. However, the introduction of SDN technology faces many difficulties due to operational and economic constraints. Therefore, an incremental deployment scenario, the so-called hybrid SDN, is preferred. The transition from a legacy network to a pure SDN may take a long time; hence, it is of vital importance to consider the network optimization problem for hybrid SDNs. With SDN-enabled devices, multi-paths, where each flow can have multiple alternative paths, can be supported in bandwidth allocation. In contrast to traditional bandwidth allocation mechanisms in pure IP networks and full SDNs, this paper proposes a utility maximization model with the coexistence of single paths and multi-paths in the network, which aims to facilitate the transition to SDNs. We also design a novel algorithm to solve the maximization model, which is no longer strictly concave. Extensive simulations are conducted to evaluate the performance of the proposed bandwidth allocation strategy. Compared with existing strategies, our strategy has a good performance in terms of utility improvement. The results also show that with an increasing number of devices deployed in the SDN, more paths can be used to allocate the bandwidth; thus, a greater network utility can be achieved.

INDEX TERMS Software-defined network, hybrid SDN, bandwidth allocation, utility maximization, multiple path.

I. INTRODUCTION

Utility is an important indicator of Quality of Service (QoS) performance [1], the level of satisfaction [2], fairness [3], etc. Substantial work has been proposed to optimize network utility in traditional Internet protocol (IP) networks, which are also called legacy networks in this paper. However, network utility is curbed by inflexible bandwidth allocation because traffic is usually routed based on the destination with a hop-by-hop routing protocol in legacy networks. For example, with Open Shortest Path First (OSPF) routing protocol, for traffic with same source and destination, usually only a single shortest path is used in bandwidth allocation. To enhance the flexibility of bandwidth allocation, Equal-Cost Multi-Path (ECMP) [4] and Unequal-Cost Multi-Path (UCMP) [5] are proposed so that multiple paths can be used in bandwidth allocation.

The software-defined network (SDN) [6], [7] is promising technology to provide more flexible and fine-grained bandwidth allocation by decoupling the control plane and the data plane. SDN technology, such as OpenFlow, can offer flow-level bandwidth allocation [8], where a flow can be forwarded based on the application rather than the source and destination pair or origin-destination traffic [9]. Additionally, in a SDN, the utility-based bandwidth allocation problem can be solved at a more fine-grained level over multiple paths. Google [10] and Microsoft [11] have migrated their networks from pure IP to SDN-enabled, which shows that network utilization and utility can be improved with SDN technology.

For various reasons, such as operational and economic constraints, the transition from a pure IP network to a full SDN can be difficult. This is particularly true in large-scale enterprise networks and Internet service provider (ISP) networks [12]. Therefore, the transition of a subset of nodes to be SDN-enabled, a so-called gradual transition, is easier to implement. The network scenario with gradual transition is called a hybrid SDN [13], [14], in which only a subset of nodes are SDN-capable. This process presents a new challenge to optimize the network utility while

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considering different deployment ratios of SDN nodes in hybrid SDNs.

In contrast to traditional IP networks and full SDNs, single-path and multi-path bandwidth allocation coexist in a hybrid SDN scenario because legacy devices and a subset of SDN-capable devices coexist in the network. When traffic enters legacy devices, usually only one deterministic switch can be used as the next hop to transmit the data ignored traditional inflexible traffic engineering, such as ECMP. By contrast, when traffic enters SDN-enabled devices, all switches linked directly with it can be used simultaneously for transmission. Therefore, new candidate paths can be used in bandwidth allocation after SDN partial deployment for some source-destination pairs, enabling improvement to the network resource utilization [15], [16]. It is vital to study the utility optimization problem with proper bandwidth allocation in hybrid SDNs. However, this issue has not been thoroughly addressed.

The main goal of this paper is to study the utility-optimized network bandwidth allocation problem to facilitate the gradual transition from pure IP networks to full SDNs. Specifically, a hybrid network scenario, where IP legacy devices and a subset of SDN-enabled nodes coexist, is considered. The utility-optimized flow-level bandwidth allocation scheme in hybrid SDN proposed in this paper has the following salient features that make it unique it from previous work.

- To the best of our knowledge, this is the first solution for utility-optimized bandwidth allocation in hybrid SDNs that considers the coexistence of single-path and multi-path scenarios.
- To address heterogeneous flows, the bandwidth allocation strategy is designed to handle both divisible and indivisible flows.
- A novel algorithm is proposed to solve the maximization model with dynamic path allocation, which is not strictly concave.

Extensive simulations have been conducted to illustrate the performance of our proposed bandwidth allocation strategy compared with other strategies, different settings of essential demand and different SDN ratios.

The rest of this paper is organized as follows: In section II, a summary of related work is provided. In section III, the description of the system model for bandwidth allocation in hybrid SDNs is given. In section IV, the problem formulation of the utility-optimized network bandwidth allocation is presented. In section V, a novel algorithm to solve the optimization model is proposed. In section VI, the results of a performance evaluation conducted with a small topology for case study and three typical topologies from the Survivable fixed telecommunication Network Design (SNDlib) are presented in detail. A conclusion is given in section VII.

II. RELATED WORK

The network bandwidth allocation problem can be formulated as a constrained maximization of the utility function [17]. The network utility can be viewed as a measure of the QoS performance [1], user or application satisfaction [18] and fairness allocation [18]–[20] based on the allocated bandwidth.

The bandwidth allocation problem in traditional IP networks has been extensively studied with single path and multi-paths [21] to maximize network utility. On one hand, in the single-path utility maximization problem, only one path can be used by each user or source-destination pair [22]–[25]. Low and Lapsley [23] use a dual algorithm to find exact solutions for the single-path case. On the other hand, the multi-path utility maximization problem is discussed in [26]–[28]. In [26], an on-line distributed solution is proposed to maximize multi-path utility. Distributed bandwidth allocation based on utility max-min fairness with multi-path routing is proposed in [27].

In a SDN, the bandwidth allocation problem can be solved at a more fine-grained level over multiple paths. The existing work on the bandwidth allocation of SDNs focuses on two objectives. The first objective is to allocate bandwidth from the network's perspective to achieve higher network bandwidth utilization and network throughput [16], [29]. The second objective is to allocate bandwidth from the flows' and the customers' perspectives to achieve fairness and improve satisfaction. The equalized network utility can be used to guarantee fairness [18] and the level of satisfaction [1], [2], [19]. Fairness criteria include the max-min fairness policy [10], α-fair policy [30] and proportional fairness policy [31]. Additionally, customer-oriented network utility is an important indicator of the level of satisfaction of customers [2].

However, bandwidth allocation in hybrid SDNs has not been thoroughly studied. In hybrid SDNs, SDN devices and legacy devices coexist. Legacy devices cannot be controlled by SDN controllers, so that the sending rates of flows from legacy devices are determined in a distributed way. SDN devices are centralized controlled, in which multi next hops can be deployed in a flexible and centralized way. By this way, multi paths can be used for flows pass through SDN devices. But, for flows only pass through legacy devices, single path can be used. Therefore, the coexistence of single paths and multi paths in hybrid SDNs must be considered. This scenario has not been studied previously.

III. SYSTEM MODEL

In this section, the system model of hybrid SDN is introduced. Additionally, the path and the bandwidth allocation problems in the hybrid SDN are discussed.

A. HYBRID SDN BACKGROUND

A hybrid SDN is a special but important scenario, where legacy forwarding devices and SDN-enabled devices coexist, as shown in Figure 1. To exchange information with legacy devices, SDN-enabled devices must be legacy-enabled so as to forward link-state advertisements (LSA). In this way, the legacy devices can detect the links of SDN-enabled devices. Similarly, SDN-enabled devices are able to detect the links of legacy devices, and information is in turn sent to

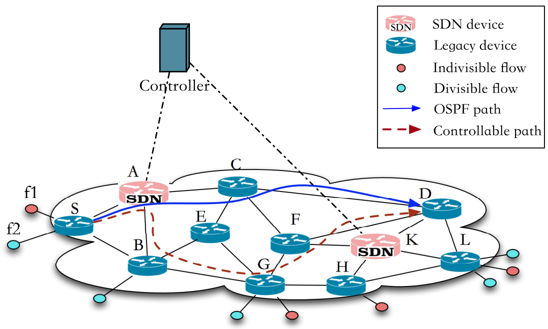


FIGURE 1. A hybrid SDN scenario.

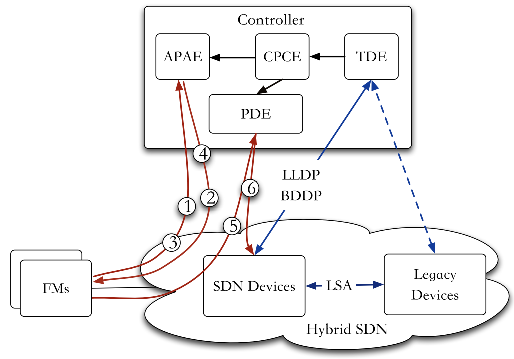


FIGURE 2. The framework of paths and bandwidth allocation in hybrid SDNs.

the controller. For example, if the legacy network performs hop-by-hop routing using a standard routing protocol such as OSPF, information about the links will be collected in the OSPF link-state database (LSDB) by the SDN-enabled devices. Moreover, with the Link Layer Discovery Protocol (LLDP), the Broadcast Domain Discovery Protocol (BDDP) and the link information of the legacy routing protocol, such as LSAs, the SDN controller has the ability to obtain the complete network information, including the network topology and the metrics of links. The detailed process of topology discovery in hybrid SDNs has been summarized in [12] and [32].

As addressed previously, hybrid SDNs consist of single-path and multi-path scenarios. Legacy devices are outside of the control of the SDN controller, and only one deterministic next hop calculated by the routing protocol can be used to transmit data. However, with SDN functionality, SDN-capable devices can allocate traffic to multi next hops. As shown in Figure 1, the shortest path from S to D calculated by the legacy routing protocol is $S \rightarrow A \rightarrow C \rightarrow D$. Since node A is a SDN-enabled device, it can choose a next hop from {B, C}. Assume that path $B \rightarrow G \rightarrow F \rightarrow D$ is the shortest path from B to D. Then, a new path $S \rightarrow A \rightarrow B \rightarrow G \rightarrow F \rightarrow D$ can be used for flows from S to D. The new path is called a controllable path, which is defined as follows:

Definition 1: A controllable path is a path that can be controlled and deployed by a SDN controller in a hybrid SDN.

B. PATH AND BANDWIDTH ALLOCATION IN HYBRID SDNs

The controllable paths a hybrid SDN may be unimaginable when the topology is large scale. In this situation, it is difficult to obtain a good solution to bandwidth allocation if all the controllable paths are taken into consideration. Moreover, when a flow is divided into many parts on multiple paths, the cost of reordering and the flow latency are also increased. To control the number of controllable paths to assign each flow, an important metric, the essential bandwidth, is defined as follows:

Definition 2: The essential bandwidth is the bandwidth the network tries to provide, which is between the upper bound and lower bound of the demand of each flow.

If the allocated bandwidth is less than the essential bandwidth, the controller should allocate more paths for this flow if possible; otherwise, no more paths should be allocated. Therefore, a subset of controllable paths, which is defined as the admissible paths, is assigned to flows by the management of the controllers. The definition of admissible paths is as follows:

Definition 3: Admissible paths are a subset of controllable paths that are finally assigned to a flow.

Thus, the essential bandwidth can be adapted according to the network strategy, which will in turn change the scope of admissible paths.

The flow manager (FM) and the SDN controller are two essential parts of hybrid SDNs. The FM decides the sending rate of flows according to the status of the network and the allocated admissible paths. The SDN controller allocates admissible paths to flows and deploys them with corresponding bandwidth. The framework of path and bandwidth allocation in hybrid SDNs is shown in Figure 2, where TDE is the topology discovery element, which uses the LLDP to discover the topology of the SDN devices and uses the LLDP, BDDP and LSA to discover the entire topology of the hybrid SDN. The CPCE is the controllable paths computation element, which can be used to find all the controllable paths using the topology information from the TDE. Meanwhile, the key SDN nodes through which the controllable paths pass can be discovered. The key SDN nodes are branching nodes that need to be configured. The APAE is the admissible path assignment element, which is used to identify the admissible paths from the controllable paths and to make the decisions about path assignment. The PDE is the path deployment element used to deploy the decision of bandwidth allocation in key SDN devices.

The process of bandwidth allocation in hybrid SDNs involves five important steps, which are marked with numbers in Figure 2. In the first step, the FM sends information about the flows, including the source, destination, demand and available bandwidth, to the controller. In the second step, the APAE assigns some admissible paths from the controllable paths to each flow in the FMs based on the topology and controllable path information obtained from the TDE and

CPCE. Then, in the third step, the FMs check whether these paths satisfy the essential demand. If not, the FMs send information to the controller for path reallocation. Then, in the fourth step, the controller adjusts the path allocation. Steps 2 to 4 may iterate several times until appropriate paths are allocated. In the fifth step, the FM sends the flow information, including the chosen paths and the sending rate of each flow on its path or paths, to the PDE. In the sixth step, the PDE deploys paths and bandwidth for each flow.

Figure 1 is used as an example to illustrate the bandwidth deployment of the PDE. Consider that f_1 is an indivisible flow, and f_2 is a divisible flow. Their demands are shown in TABLE 1. If path $S \to A \to B \to G \to F \to D$ is chosen by the flow manager of f_1, it should communicate with the controller to deploy this path for f_1. The next hop of flow f_1 in the flow table of the node A should be node B, as shown in TABLE 2. For divisible flow f_2, if $S \to A \to C \to D$ with 20 MB/s and $S \to A \to B \to G \to F \to D$ with 10 MB/s are determined, then, the entry of the node A is shown in TABLE 2.

TABLE 1. The demand of flows in Figure 1.

Flow	Upper bound	Lower bound	Essential demand
f_1	15	5	10
f_2	30	10	15

TABLE 2. The flow table of node A.

Flow	Next Hop	Allocated Bandwidth (MB/s)
f_1	B	10
f_2	B	10
	C	20

In conclusion, the bandwidth allocation in hybrid SDNs can be scheduled with multi-paths with the divisibility of flows taken into consideration. The flow manager adjusts the flows' sending rates and their chosen paths, and it should communicate with the SDN controller to deploy these paths in the hybrid network.

IV. PROBLEM FORMULATION

The main goal of this paper is network utility optimization through bandwidth allocation. The hybrid SDN scenario, in which legacy devices and SDN-capable devices coexist in the network, will be considered. With the goal to optimize the utility, two problems shall be studied, i.e., which paths to select for the flow and how much bandwidth will be allocated to each path. The parameters and variables used in our model are summarized in TABLE 3. The problem formulation will be introduced in the following section.

In a hybrid SDN, for each flow, the paths that can be used to transmit the data include the least-cost path calculated using the routing protocol and the controllable paths, which can be controlled by SDN devices. As addressed above, the number of controllable paths may be very large in a large-scale SDN, which will increase the complexity of the bandwidth allocation problem. Therefore, a set of paths, which is called the admissible paths in this paper, will be selected from the controllable paths. This selection will be made by the SDN controller. The set of admissible paths of a flow f is defined as follows:

TABLE 3. List of notation.

Parameter	Meaning
N, E	The set of all forwarding devices and the set of physical links between them.
$x(p)$	The allocated bandwidth of path p.
$U_f(x)$	The utility function of pair $s-d$ with allocated bandwidth x.
B_e	The bandwidth capacity of link e.
F	The set of flows.
F_{in}, F_d	The sets of the indivisible flows and divisible flows.
P	The set of admissible paths in the SDN.
P_f	The set of admissible paths for flow f.
π_e^p	Boolean indicating whether link e is in path p.
τ_f^p	Boolean indicating whether path p is used for flow f.
d_f, D_f	The lower-bound and upper-bound bandwidths of flow f.
x_f^p	The bandwidth allocated to flow f of path p.
Ed_f	The essential bandwidth of flow f.

$$P_f = [p_f^1, p_f^2, \ldots, p_f^{n_f}]^T, \quad \forall f \in F. \tag{1}$$

In this paper, bandwidth allocation in hybrid SDNs is formulated as an optimization problem to maximize the network utility subject to some constraints, such as link capacity. It is assumed that the utility functions of all the flows are continuous, increasing and strictly concave [27]. The vector of the allocated bandwidth of all the admissible paths to all flows is:

$$x = [x_{f_1}^{p_{f_1},1}, \ldots, x_{f_1}^{p_{f_1},n_{f_1}}, \ldots x_{f_n}^{p_{f_n},1}, \ldots, x_{f_n}^{p_{f_n},n_{f_n}}]^T.$$

The admissible paths are determined by the assignment of the SDN controller and the demands of the flows.

The utility optimization model is as follows:

$$\max_{\mathbf{x}} \sum_{f \in F} U_f(\sum_{p \in P_f} x_f^p) \tag{2a}$$

subject to

$$\sum_{p \in P} x_f^p \pi_e^p \leq B_e, \quad e \in E, \tag{2b}$$

$$d_f \leq \sum_{p \in P_f} x_f^p \leq D_f, \ \forall f \in F, \tag{2c}$$

$$x_f^p \geqslant 0, \quad \forall p \in P_f, \ f \in F. \tag{2d}$$

Inequality (2b) ensures that the total amount of traffic over a link is less than its capacity. Inequality (2c) ensures that the bandwidth allocated to a flow is within its range of bandwidth demand. Inequality (2d) ensures that the flow on an admissible path is non-negative.

The Boolean parameter τ_f^p indicates whether path p is used by flow f. It is defined as follows:

$$\forall p, f : \ \tau_f^p = \begin{cases} 0, & x_f^p = 0, \\ 1, & x_f^p > 0. \end{cases}$$

As discussed previously, two types of flows, i.e., divisible and indivisible, will be considered in this paper. These flows are defined by:

$$F = F_d \cup F_{in} = [f_1, f_2, \ldots., f_n]^T.$$

Therefore, the number of paths for one flow should satisfy the following restraints:

$$\sum_{p \in P_f} \tau_f^p = 1, \quad \forall f \in F_{in}, \tag{2e}$$

$$\sum_{p \in P_f} \tau_f^p \geq 1, \quad \forall f \in F_d. \tag{2f}$$

For indivisible flows, only one path can be used for routing (2e). However, for divisible flows, the number of paths may be greater than one (2f).

Different flows with different QoS requirements have different utility values for the same bandwidth. The utility function can be defined to be strictly concave, such as a logarithmic function [3]. The objective function (2a) is not strictly concave because the $\sum_{p \in AD_{sd}} x_a(p)$ is linear [26]. In other words, if multiple paths are used to allocate divisible flows, the objective function (2a) is concave, even though the utility functions of all the flows are strictly concave. Therefore, it is difficult to obtain the optimal solution. In this paper, a novel algorithm is proposed as a feasible solution to the utility optimization problem.

V. ALGORITHM

In this section, a novel algorithm is proposed to solve the utility optimization problem presented in section IV. The proposed algorithm for the bandwidth allocation problem is decomposed into three parts. The first part is to determine the sending rate, i.e., the bandwidth, for each flow. The second part is to update the link price according to the sending rates of the flows. The third part is to assign paths to the flows and to deploy them with the proper bandwidth for each flow.

A. DETERMINATION OF THE SENDING RATES OF THE FLOWS

The sending rates of the flows are calculated in an iterative way to find an approximately optimal value. First, a Lagrange function is formulated according to (2). Second, the Karush-Kuhn-Tucker (KKT) approach is used to obtain the optimal result. Third, we introduce the ideas of the sub-gradient method used in [26] to route and allocate bandwidth to flows. According to the problem formulation, the Lagrange function is defined by

$$\begin{aligned} &L(\mathbf{x}, \lambda, \varphi, \xi, \mu) \\ &= \sum_{f \in F} U_f \left(\sum_{p \in P_f} x_f^p \right) + \sum_{f \in F} \lambda_f \left(D_f - \sum_{p \in P_f} x_f^p \right) \\ &\quad + \sum_{f \in F} \varphi_f \left(\sum_{p \in P_f} x_f^p - d_f \right) + \sum_{f \in F} \sum_{p \in P_f} \xi_{f,p} x_f^p \\ &\quad - \sum_{e \in E} \mu_e \left(\sum_{p \in P} x_f^p \pi_e^p - B_e \right), \end{aligned}$$

where $\lambda = [\lambda_1, \lambda_2, \ldots, \lambda_F]^T$, $\varphi = [\varphi_1, \varphi_2, \ldots, \varphi_F]^T$, $\xi = [\xi_{1,1}, \ldots, \xi_{1,p_1}, \ldots, \xi_{F,p_F}]^T$ and $\mu = [\mu_1, \ldots., \mu_E]^T$. λ, φ, ξ and μ are non-negative Lagrange multipliers. μ_e represents the price per unit bandwidth at link e. Therefore, the price of path p can be defined as: $R_p = \sum_{e \in E} \mu_e \pi_e^p$.

The bandwidth allocated to flow f is: $X_f = \sum_{p \in P_f} x_f^p$. Therefore, the allocated bandwidth of a link is:

$$X^e = \sum_f \sum_{p \in P_f} \pi_e^p x_f^p. \tag{3}$$

The optimal solution of $\mathbf{x}$ must satisfy the following KKT conditions:

$$U_f'(X_f) - \lambda_f + \varphi_f = R_p - \xi_{f,p}, \tag{4a}$$

$$\lambda_f \left(D_f - X_f \right) = 0, \tag{4b}$$

$$\varphi_f \left(X_f - d_f \right) = 0, \tag{4c}$$

$$\xi_{f,p} x_f^p = 0, \tag{4d}$$

$$\mu_e \left(X^e - B_e \right) = 0, \tag{4e}$$

$$\lambda_f, \varphi_f, \mu_e, \xi_{f,p} \geq 0. \tag{4f}$$

As shown in equations (4b) and (4c), if X_f is within the region $[d_f, D_f]$, both the lower-bound and upper-bound prices (λ and φ) converge to zero. From equations (4a) and (4d), it is easy to draw the conclusion that the path used to route flow f must be the one with the lowest price. The minimum price of the path used by flow f is defined as: $R^f = \min_{p \in P_f} R_p$. The dual decomposition results of each flow f are also the optimal bandwidth allocated to it with given R_f:

$$X_f^* = \sum_{p \in P} x_f^*(p) \tau_f^p = \left[U_f'^{-1}(R^f) \right]_{d_f}^{D_f}, \quad \forall f \in F, \tag{5}$$

where $x_f^*(p)$ is the optimal bandwidth allocated to flow f in path p. Then, X_f^* is the total optimal bandwidth allocated to flow f in all the paths. The range of X_f^* is restricted to between d_f and D_f. Additionally, X_f^* should be unique if the utility function is strictly concave. A detailed description of this process is given in Algorithm 1.

As noted above, the objective function formulated in section III is not strictly concave; therefore, the first-order Lagrange algorithm usually oscillates. To overcome this problem, an algorithm based on a sub-gradient approach is used. The algorithm decomposes the original algorithm into a flow-control problem and a routing problem. The flow-control problem is to determine the total data rate of a flow. The routing problem is to decide how to split the total data rate among a set of paths for a divisible flow and how to choose the best path for an indivisible flow.

According to the above analysis, only those paths with the minimum price can be used to allocate bandwidth if the flows are indivisible. By contrast, for divisible flows, the problem is how to split the total data rate among the admissible paths. For each flow, we use the following first-order Lagrange algorithm to update the data rate:

$$X_f(t+1) = \left[U_f'^{-1}(R^f(t)) \right]_{d_f}^{D_f}, \tag{6}$$

where $R^f(t)$ is the lowest path price of flow f in period t.

Algorithm 1 Bandwidth Allocation for Flows

At times t = 1, 2, . . ., flow f

1: Communicate with the controller to obtain the admissible paths AP_f of flow f.
   Find the admissible path: P_f.
2: Receive from the network of the link price μ_e, and compute R^f, which is the minimum path price of all the paths in P_f. The path with the minimum price is SP_f.
3: Compute the rate of flow f with (6)
4: **if** $f \in F_d$ **then**
5:    Update the rate of flow f in path P_f:
      $x_f^p \leftarrow \left[X_f^p - r(R_{p_f} - R^f)\right]^+$
6:    The rate of the path with the minimum price:
      $x_f^{SP_f} \leftarrow \left[X_f - \sum_{p \in P_f \setminus SP_f} x_f^p\right]^+$
7: **else if** $f \in F_{in}$ **then**
8:    Update the rate of flow f in path P_f:
      $x_f^p \leftarrow 0$
9:    The rate of the path with the minimum price:
      $x_f^{SP_f} \leftarrow X_f$
10: **end if**
11: Communicate all the new flow rates x_f^p to links l contained in paths P_f.
12: Communicate all the new flow rates x_f^p to the controller.
13: **if** $X_f \leq Ed_f$ for sufficient time **then**
14:    Communicate with the controller to ask for new admissible paths.
15: **end if**

If the flow is indivisible, the bandwidth allocation should be:

$$x_f^p(t+1) = \begin{cases} X_f(t+1), & p \in R_f \\ 0, & \text{otherwise.} \end{cases}$$

If the flow is divisible, the bandwidth allocation should be:

$$x_f^p(t+1) = \begin{cases} \left[X_f(t+1) - \sum_{p \in P_f \setminus SP_f} x_f^p(t+1)\right]^+, & p \in R_f, \\ \left[x_f^p(t) - r(R_{p_f}(t) - R^f(t))\right]^+, & \text{otherwise,} \end{cases}$$

where t is the iteration index, r is a sufficiently small positive step size and $[\cdot]^+$ is the projection of $[0, \infty)$, which is defined by $[z]^+ = max\{0, z\}$. In each step, the allocated bandwidth of the paths should be decreased if the corresponding price of the path is higher.

As shown in Algorithm 1, the flow manager communicates with the controller to ask for admissible paths to route flows. Then, the flow manager starts the calculation with the assigned admissible paths (lines 2-3). For divisible flows, the bandwidth allocation is shown in lines 4-6. For indivisible flows, the bandwidth allocation is in lines 7-10. After the flow manager determines the data rates of the flows in each admissible path, it updates the prices of the links (line 11). Then, the flow manager communicates with the controller to deploy the paths and their allocated bandwidth (line 12). Finally, if the allocated bandwidth can satisfy the essential demand for a sufficiently long time, the flow manager communicates with the controller for path reallocation (lines 14-15). It should be noted that the calculation is performed iteratively, and the iteration stops if the algorithm approximately converges.

B. UPDATE OF THE LINK PRICE

According to the allocated bandwidth X^e calculated using Algorithm 1, the link price should be updated in a gradient manner [17], as given by:

$$\mu_e(t+1) = \left[\mu_e(t) + r(X^e(t) - B_e)\right]^+, \tag{7}$$

where t is the iteration index, r is a sufficiently small positive step size. If the allocated bandwidth is greater than the link capacity, the price will be increased and vice versa. With this definition, the price of overloaded paths will be decreased, so these paths may not be used in the subsequent path assignments. The algorithm for link price updating is given in Algorithm 2.

Algorithm 2 Algorithm for the Price Update of Links

At times t = 1, 2, . . . , link e

1: Receive flow rates x_f^p for all paths that contain link e.
2: Compute the occupied rate on link e with (3).
3: Compute a new price of this link with (7).
4: Broadcast new prices μ_e to all flows f of the legacy nodes whose paths contain link e and the SDN controller.

According to the allocated bandwidth X^e, links should update their price if some X^e are larger than the link capacity. Then, the new link price will be broadcast to the flow managers and the SDN controller.

C. PATH ASSIGNMENT AND DEPLOYMENT IN THE SDN CONTROLLER

Admissible path assignment and path deployment are two key components of bandwidth allocation in the SDN controller in hybrid SDNs. The admissible path assignment and deployment algorithm is given in Algorithm 3.

As shown in the algorithm (lines 4-10), if the admissible paths assigned to the flow manager cannot satisfy the essential bandwidth requirement of a flow, the controller should find new admissible paths with the minimum price and assign the new admissible paths to this flow (lines 4-6). However, if some admissible paths are underutilized, the controller can make a decision to recall them (lines 7-8). Finally, the controller inserts new flow entries into the flow table with the path deployment algorithm, according to the received x_f^p.

D. CONVERGENCE ANALYSIS

The algorithm converges to a unique bandwidth allocation and an equilibrium price vector when and only when all the lower-bound bandwidth of the flows can be provided by

Algorithm 3 Path Assignment and Deployment in SDN Controller

Path assignment in the SDN controller:

Find all controllable paths CP and SDN devices in these paths according to the topology information.
Receive the link price μ_e from the network.
Communicate with the flow manager of f.
if the controller determines to allocate a new path **then**
    SCP_f : find a new shortest controllable path using link price μ_e which has not been assigned to f.
    $AP_f \leftarrow AP_f \bigcup SCP_f$
else if the controller determines to recall a path p from flows **then**
    $AP_f \leftarrow AP_f - p$
end if
Assign the set of new admissible paths AP_f to flow f.

Path deployment in the SDN controller:

Receive x_f^p from flow managers.
Find and deploy the SDN devices in all paths p whose $x_f^p > 0$.

the network. The convergence analysis is presented in the following section.

From (6), it is easy to see that the allocated bandwidth of a flow is determined by the minimum price of its allocated paths. Thus, if the price of the links converges, the allocated bandwidth of the flows should also converge. As shown in (7), the algorithm converges if $\mu_e(t+1) \rightarrow \mu_e(t)$ is true. (4e) and (7) show that the problem is convergent if the condition $\mu_e(t) \rightarrow 0$ or the condition $X^e(t) - B_e \rightarrow 0$ is satisfied. For $\mu_e(t) \rightarrow 0$, the algorithm converges when $X^e(t)$ is less than B_e, which means all the upper-bound demands are satisfied. Therefore, in this case, the price of the link should be decreased to zero. If $X^e(t)$ is larger than B_e, the price of link μ_e will be increased; subsequently, the $X^e(t)$ would be decreased until $X^e(t) = B_e$. Then, the price of the link converges to a steady-state value which may not be zero. However, the algorithm does not converge when $X^e(t)$ is larger than B_e when only the lower-bound demands are provided. Because X_f is always not less than its demand lower bound and the price is always increasing, the selection of the lower bound of the bandwidth demand should be within the capacity of the network; otherwise, the algorithm will not converge. Admission control should be applied before bandwidth allocation for flows to ensure the convergence of the bandwidth allocation algorithm.

VI. PERFORMANCE EVALUATION

In this section, we first use a simple but illustrative case to demonstrate the performance of the algorithm in hybrid SDNs. Second, the topology INDIA35 from the SNDlib is used to show the utility improvement compared with other algorithms and the performance with different essential demand settings. Two additional topologies (TA2 and GERMANY50) from the SNDlib are used to illustrate the network utility improvement with SDN gradual deployment. INDIA35 has 35 nodes and 80 links, and TA2 has 65 nodes and 108 links. GERMANY50 has 50 nodes and 88 links, as shown in TABLE 4. The experiments are performed on computer with an Intel Core i7 (2.9 GHz) CPU and 16 GB memory.

TABLE 4. Information of topologies.

Topology	Nodes	Links	Flow number
INDIA35	35	80	100
TA2	65	108	100
GERMANY50	50	88	50

A. CASE STUDY

Figure 3 depicts the topology of the network for the case study. There are 9 forwarding devices and one SDN-enabled device. Node 2 is a SDN forwarding device that can be controlled by the SDN controller. The links are unidirectional, and the bandwidth capacity is marked, as shown in Figure 3.

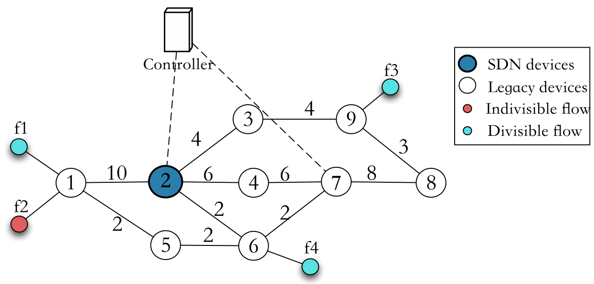
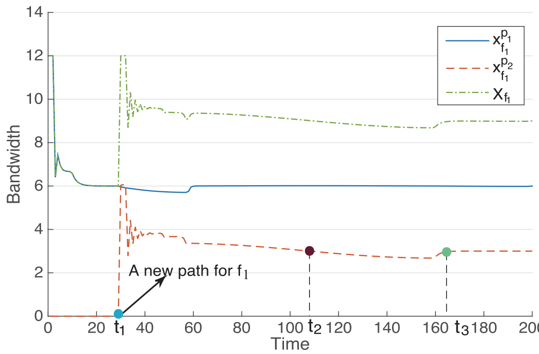


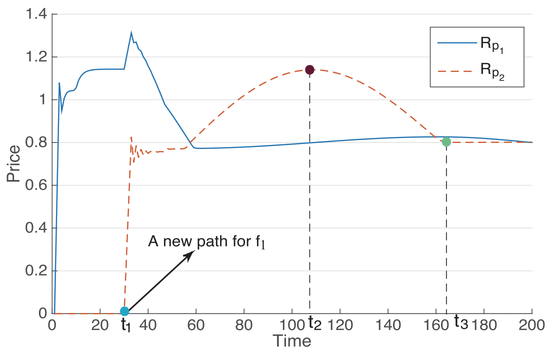
FIGURE 3. A nine-node hybrid SDN for the case study.

If Figure 3 is a legacy network, in which the bandwidth allocation is viewed as a single-path allocation problem based on the legacy routing protocol, the traffic from node 1 to node 8 can use only the OSPF path ($p_1 : 1 \rightarrow 2 \rightarrow 4 \rightarrow 7 \rightarrow 8$). However, if node 2 is updated to support SDN, it is able to choose the next hops from nodes $\{3, 4, 6\}$. Therefore, two new controllable paths, $p_2 : 1 \rightarrow 2 \rightarrow 3 \rightarrow 9 \rightarrow 8$ and $p_3 : 1 \rightarrow 2 \rightarrow 6 \rightarrow 7 \rightarrow 8$, can be used for flows from node 1 to node 8. The maximum bandwidth that can be allocated to the flows from node 1 to node 8 is increased from 6 MB/s to 10 MB/s. If only the divisible flow f_1 exists in the network, the maximum allocated bandwidth is 10 MB/s. By contrast, if only the indivisible flow f_2 exists in the network, the maximum allocated bandwidth is 6 MB/s. If flows f_1 and f_2 coexist, they would share the limited bandwidth based on their demand and utility functions. The maximum bandwidth that can be allocated is 10 MB/s in this case. If four flows coexist in the network, they would share all the bandwidth capacity of the links. The simulation results of a case study under different conditions, i.e., 1 flow and 4 flows, are presented.

In first case, it is assumed that a single divisible flow f_1 from node 1 to 8 exists in the network, whose D_{f1} is 12 MB/s, d_{f1} is 5 MB/s and Ed_{f1} is 8 MB/s. The utility function is given by $U_{f_1}(x) = 4\log(x+1)$. In this case, the step size r is 0.03. The simulation results are shown in Figure 4.



(a)



(b)

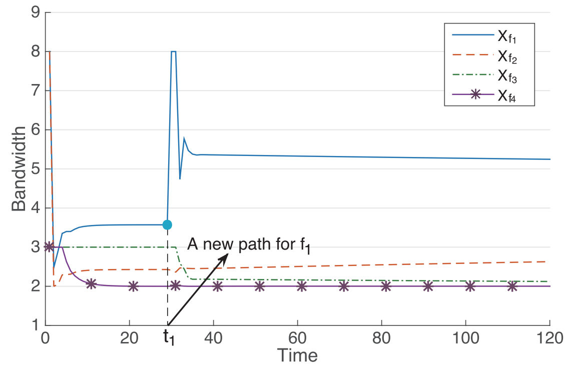
FIGURE 4. Simulation results of the case study with one divisible flow. (a) Simulation result of the bandwidth allocation of one flow. (b) Simulation result of the path price.

Figure 4(a) and Figure 4(b) show the allocated bandwidth and the prices of the paths that can be used by flow f_1 versus the iteration time. According to the legacy routing protocol, the shortest path is p_1. First, only the shortest path p_1 is assigned for flow f_1. Then, the maximum bandwidth allocated to it converges to 6 MB/s from time 10. However, the bandwidth assigned to flow f_1 cannot meet the essential bandwidth Ed_{f_1}, which is 8 MB/s. The flow manager of flow f_1 should ask for a new path assignment. Then, path p_2 is allocated at time t_1. At this time, the curves of the bandwidth and path price clearly change due to the addition of the new path. As shown in Figure 4(b), from time t_1 to t_2, the price of p_2 increases dramatically because the allocated bandwidth is beyond the capacity of the link between node 9 and node 8. Additionally, the growth rate during this period shows a decreasing trend because the allocated bandwidth of p_2 gradually decreases to 3MB/s, as shown in Figure 4(a). After time t_2, the price of p_2 begins to decrease because the allocated bandwidth is less than 3 MB/s, which does not exceed its capacity. At time t_3, the allocated bandwidth and path price of p_2 converge. Finally, at approximately time 200, the bandwidth allocated to f_1 converges to 9 MB/s with 6 MB/s in p_1 and 3 MB/s in p_2. The results are consistent with our analysis.

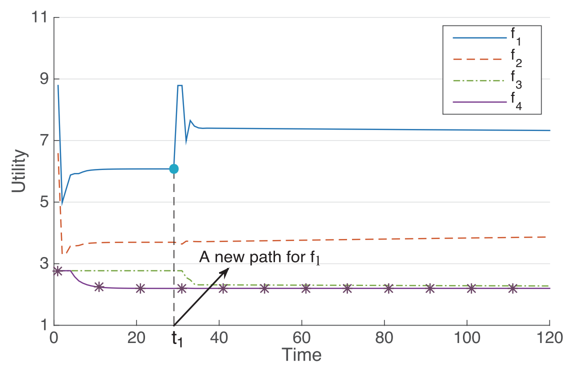
In another case, four flows, named f_1, f_2, f_3 and f_4, are included in the network, as shown in Figure 3. Three flows (f_1, f_3 and f_4) are divisible, and flow f_2 is indivisible. The utility function is given by $U_f(x) = a_f \log(x+1)$. The coefficients of the utility function and the information of the flows are shown in TABLE 5. The simulation results are shown in Figure 5.

TABLE 5. Four-flow information.

Flow	Source	Destination	D_f	d_f	Ed_f	a_f
f_1	1	8	8	2	4	4
f_2	1	8	8	2	2	3
f_3	9	2	3	1	1	2
f_4	6	8	3	1	1	2



(a)



(b)

FIGURE 5. Simulation results of the case study with four flows. (a) Simulation result of the bandwidth. (b) Simulation result of the utility.

Figure 5(a) and Figure 5(b) show the allocated bandwidth and the network utility of four flows versus the iteration time, respectively. At time t_1, the new controllable path p_2 is allocated to flow f_1 because its essential demand is not satisfied. Thus, the bandwidth and utility curves of f_1 change suddenly. After time 120, this algorithm is almost converged. Flow f_1 is a divisible flow, which is assigned to path p_1 with 3.3 MB/s and path p_2 with 1.9 MB/s. Flow f_2 is an indivisible flow, which is assigned to path p_1 with 2.7 MB/s. Because the coefficient of f_1 is larger than that of f_2, more bandwidth is allocated to f_1. Although f_3 and f_4 are divisible, there are no controllable paths for them other than the shortest path. Flow f_3 and flow f_4 choose path $9 \rightarrow 3 \rightarrow 2$ with 2 MB/s and $6 \rightarrow 7 \rightarrow 8$ with 2.1 MB/s, respectively. Finally, the algorithm converges to a total network utility of approximately 15.7.

This case study shows that dynamic path allocation can improve the network utility and satisfy the essential bandwidth demand. Additionally, our proposed algorithm has good performance in convergence.

B. PERFORMANCE EVALUATION WITH DIFFERENT ALGORITHMS, ESSENTIAL DEMANDS AND SDN DEPLOYMENT

Three topologies from the SNDlib are used to demonstrate the performance of our proposed bandwidth allocation scheme. The utility function is given by $U_f(x) = a_f \log(x + 1)$. The coefficient a_f is randomly generated between 1 and 10. The flows are generated randomly with different sources and destinations.

1) UTILITY IMPROVEMENT COMPARED WITH OTHER ALGORITHMS

The proposed bandwidth allocation algorithm in this paper is compared with two other bandwidth allocation strategies, i.e., the Network Throughput Maximum (NTM) [16], [29] and the Utility Maximum with Static Paths allocation (UMSP) [26], [27]. The objective of NTM is to maximize the network throughput via bandwidth allocation and dynamic path allocation. The UMSP attempts to maximize the network utility with static allocated paths. The simulation results are shown in Figure 6 with 40% of the forwarding devices in the INDIA35 network migrated to SDNs, which are selected randomly. The capacities of the links are randomly set ranging from 40 MB/s to 60MB/s. The upper-bound bandwidth demands of the flows D_f are between 10 MB/s and 30 MB/s, and the d_f values are between 2 MB/s and 5 MB/s. Approximately 30% of the flows are randomly chosen to be indivisible.

Figure 6 shows the network utility versus the number of experiments with 100 randomly generated flows. The proposed scheme clearly has better performance than that of the other two schemes because the proposed scheme considers utility as the most important factor for bandwidth allocation. The NTM performs worst for most of time because it considers only the throughput and ignores the utility. However, in some experiments, the NTM has better performance than that of the UMSP because the NTM supports dynamic path allocation. Furthermore, the bandwidth allocation strategy with dynamic path allocation is able to improve the network utility.

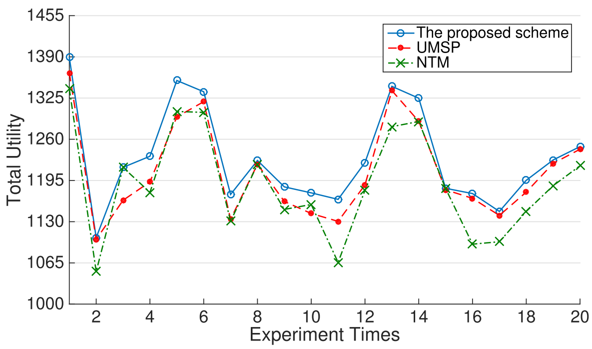


FIGURE 6. Performance with different bandwidth allocation strategies.

2) PERFORMANCE WITH DIFFERENT ESSENTIAL DEMAND SETTINGS

In this experiment, the INDIA35 network is used for illustration. The capacities of the links are randomly set ranging from 50 MB/s to 80/s The upper-bound bandwidth demands of flows D_f are between 30 MB/s and 50 MB/s, and the d_f values are between 1/5 and 1/10 of the D_f. Approximately 40% of the devices are randomly selected to be SDN-enabled. The number of flows is 100, with randomly generated sources and destinations, and 30% of the flows are randomly chosen to be indivisible.

Figure 7 shows the distribution of the satisfaction degree of the flows. As shown in the figure, the horizontal axis is the satisfaction degree, which is assumed to be $\eta_f = \frac{U_f(X_f)-U_f(d_f)}{U_f(D_f)-U_f(d_f)}$, and the vertical axis is the percentage of flows. According to the definition of the satisfaction degree, when the allocated bandwidth reaches the upper bound and the lower bound, the satisfaction degrees are 100% and 0%, respectively. There are three curves in this figure whose essential demands are set to be the bandwidth demand with the lower-bound demand and $\eta = 0.2, 0.5$.

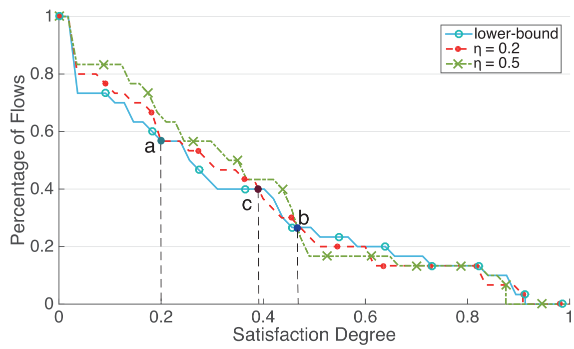


FIGURE 7. The distribution of the satisfaction degree with different essential demands.

As addressed in Section III, the essential demand is the bandwidth the network attempts to provide, which is between the upper bound and lower bound of the flow demand. Due to network capacity limitations, the essential demand cannot be guaranteed for all flows. For example, the essential demand setting with $\eta = 0.2$ means the network attempts to offer at least 20% satisfaction to all flows within its capacity. However, due to the network bandwidth insufficiency, only approximately 60% of the flows exceed 20% satisfaction.

Therefore, the essential demand setting is important for path allocation and bandwidth allocation.

Comparison of the curves with $\eta = 0.2$ and the lower bound shows that the satisfaction degree is improved when the essential demand is set to 0.2. The improvement is maintained for satisfaction degrees between 20% and 40%, as indicated by 'a' and 'c', respectively, in the figure. After 'c' point, the satisfaction degree with $\eta = 0.2$ will decrease and become worse than that with the lower bound because the network controller will attempt to allocate paths and bandwidth to flows to reach the essential demand. Therefore, for the curve with $\eta = 0.2$, most of the flows achieve approximately 20% satisfaction. Only a small percentage of the flows reach satisfaction degrees much larger than the essential demand. This also implies fairness. This observation indicates that higher essential demand will result in higher satisfaction degrees for most flows. However, this might not be true when the network capacity is too limited to guarantee the essential demand for most of the flows. This is reflected by the curve with $\eta = 0.5$. The percentage of flows of the curve with $\eta = 0.5$ is higher than that of the other two curves when the satisfaction degree is less than 0.47, which is marked with 'b'. But, the percentage of flows whose satisfaction degree can reach or exceed 50% is quite low because the network capacity is not able to guarantee the essential demand with 0.5. Hence, the network administrator is able to adapt the essential demand of the network to provide a reasonable satisfaction degree for all the flows.

3) PERFORMANCE WITH VARIOUS SDN DEPLOYMENTS

Three topologies from SNDlib are used to illustrate the network utility improvement with gradual SDN deployment. The TA2, GERMANY50 and INDIA35 networks are used to illustrate the relationship between SDN deployment and network utility. The upper-bound bandwidth demands of flows D_f are between 10 MB/s and 30 MB/s, and the d_f values are between 2 MB/s and 5 MB/s. The Ed_f values are between 5 MB/s and 10 MB/s. The step size of each iteration is 0.002. The SDN deployment sequence is generated based on the betweenness centrality. It is an indicator of a node's centrality in a network and is equal to the number of shortest and available paths from all vertexes to all others that pass through that node.

The utility improvement versus different SDN deployment ratios in the network is shown in Figure 8. Three topologies (TA2, GERMANY50 and INDIA35) are used for illustration. The number of flows is set to 100. As shown in the figure, the utility improvement increases with SDN deployment because more paths can be used for bandwidth allocation when more SDN devices are deployed in the network. The number of paths used for bandwidth allocation is marked on the figure. This experiment proves that the utility is improved when more SDN devices are deployed in the network. For example, when 40% of the devices are SDN devices, the utility improvements of TA2, GERMANY50 and INDIA35 are 15.37%, 3.26% and 11.37 %, respectively. The utility improvement varies with the topology and flows.

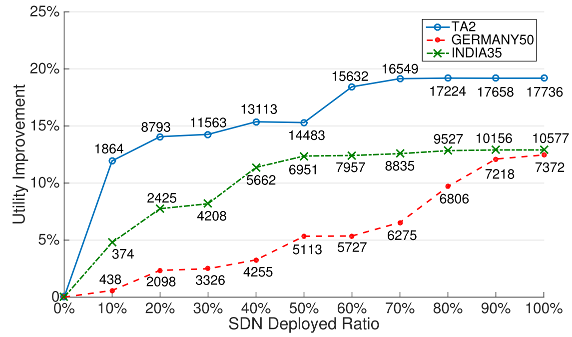


FIGURE 8. Utility improvement with different SDN deployment ratios.

The TA2 topology is used to illustrate the performance of the utility improvement with different sets of flows. The number of flows is randomly generated from 50 to 100, among which approximately 10% of the flows are randomly chosen to be divisible. Twenty sets of flows are randomly generated to test the performance of the hybrid bandwidth allocation in hybrid SDNs, as shown in Figure 9.

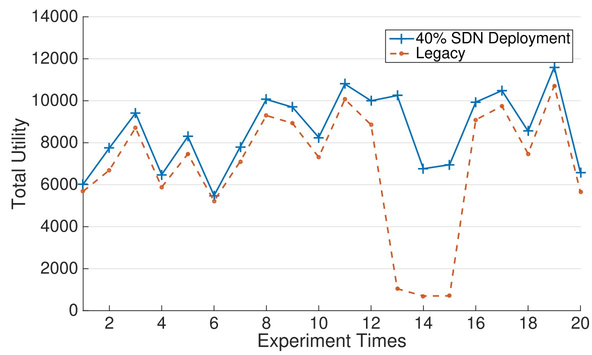


FIGURE 9. Network utility with different flows.

In Figure 9, the horizontal ordinate is the number of experiments. The vertical ordinate is the network utility, which is defined as the sum of the utilities of all the flows. There are two curves in this figure. One shows the performance with 40% devices migrated to SDN. The other shows the network utility in the legacy network with the shortest paths. It is easy to draw the conclusion that the utility improvement varies with the different sets of flows. However, it cannot be ignored that in all the experiments, the network utility with 40% SDN devices is better than that of the legacy network.

VII. CONCLUSION

The hybrid SDN, where SDN devices coexist with legacy devices, is a special but important scenario. Hybrid SDNs have advantages that can be used in bandwidth allocation, such as that there are new paths to route flows and that the SDN controllers can centrally assign and deploy these paths to flows. Therefore, if these advantages can be exploited, the network bandwidth allocation in the hybrid SDNs can promote the network utility. In this paper, a network bandwidth allocation scheme for hybrid SDNs is proposed to maximize the network utility. A flow-level strategy with dynamic multiple-path allocation is proposed to solve this problem. Experiments prove that our proposed bandwidth allocation strategy has good performance in terms of utility improvement compared with other strategies. Additionally, the simulation results show that the distribution of utility satisfaction is affected by the essential demand setting. The simulation results also show that improvement in network utility can be achieved with an incremental deployment of SDN devices in an existing network.

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