An Approach to Improve the Cooperation Between Heterogeneous SDN Overlays

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***Abstract*—The overlay network has been widely developed in recent years. There may be various overlays that co-exist with each other upon the same underlying network. These overlays have heterogeneous performance goals, and they will compete for the physical resources, so that a sub-optimal performance of the overlays may be achieved. Moreover, the heterogeneity of the overlays makes them difficult to coordinate with each other to improve their performance. We introduce the concept of SDN to the deployment of overlay network and propose an approach to make the overlays cooperate with each other. A cooperative solution is proposed for co-existing overlays to improve their performance while leveraging their heterogeneous performance goals. Simulations are performed to evaluate the cooperative solution.**

***Index Terms*—Software Defined Network, Co-existing Overlays, Asymmetric Nash Bargaining Solution**

I. Introduction

The overlay network has been popularly used by the Service Providers (SPs) to provide different kinds of services developed over the past few years. Due to the variety of the services provided by the SPs, current overlay networks have heterogeneous performance goals. For instance, the real-time streaming overlays minimize the latency of the overlay flows while the content delivery overlays maximize the bandwidth of their flows.

The software defined network (SDN) provides an API for packet forwarding devices, so that the control plane can be separated from the data plane. This characteristic of SDN improves the flexibility in programming the network, which is very suitable for SPs to provide heterogeneous services. By applying the concept of SDN, it is much easier for SPs to deploy heterogeneous overlays.

In this paper, we focus on the scenario that multiple heterogeneous overlays are deployed on top of the same underlying network. It has been demonstrated that the interaction between co-existing homogeneous overlays may result in a sub-optimum performance of the network. Similarly, the co-existing heterogeneous overlays may also compete for the physical resources and interfere with each other, even though they take physical resources for heterogeneous demands.

Several cooperative solutions have been proposed for the homogeneous overlays. However, these solutions are not suitable for the heterogeneous overlays. To make heterogeneous overlays coordinate with each other, there are two main problems should be solved. The first one is how to may an overlay realize the heterogeneous performance goals of other overlays. The second one is how to leverage the performance of overlays according to their heterogeneous performance goals.

In this paper, we introduce the concept of SDN to the deployment of overlay. A framework for overlays is proposed to manage heterogeneous overlays. A cooperative solution based on the asymmetric Nash bargaining solution is also proposed. The performance of the heterogeneous overlays will be improved. A near Pareto optimal will be achieved, and the performances of the co-existing overlays are improved.

The rest of this paper is organized as follows. Section II introduces the related work. Our framework is introduced in Section III. Section IV proposes the cooperative solution. And Section V shows the simulation results to illustrate the effectiveness of our proposed approach. Finally, conclusions are given in Section VII.

II. Related Work

The ossification of the Internet has been studied for years. In recent years, the idea of “programmable networks” is introduced, and the SDN [1] attracts significant attention from both academia and industry. Several SDN architectures have been designed, for instance, Openflow [2] and ForCES [3]. Moreover, the concept of SDN has been applied to design varies of overlay networks [1].

The scenario of multiple overlays has been studied in recent years. Qiu et al. [6] analyze how the multiple co-existing overlays interfere with each other. They point out that the overlay source routing leads to a near global optimal at the expense of overloading certain links. Jiang et al [1] demonstrate the sub-optimality of overlay routing. They also propose a pricing scheme for overlays to achieve a global optimal performance. In [7], Keralapura et al. study how the oscillations may be caused by overlay routing. The authors in [8] study the interaction between overlays and underlays in

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multi-domain networks. In our previous works [9] and [10], we propose game-theoretic solutions for latency sensitive overlays.

There are also researches on improving the coordination between heterogeneous overlays. Kwon et al. [11] introduce an architecture called Synergy, which makes co-existing overlays share their resources with each other. However, the privacy of the overlays should be concerned with. Some researchers work on merging the co-existing overlays. The authors in [12] propose a cooperative strategy for overlays based on a master-slave model, so that the redundant maintenance cost of the overlays is reduced.

III. The Cooperative Framework

In general, co-existing heterogeneous overlays are unaware of each other, and it is difficult for an overlay to solve the overlay routing problems of other overlays. A cooperative framework is designed to handle this situation, which is showed in Fig. 1.

We apply the concept of SDN to the deployment of overlays. An overlay node is selected as the SDN controller and all overlay nodes work as switches, so that the control plane of overlay routing is separated from the data plane. Therefore, it is much easier for an overlay to realize the heterogeneous services of other overlays. Each SDN controller collects and maintains the information of its overlay network. It also uploads its information to the data server periodically. After all the overlays have their information uploaded, the data server will have a clear sight of the status of all the co-existing overlays. When an overlay has a service demand, the SDN application inquires its SDN controller for the guidance of overlay routing. Then, the SDN controller will send its demand to the data server. The data server will broadcast the demand to other SDN controllers. Thereafter, all the overlays visit the data server for the status of the network, so that they can decide how to route their overlay flows cooperatively. By applying the cooperative solution which is introduced in Section IV, overlays can cooperate with each other and improve their performance.

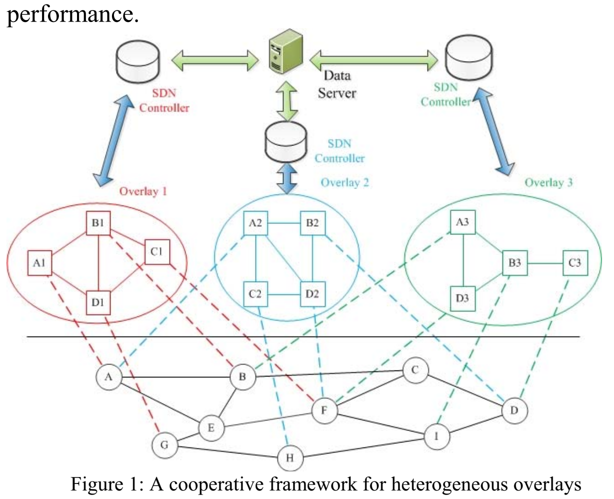

Figure 1: A cooperative framework for heterogeneous overlays

IV. Improving the Cooperation Between Heterogeneous Overlays

A. Modeling the Routing of Heterogeneous Overlays

We focus on the scenario that the heterogeneous overlays are built on top of a physical network. The topology of the physical network can be considered as a static graph $G=(N,L)$, where N represents the set of physical nodes and L represents the set of physical links. For a link $l\in L$, it has a finite capacity c_l, and there is traffic traveling on it. Let u_l denote the total traffic on link l, and let $U=(u_1,u_2,\cdots,u_{|L|})^T$ denote the traffic vector of the physical links in the network. Let r denote a route in the physical network, and let R denote the set of all the routes. For a route r, it consists of a chain of physical links. To indicate whether a physical link consists in a route, we propose a $|L|\times|R|$ matrix A. For link $l\in r$, $A_{lr}=1$, and $A_{lr}=0$ otherwise.

The topology of an overlay can also be treated as a graph $H=(N',L')$, where N' denotes the set of overlay nodes and L' denotes the set of overlay links. The set of overlay routes is denote as R'. Since the overlay network is built on the top of the physical network, the graph of an overlay H can be mapped onto the graph of physical network G. The set of overlay nodes N' can be mapped as a set of the physical nodes where they are deployed on, which is a subset of N. Since an overlay link l' consists of a chain of physical links, it can be mapped onto a physical route r. Thus, the set of overlay routes R' is a subset of R.

Consider a scenario that several heterogeneous overlays are built on top of one physical network. Let S denote the set of all the overlays. Then, an overlay s is denoted as a graph $H_s=(N'_s,L'_s)$. When an overlay s flow f is generated to provide services, its message is sent from the source node to the destination node with a traffic demand and a performance goal. Let F represent the set of all overlay flows, and $F^{(s)}$ represent the set of flows which belong to the overlay s. Let $R_s^{(f)}\subset R'_s$ be the set of all possible overlay routes that can be used by overlay flow f. To indicate whether a route serves a certain flow, we propose a $|F|\times|R|$ matrix B, where $|F|=\sum_{s\in S}|F^{(s)}|$. If route r is a possible path that can be used by flow f, $B_{fr}=1$, $B_{fr}=0$, otherwise.

We use a vector $v^{(s,f)}=(v^{(s,f,1)},v^{(s,f,2)},\cdots,v^{(s,f,|R|)})^T$ to represent the traffic allocation of an overlay flow f, where $v^{(s,f,r)}$ denotes the amount of traffic assigned to the route r. Let $v^{(s)}=(v^{(s,f_1)},v^{(s,f_2)},\cdots,v^{(s,f_k)})^T$ ($k=|F^{(s)}|$) be the traffic arrangement vector of an overlay s, which shows how the SDN controller arranges all the flows in overlay s. Therefore, the traffic allocated on each route by all the overlays can be showed by a traffic deployment vector $v=\sum_{s\in S}v^{(s)}$.

With the traffic arrangement vector of an overlay s, we can calculate how much traffic of overlay s deployed on a physical link l, that is $u_l^s = \sum_{f \in F^{(s)}} \sum_{r \in R^{(f)}} A_{lr} \cdot v^{(f,r)}$. Thus, the traffic vector that overlay s deploys on the physical network can be interpreted as $U^{(s)} = Av^{(s)}$. The amount of traffic traversing link l is $u_l = u_l^{bg} + \sum_s u_l^s$, where u_l^{bg} is the background traffic on the physical network. Thus, the traffic vector can be calculated as $U = U^{(bg)} + \sum_s U^{(s)}$. Since we focus on the horizontal interactions rather than the vertical interactions, we assume that there is no background traffic: $U^{(bg)} = 0$. So we have $U = \sum_s U^{(s)} = Av$. Note that the total traffic traveling in each physical link should not be arranged beyond the link capacity, that is $U \le c$. Thus, $Av \le c, v \ge 0$, where $c = (c_l \mid l \in L)^T$ indicates the capacity of each physical link.

For an overlay s, we denote the performance function of a route r as:

$$\beta_r^s(U) = \beta_r^s(U) = \beta_r^s(Av^{(s)} + Av^{(-s)}), \quad (1)$$

where the vector $v^{(-s)} = \sum_{i \in S, i \ne s} v^{(i)}$ denotes the traffic deployment of all the other overlays except overlay s. Note that, $\beta_r^s(\cdot)$ should be defined according to the performance goal of overlay s. And the performance of an overlay s is the sum of the performances of all its overlay flows:

$$perf^{(s)} = v^{(s)^T}[B\beta^s(Av^{(s)} + Av^{(-s)})], \quad (2)$$

where $\beta = (\beta_1, \beta_2, ..., \beta_{|R|})^T$ denotes the performance functions of all routes. To optimizing the performance of an overlay s, its SDN controller solves the following optimization problem in a constraint condition:

$$maximize: perf^{(s)}(v^{(s)}) = v^{(s)^T}[B\beta(Av^{(s)} + Av^{(-s)})], \quad (3)$$

$$subject\ to: A(v^{(s)} + v^{(-s)}) \le c, v^{(s)} \ge 0. \quad (4)$$

B. Improving the Cooperation Between Heterogeneous Overlays

To improving the cooperation between heterogeneous overlays, the fairness between overlays should be concerned with. The asymmetric Nash bargaining solution (ANBS) is introduced to solve the cooperative overlay routing problem. By applying ANBS, overlays cooperate to achieve a win-win solution, so that they can improve their performance without hurting each other.

The optimization objective is shown as:

$$\text{maximize } ANBS = \prod_s (perf^{(s)} - \overline{perf}^{(s)})^{\varphi_s}, \quad (5)$$

where $\overline{perf} = (\overline{perf}^{(1)}, \overline{perf}^{(2)}, ..., \overline{perf}^{(|s|)})$ is the disagreement vector, which can be set as the performance of the overlays at the start of the cooperation. The parameter φ_s represents the trend of the cooperation, and $\forall s \in S$, $0 < \varphi_s < 1$, $\sum_s \varphi_s = 1$. It can be calculated as: $\varphi_s = \omega_s / \sum_S \omega_s$, where ω_s is the weight of an overlay s. The higher weight an overlay has, the better its performance will be improved. Therefore, to balance the benefit of heterogeneous overlays, the weight of an overlay should be set properly. How to set the weight of an overlay is discussed in Section VI-C.

Since the optimization problem in Eq. 5 is difficult to solve centralized, we provide a distributed solution for co-existing overlays. For an overlay s, its SDN controller solves the following optimization problem:

$$\begin{aligned} &maximize: \varphi_s \ln(v^{(s)^T}\left[B\beta(Av^{(s)} + Av^{(-s)})\right] - \overline{perf}^{(s)}) \\ &-\lambda_{-s}Av^{(-s)} - \gamma Av^{(s)} + \lambda_s Av^{(-s)} \end{aligned}, \quad (6)$$

where λ_i ($i \in S$) denotes the disagreement between co-existing overlays, and γ represents the cost of overloading physical links. The value of λ_i and γ can be obtained from the data server by the SDN controllers. Please refer to [9] for more details of the derivation of the distributed solution.

C. Balancing the Weights of Overlays

To simplify the setting of overlay weights, a weight decision process is proposed in this sub-section.

Let the vector of the weight of the overlays denote as $\omega = (\omega_1, \omega_2, ..., \omega_{|s|})$. Since the convergence state of the cooperation is decided by the weight vector ω, we represent the performance function of an overlay s as: $\theta_s(\omega)$.

During the weight decision process, overlays sequentially propose the values of their weights. In any period t, an overlay s proposes its new weight $\omega'_s > \omega_s^{t-1}$. Then, each overlay decides whether to accept or reject the weight. Suggest the proposed weight is accepted, the weight vector of the overlays becomes $\omega' = (\omega_1^{t-1}, ..., \omega'_s, ..., \omega_{|s|}^{t-1})$. Therefore, the performance of the overlays will be $\theta(\omega') = (\theta_1(\omega'), ..., \theta_{|s|}(\omega'))$. For an overlay $i \ne s$, let σ_i denote the decision of an overlay s, so we have:

$$\sigma_i = \begin{cases} 1-\rho, & \text{if } \theta_i(\omega') > \theta_i(\omega^{t-1}) \\ \rho, & \text{if } \theta_i(\omega') \le \theta_i(\omega^{t-1}) \end{cases}, \quad (7)$$

where ρ is the irrational probability of an overlay. Therefore, the acceptance possibility of ω'_s is: $p_s = \prod_{i \in S, i \ne s} \sigma_i$.

If ω'_s is accepted by all the overlays, the weight of overlay s is updated to $\omega_s^t = \omega'_s$ and the performance of the overlay s will be improved. Otherwise, the weight will remain the same. Then, the next period $t+1$ starts, in which overlay $s+1$ proposes its new weight. The process is ended when there is no weight updates during the last $|S|$ periods. The initial weight of each overlay is set as 1. And the step length of each overlay is limited as $\omega'_s - \omega_s^{t-1} \le 1$. Therefore the weighs of overlays will converge to a stable state after several periods.

V. Performance Evaluation

A. Simulation Enviorment

In this section, simulations are performed to estimate the proposed cooperative solution. We focus on the scenarios

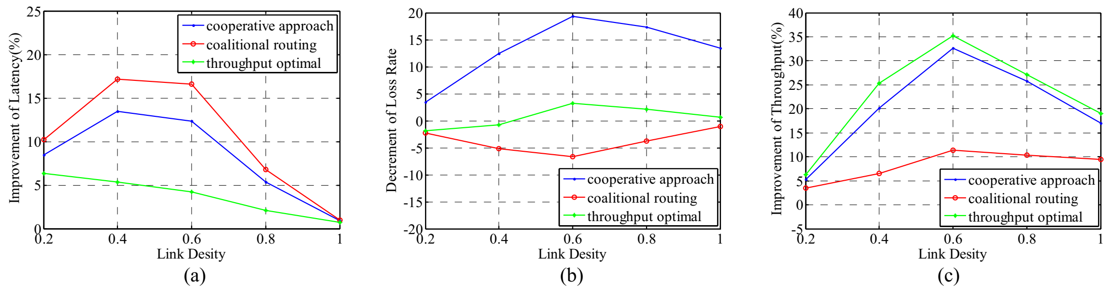

Figure 2: The improvement of overlay performance by using different routing strategies in scenarios with different link densities.

where several heterogeneous overlays are deployed on top of a native network. The native network of the ISP is generated by using the Waxman-Salama model. The bandwidth of a physical link ranges from 10 to 20 Mbps. We evaluate our cooperative solution by applying it to heterogeneous overlays, which are latency, packet loss, and throughput. The topology and service demand of each overlay is generated randomly.

B. Results and Discussion

Using the performance of selfish overlay routing as a reference, we compare the performance improvements of our cooperative approach, the coalitional routing in [10], and the throughput optimal routing.

We apply these approaches to the scenarios that the link density of the native network ranges from 0.2 to 1. Figure 2 illustrates the performance improvement of heterogeneous overlays. When the link density is very small, all three approaches perform not very well. It is because the physical resources can hardly satisfy the traffic demands of the overlays. As the link density grows, all three approaches perform much better.

Figure 2(a) shows that the latency of latency sensitive overlays reduced by our cooperative approach is a little bit less than the coalitional routing, and the throughput optimal routing reduces the latency slightly. However, as Fig. 2(b) shows, both the coalitional routing and throughput optimal routing have negative impact on the performance of loss-rate sensitive overlays, while our cooperative approach reduces the loss-rate efficiently. And Fig. 2(c) shows that the coalitional routing improves the performance of throughput sensitive overlays by reducing their latencies. Since we take into consideration the bandwidth shared by throughput sensitive flows, our cooperative approach archives a near optimal performance.

VI. CONCLUTIONS

This paper focuses on improving the interaction between co-existing heterogeneous overlays. The concept of SDN is applied to build overlays and a cooperative framework for the heterogeneous overlays is proposed. A cooperative solution based on ANBS is introduced to guide the overlays to improve their performances. We also proved a weight balancing solution to enhance the ANBS. Simulations are performed to evaluate the cooperative solution. The results show that our solution can improve the performance of heterogeneous overlays.

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