A Framework for Fine-Grained Inter-Domain Routing Diversity Via SDN

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***Abstract*—The Internet reserves numerous potential path diversity among densely connected autonomous systems (ASes). However, the Internet routing is controlled by Border Gateway Protocol (BGP), which has limitations in the path diversity expression and cooperation between ASes. The emergence of software defined networking (SDN) scheme provides flexible control over networks. In this paper, we leverage the programmability of SDN, and propose a new routing control plane, named RCS. It can support flexible inter-domain forwarding control, and enable network functions chaining along inter-domain paths. In RCS, network functions are abstracted and disseminated between SDN ASes. Customer networks can set up their desired routing paths for particular applications, such as multipath routing. RCS can be deployed incrementally to apply SDN to current inter-domain settings. In our primary analysis based on BGP data, the provision of customizable forwarding control at only a few ASes can lead to a large of potential path diversity.**

***Index Terms*—software defined networking (SDN); Internet routing; inter-domain SDN; BGP;**

I. Introduction

The Internet is composed of a large and growing number of autonomous systems (ASes). These ASes use Border Gateway Protocol (BGP) to exchange reachability information and create routes for inter-domain routing. The Internet service providers (ISPs) primarily operate their networks as pipelines that provide fundamental reachability for the whole Internet. As the boom of the Internet, requirements from business and innovations make ISPs could not stay on simply pipelines supplying best-effort packet delivery. For example, The Internet is meeting the issues from mission-critical QoS-aware applications (e.g., real-time communication). The current inter-domain system is rigid and facing the emerging requirements of novel inter-domain routing, such as multi-path routing, flexible routing policies among ASes, and new Internet routing scheme.

BGP routing makes decisions based only on destination IP prefixes. Each border router in an AS has a deterministic nexthop to a specific destination. Although there may exist multiple diverse inter-domain paths from one AS to a destination prefix, routing based on destination IP prefixes needs to determine a single "best" path for a given destination. An AS usually learns only the best selected routes and do its own choice, and then exports the best routes to immediate neighbors. In this process, many suboptimal routes have been discarded, and don't appear in remote route choices. A proposal of additional AS path announcement [11] is used for the case of iBGP route optimization. BGP Flowspec [2] can disseminate flow-level information in BGP, but it is used for inter-domain coordination of DDoS traffic filtering. There are also some requirements that different inter-domain routing policies are applied to different source addresses or applications. This fine-grained forwarding path diversity cannot be expressed with only destination IP prefixes in BGP.

Software Defined Networking (SDN) scheme decouples network control plane and data plane. Such that they can evolve independently. At present, SDN has been applied to intra-domain networks within separate administrative domains, such as enterprise networks and data centers. It is a challenge to extend SDN to inter-domain settings. The work SDX [8] was proposed. It is deployed on an IXP and impact the inter-domain traffic between the IXP's member networks. The work CXP [10] further extends SDX. It uses SDN centralized control over multiple IXPs to create QoS-aware end-to-end paths. WE-Bridge [14] proposes an approach for inter-domain SDN to create peer session and exchange network views between SDN domains. But WE-Bridge will face a network view scalability issue when applying it to large-scale inter-domain area.

In this paper, we propose an inter-domain routing control framework, named *route chaining system* (**RCS**). It is a SDN-based control plane for inter-domain routing. RCS is built based on the fundamental BGP routing on the Internet. It can enable incremental application of SDN on the Internet to optimize BGP routing control. Each AS can export some network functions (e.g., path diversity) about flow control ability to RCS, which then distribute these functions among other RCS ASes. And then, other ASes may pay for and set up desired fine-grained inter-domain paths using the functions on selected ASes. This will extend AS business model. Our experimental analysis shows that the provision of forwarding control at only a few ASes will result in a large of potential path diversity.

This paper is organized as follows. In Section 2, the design of RCS is presented. The result of a primary experimental analysis is showed in Section 3. The related work and conclusion are described in Section 4 and 5 respectively.

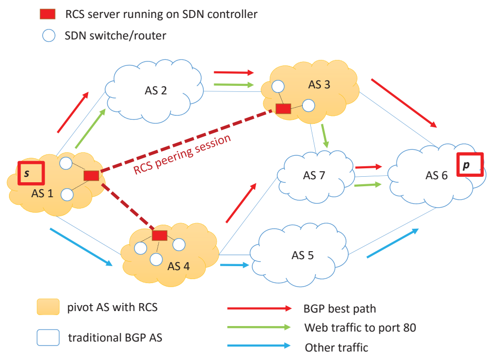

Fig. 1. An example of RCS and pivot ASes.

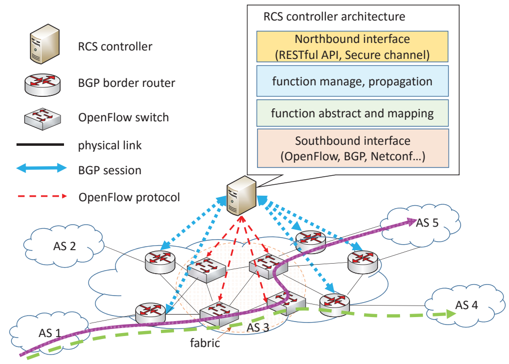

Fig. 2. RCS controller architecture and the structure of pivot AS.

II. The Design of RCS

This section presents the design of RCS. Firstly, we present an overview with an example. Then, we describe the mechanisms for network resources dissemination and choice in RCS. After that, we propose an economic model that can be fostered in the ecosystem of RCS.

A. Overview

RCS provides an control plane where ISPs can abstract and publish network services, and customers make choices and set up selected services. The following presents the sketch of RCS design: 1) The ASes operate some services, including the necessary BGP routing, and other diverse services based on cloud and SDN/NFV technologies. The ASes that deploy RCS (i.e., RCS-enabled ASes) are called *pivot* ASes. They are points where routes can be configured by users. RCS abstracts AS-hosted services into a set of packet patterns (e.g., 5-tuple) and actions (e.g., forwarding). 2) In BGP, each BGP router needs to decide the single best route from the learned routes and then propagate out. RCS decouples network service resources propagation and decisions. The RCS nodes in one AS peer with other RCS nodes in other ASes, and disseminate abstracted services. By dissemination, pivot ASes can learn the service messages from their peering pivot ASes. 3) Based on service information, a pivot AS can make its choices for desired requirements, and then set up service rules (i.e., patterns and actions) to responsible pivot ASes to enable forwarding path diversity (or other services) for specific traffic. The pivot ASes at the edge of the Internet (e.g., eyeball ISPs or content providers) mostly use RCS services to customize their routing path for specific traffic; while the nodes in transit networks can create new services based on the choices combining other AS services, and publish them into the RCS. 4) Evolutionary deployment. At first, RCS can be deployed in individual ASes to optimize routing selection or enable path diversity for BGP routing. It doesn't require every AS to deploy RCS to take effect. The whole deployment needs high cost and is unnecessary. In fact, our experimental analysis shows that only a small number of important ASes used as pivot ASes can enable notable path diversity.

We illustrate RCS by an example. The ASes that participate in RCS should deploy SDN techniques on existing IP networks, such as SDN-IP [13] or SDN fabric [3], to enable flow-level IP traffic control in their administrative domain. And then, RCS runs on SDN controllers, and collects IGP and BGP routing information in this domain. As shown in Figure 1, we assume that the best path to a destination prefix p in AS 6 from `AS 1` to p is (1-2-3-6), and the best path from `AS 4` to p is (4-7-6) in BGP routing. AS 3 and AS 4 export some network function resources to AS 1 by RCS peering session. For example, AS 3 announces to AS 1 a network service function represented by `(src=*, dst=p, act=forward to AS7 with AS path 3-7-6)`, which means AS 3 can supply a network function that provides an alternative BGP route to p with AS path (3-7-6), and you can set up this function to enable path diversity for your traffic by specifying source addresses. AS 4 may announce to AS 1 a function `(src=*, dst=p, act=forward to AS5 with AS path 4-5-6)`. AS 1 will learn these functions from AS 3 and 4. Based on BGP routing and leaned functions, AS 1 will compute and set up desired rules by filling in the function `src` with the specific source prefix s of AS 1 to enable path diversity at AS 4 for the traffic from s to p. The same to AS 3. And AS 1 set up rules in itself by SDN to switch the traffic matching `(dstport=80)` to AS 2, and other traffic to AS 4. Finally, the Web traffic to port 80 will not take the BGP best path, but the path (1-2-3-7-6), which is a concatenation of BGP path (1-2-3) and (3-7-6) by pivot AS 3, based on transport layer ports and source and destination IP addresses. This concatenated path is called *routing chain*. Similarly, the other traffic from s to p could be directed to the path (1-4-5-6) through pivot AS 1 and AS 4.

B. Architecture of RCS controller

Figure 2 shows an illustration of RCS controller architecture and an example of the structure of RCS-enabled pivot AS. Here, we present a conceptual architecture of RCS controller. It mainly divided into four parts, including the southbound and northbound interfaces, network function abstract and mapping, and function management and propagation.

1) **Southbound interface**. An AS can supply network functions (or services), such as traffic forwarding or filtering, by substrate infrastructure composed of physical devices or cloud platform. RCS nodes provide a centralized management for these functions. The southbound interface of RCS interacts with substrate infrastructure. It can be implemented with OpenFlow protocol, BGP, Netconf, application RESTful API or other protocols, etc. For example, in Figure 2, the southbound interface includes OpenFlow protocol and BGP. The RCS controller learns available BGP routes from AS BGP border routers. For one destination prefixes, it may learn multiple routes with different AS nexthops. These learned routes will be used to compute and abstract network functions of inter-domain routing path diversity by RCS controller. When the AS 3 receives a request of a network function switching the export AS of one traffic flow from AS 4 to AS 5, the RCS controller uses OpenFlow protocol to install the corresponding flow entries into the switch fabric to direct incoming traffic to the specific export BGP border routers to accomplish this request.

2) **Network function abstract and mapping**. This component implements a primary abstract of network functions. In this module, network operator can define the function names, and the mapping between function names and the program fulfilling that function. It gives the raw network functions that can be called by upper layer. And then, operators further abstract raw network functions into $match$+$action$ network function information (NFI), which can be propagate out. It also collects the network views of underlying network substrate, such as topology, link bandwidth, QoS metrics, and manage the mapping between network view to physical network links and devices.

3) **Network function propagation**. This module is mainly responsible for the propagation of network functions supplied by the AS. It provide a network function dissemination mechanism, by which it can peer with other RCS controllers of pivot ASes, and receive and propagate NFIs. This will make network functions be publicly leaned and accessible.

4) **Northbound interface**. The northbound interfaces of RCS are used to program services for users. It provide interfaces for remote users to request this AS to execute desired network functions. The form of interfaces can be Web RESTful APIs, or remote secure channel encapsulated by SSL. This component is also responsible for necessary authority and authentication for the security of network service access.

Because the $match$ abstract in network function may have multiple fields of IP packet header, such as source and destination IP prefixes, it will cause the expansion of the number of installed forwarding entries. This is the capacity scalability issue of the data plane of a pivot AS. Many ways can alleviate the scalability issue. We can apply MPLS tagging (e.g., SDN fabric [5][3]) or the MPLS-like routing paradigm segment routing [19], to the switch fabric. A price leverage that the network function expending more data plane cost will have expensive price is also an approach to adjust the active flow entries in data plane.

C. Network function abstract

A pivot AS abstracts its network services into network function blocks (NFBs). A NFB consists of three parts: a set of matching patterns and actions, and an attribute. The programmable elements supplied by pivot ASes are reflected by these NFBs. The $match+action$ set defines instructions of this NFB, and the attribute defines some properties about this NFB, including AS path, service-level agreement (SLA) properties. The matching pattern takes the IP flow 5-tuple fields as basic match fields, which are supported by the switches of OpenFlow specification. It also can extend matching pattern to application layer if the substrate network support it. Each field may be an exact value, wildcard or a range of values. These values indicate a set of match field values that is permitted to be set. An action set is a set of actions defined by that AS, such as "*drop*", "*forward packet to a specific nexthop*", etc. Some NFBs express network services related to inter-domain routing, such as matching a certain pattern then forwarding to a AS hop. In a routing related NFB, the attribute at least contains a AS path to the destination IP prefix to avoid forwarding AS path loop when calculating route chaining. Some NFBs are not related to routing and have nothing to do with changing BGP routing path, such as packet filtering. Such NFBs can ignore AS path attribute because it can be obtained from BGP routing.

D. Network function dissemination

Pivot ASes create RCS peering connection with other pivot ASes and propagate NFBs among them. For one pivot AS, it can peer with any other pivot ASes. In practice, it should select the pivot ASes that is close in geographical location or AS topology. NFBs are propagated through network function messages (NFM). a NFM message includes many entries of updates. An update entry contains a group of NFBs, the type (i.e., announcements or withdraws) of the group of NFBs. The announcements have the NFB access points IP addresses and the number of the AS supplying the NFBs, and the propagating AS path to avoiding advertisement AS loop.

Becuase RCS is based on the BGP routing, the dissemination of NFBs between peering pivot ASes sometimes take AS business relationships [**?**] into account. NFBs have different disseminating scheme:

1) The NFBs that are not related to routing, just individual functions of an AS, can be flooding to every peer pivot ASes. They can be set up on any BGP routing path.

2) The NFBs that change forwarding path to an available non-best BGP routing path should propagate according to the valley-free principle of AS business relationships [7]. The distance between two peering pivot ASes may contain multiple AS hops. For the one AS a in a pair of peering pivot ASes, if the other peer pivot AS b appears in the a's BGP routes learned from customer ASes, a can announce to b the NFBs of destination prefixes learned from all other BGP neighbor ASes. If b appears in the a's BGP routes learned from provider ASes or the ASes with peer-peer relationship, a should announce to b the NFBs of destination prefixes learned from BGP customer

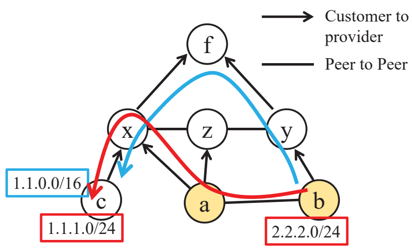

Fig. 3. An example where pivot AS c provides a non-valley-free transit path for the flow with source prefix 2.2.2.0/24 and destination prefix 1.1.1.0/24

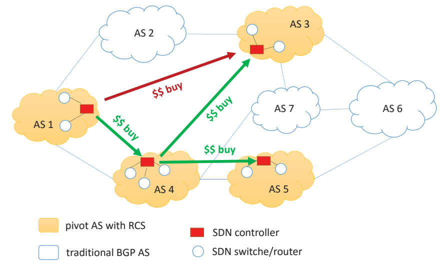

Fig. 4. The possible business model in RCS.

ASes. The NFBs that may violate valley-free principle are also allowed to be propagated in RCS, Other pivot ASes can receive them, but may not successfully request the execution.

3) A pair of pivot AS may negotiate a non-valley-free routing path. For example, in Figure 3, AS b and AS a have a peer-peer business relationship in BGP routing. And both AS b and AS a are pivot AS, and they create a RCS peer session between them. In BGP routing, AS b appears in the AS a's BGP routes learned from AS b itself (AS path is (b)) and the provider AS z (AS path is (z,y,b)). Suppose that AS a announces a non-valley-free NFB to AS b that is `(src=*, dst=1.1.1.0/24, ASPATH=(a,x,c))`, and AS b has received this NFB. If AS b wants to enable this function to obtain a shorter path (b,a,x,c) to 1.1.1.0/24 in AS c, it should negotiate with AS a (e.g., pay for this service) to allow it use this NFB. Then, AS b sets up this function at AS a. Finally, a new transit relationship between them is created, which cannot work in BGP routing. This example RCS can provide flexible and particular path diversity.

In NFB propagation, each pivot AS may continue or stop propagating some NFBs to its peering neighbors. It also can create its new NFBs based on learned NFBs from neighbor pivot ASes.

E. Path and network functions chaining

After collecting NFBs from its neighbors, a pivot AS can make its own choice based on these pivot information and BGP routing. It can select multiple pivot ASes and related NFBs, and then combine them with BGP routing to create desired routing path and function chains. There is no general and best algorithm on how to create a path and function chain satisfying multiple constraints of QoS, or connecting a series of functions. But two critical things should be guaranteed: 1) The desired matching fields and actions are subsets of the intersection of match and action sets supplied by the selected pivot ASes on the path to the destination. Under this condition, you can set up the desired match and action at each selected pivot AS; 2) Avoid forwarding path loop. The AS path information contained in NFBs is used for this intent. When we plan and compute the path to a destination based on the combination of AS path segments from NFBs and BGP routing, the AS path loop can be checked. To improve efficiency, we should use the minimum number of pivot ASes to construct a routing path chain. This way help to reduce computing complexity and dynamics of NFBs from pivot ASes.

By selection and computation about routing chains, the pivot ASes and the match rules and actions to be set up can be determined. And then, the customer AS set up these function rules at the corresponding pivot ASes to construct routing chains on the Internet. If the customer AS receives successful acknowledges, it can set up local SDN rules to forward traffic to these routing chains. RCS supports multiple ways to set up routing chains for a customer AS. Because the customer AS knows what pivot ASes are chosen. It can notify the related pivot ASes to install correct rules directly. This way relies on the pivot AS information and authentication from registration. Another way is to delegate a upstream provider pivot AS to set up routing chains.

F. Business model

RCS promotes network service providers creating new business model. In the ecosystem of RCS, NFBs are considered as the programmable service resources provided by pivot ASes. Two business model can be taken in RCS. One is a direct lease model. A pivot AS creates particular and various network functions, and take them into NFBs. Some of NFBs can be distributed freely, and any other pivot AS can use these free functions. Some NFBs may be significant and high cost, and other pivot ASes can directly buy these NFB resources of this AS, and directly peer with this pivot AS to set up desired network functions at this AS. The direct lease has a higher efficiency in application of network service resources.. However, direct lease may cause lots of direct peering session, which will increase the communication and computing cost for customers and service providers. Another approach is a hierarchical model like today's Internet. In this model, two pivot ASes may have customer-provider or peer-peer relationship. A customer pivot AS can create RCS peering session with provider pivot ASes, and purchase service from them. A provider AS makes its own network functions, and also transit other pivot AS's network functions to its customers. For example, in Figure 4, AS 1 is a customer of AS 4, and AS 4 is a customer of AS 3 and 5. They has a hierarchical business model. AS 1 also has a direct lease relation with AS 3.

III. Experiments

In this section, we give a primary evaluation on the effect of pivot ASes on path diversity on the Internet. We collect the Internet IPv4 AS topology with annotation of AS relationships from CAIDA [18] of the date 2014/08/01. And, we gather IPv4 BGP routing tables from RIPE [21], RouteViews [23], Internet2 [20], and PCH [22] of the same date. These BGP tables are observed from about 1550 different AS vantage points. BGP AS paths are extracted from these BGP tables. We discard the AS paths containing loops and private AS numbers. To rank AS nodes, we use the metric AS customer cone [15]. The customer cone of AS x means the set of ASes that can be reached by starting from x and go along provider-customer links. We collect the dataset of AS cone from CAIDA, and sort AS nodes in decreasing order. And then take the top N, $(N = 100, 300, 500)$ AS nodes as the pivot ASes deployed with RCS system in our analysis. We denote these samples as `cone100, cone300, cone500` respectively in the following results.

Firstly, we analyze the pivot ASes distribution on the observed AS paths. If a path traverses one or more pivot ASes, we say this path is covered by these pivot AS nodes. And it implies that this path may be impacted by these pivot ASes. We have statistics on the distribution of pivot AS in these BGP AS paths. The result is shown in Figure 5. We can see that more than 90% AS paths are covered by at least one pivot AS (and `cone100` has little of paths not covered by any pivot AS). It has about 60%∼80% AS paths covered by more than one pivot ASes from `cone100` to `cone300`. This shows that most AS paths can be influenced by only a small number of ASes with larger size of customer cone. Because these ASes are important transit networks on the Internet.

And, we analyze the control networks comprised of the pivot ASes. We assume that if two pivot ASes are logically neighboring (i.e. there are only non-pivot ASes between them) in an AS path, there will be a peering connection between them. In this way, a logical network of pivot ASes is formed. The average shortest path length is 1.64, 2.08, 2.29 for the logical network with the pivot ASes of cone100, 200 and 300 respectively. Figure 6 shows the distribution of shortest path length. Most path lengths are very small, which indicates fast propagation of NFB messages in these networks.

We estimate the potential path diversity by the following way. If a path P from AS a to c traverses a pivot AS b, we will compute all the possible shortest paths from b to c, and concatenate them with the path segment from a to b in the path P. Then, we get a set of diverse paths from a to c. In this way, we infer the diverse paths based on observed BGP AS paths and pivot ASes. The statistical results show that, for cone100/200/300, there are about 34 and 75 average of diverse paths between the same start and end ASes in the observed BGP AS paths. In Figure 7, about 40% and 75% BGP AS paths have more than one diverse paths for cone100/200/300. And about 10% and 20% BGP AS paths have potential 10 and 100 diverse AS paths based on cone100 and cone300.

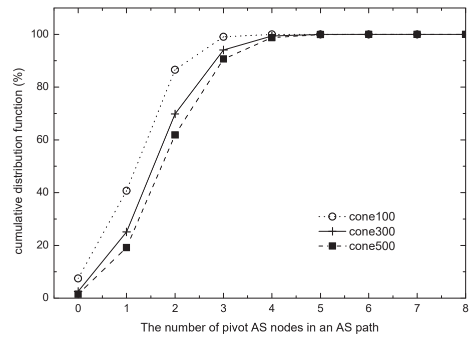

Fig. 5. The distribution of pivot ASes on observed BGP AS paths.

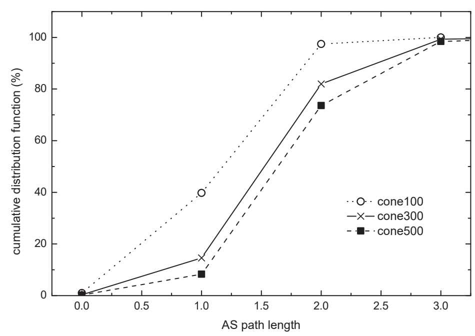

Fig. 6. The distribution of shortest path length of the logical networks that consists of the pivot ASes from cone100/200/300.

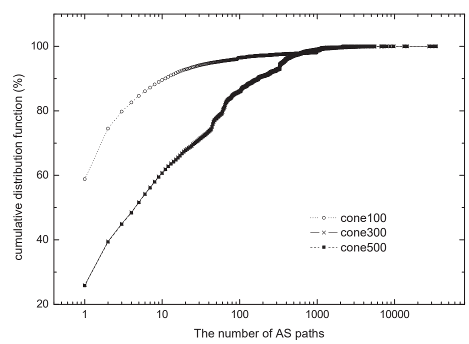

Fig. 7. The distribution of diverse paths derived from BGP AS paths.

This implies that some routes in BGP can have a large degree of path diversity. This result needs to examined by more real Internet routing data. Our primary analysis show that a small number pivot AS (i.e., cone100/200/300) can get a powerful path diversity if we select the important transit ASes to deploy RCS.

IV. Related Work

There are several related works on applying SDN to inter-domain routing. The work RCP (Routing Control Platform) [6]

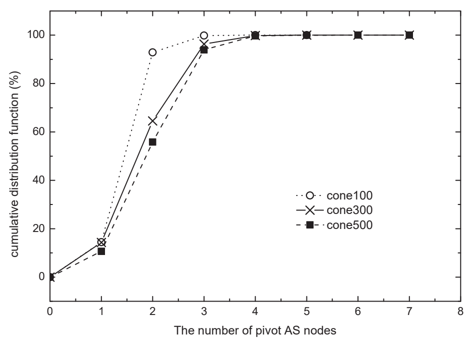

Fig. 8. The distribution of pivot ASes on the derived diverse AS paths.

[4] firstly proposes a separation of routing control plane with packet forwarding to overcome the limitations of BGP routing. In RCP, a separate routing control platform is dedicatedly responsible for routes distribution and path selection on behalf of IP routers. Recently, the work RouteFlow virtual routers [16] and a further distributed system RFCP [17] building upon RouteFlow implement the principles of logically centralized routing control of RCP in the environment based on SDN/OpenFlow.

Some works study the incentives and business model to improve Internet routing by suggesting routing control logic is outsourced to third party called mediators. In the model RAS (Routing-as-a-Service) [12], routing service providers build virtual links on ISPs (Internet Service Providers) networks, and calculate end-to-end paths spanning multiple ASes for end customers.

To enable incremental deployment for SDN, a research work of SDN-IP network peering [13] were conducted by us from 2013. This work focuses on the interaction between BGP based SDN domain and legacy BGP. This solution applies the BGP between the SDN and IP domains or between SDN and SDN domains. Gupta et al. [8] present a software defined Internet exchange (SDX) to bring SDN enable features to practical operation in today's BGP inter-domain routing. CXP [10] extend SDX to multiple IXPs' cooperation with centralized control. WE-Bridge [14] proposes an approach for inter-domain SDN to create peer session and exchange network views between SDN domains.

V. Conclusion

In this paper, we propose a routing control plane, named RCS. It can enable incremental application of SDN on the Internet to create customized path diversity in BGP routing control. In RCS, each AS that enables SDN control in its domain can export some pieces of its flow control functions (e.g., available multiple routing paths) to its peering RCS neighbor ASes, which will further distribute these network function pieces among these RCS ASes. And then, all other RCS ASes may learn these published network functions and remotely set up desired fine-grained inter-domain paths in selected ASes. Our experimental analysis shows that the provision of forwarding control at only a few (100/200/300) ASes will result in a large of potential path diversity. We believe that a new control plane that can provide programmability for customer-specific routing path will benefit Internet architectural evolvement.

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