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Design and Implementation of Monitoring Schemes for Software-Defined Routing over a Federated Multi-domain SDN Testbed

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***Abstract* — Emerging Software-Defined Networking (SDN) paradigm has been widely affecting most networking fields. However, the real-world SDN application for inter-domain routing management is still limited since the routing exchange among wide-area networks is quite complicate due to the extreme scale of global Internet connectivity. Several SDN-leveraged routing ideas are being proposed to improve the routing exchange among wide-area networks. Thus, in this paper, an on-going experience for experimenting and validating the inter-domain routing proposals over OF@TEIN federated testbed in Asia is shared. By focusing on the design and implementation of monitoring deployment for visibility support, we try to identify practical key points and provide improved monitoring for validating the performance and anomaly of the exchange. Other design considerations are also discussed together with possible future research directions.**

***Index Terms* — SDN-leveraged routing, federated multi-domain testbed, monitoring, measurement, visibility.**

I. Introduction

As the Software-Defined Networking (SDN) [1] enables the possibility on programming network operation with softwarized methods, it becomes a popular topic in research and education fields. The most significant advantage of SDN is its flexible controllability on network provision, and it also offers a framework to manage the network status. In the legacy network architecture, the network interaction depends on protocol negotiation among network nodes, and operators may need to setup proper configurations on network devices to let them know how to recognize the forwarding information. However, in SDN, this work can be done by the controller well, and the protocol negotiation among SDN devices is no longer needed. The SDN controller is able to centrally instruct network devices how to treat incoming packets. Furthermore, optimization mechanisms such as traffic engineering, fault-tolerance, security and measurement can be easily implemented on SDN-enabled network due to its characteristic of centralized control.

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Nowadays, SDN is gradually applied on network field [2]. Jarschel et al. [3] summarized several use cases, pointing out the key attributes of SDN, and reviewed some start-up cases toward large-scale SDN appliance on Wide Area Network (SD-WAN). For example, Google [4] used software-based control mechanism running on commodity servers to perform the simplified coordination for changes of network status. For another, Microsoft [5] designed a new architecture to carry more traffic and support flexible adaption with the software-driven mechanism. Moreover, in exchanging Internet traffic between Internet Service Providers, Gupta et al. [6] addressed the difficulties of making WAN traffic delivery, and they also proposed an experimental design with Software-Defined Exchange (SDX) method to process traffic exchange among routers participated in the internet exchange point. These novel researches are the instances for improving network operation with the SDN techniques over the wide-area environment.

Even the SDN is already applied on research, educational and commercial solutions, deploying SDN techniques into WAN environment is still a crucial task. Sezer et al. [7] presented a discussion about the difficulties when SDN is raised in different aspects. Due to the characteristic of WAN, any routing effects has to be careful to keep the network work with stability and consistently. Operation such as fluctuating and symmetric route should be avoided. The improper configurations may lead packet transmission corrupted. Nevertheless, there are several integration issues need to be considered. For example, the routing decisions made by SDN controller must be reliable. Moreover, establishing a valid supervisor for monitoring network behavior is necessary. Hence, how to acquire the measurement and monitoring is an important issue in routing exchange of SDN.

Due to the necessity on exploring and verifying SDN innovations, the network testbed plays an important role on research and education purposes. There are many colleagues and institutes build their testbeds for conducting experiments. For creating a testing environment approaching to wide-area network, the OF@TEIN testbed [8] provides such a service, and authors of this paper manage part of testbed sites collaborated with the OF@TEIN testbed. Because of the newly implemented SDN method, the testbed nodes are able to use public IPs to make data transmission with each other. The testbed network is built as integrated control architecture with OpenFlow [9] and BGP [10]. In this circumstance, network operation on delivering packets is similar to the WAN-based routing. The operation for inter-connecting testbed sites is claimed to be the Software-Defined Routing (SD-Routing) Exchange by the authors. Because of the importance of system operation and management, there is demand to monitor the experiment network of the testbed. This paper introduces the plan for making measurement and observation on the inter-connection among testbed sites. The paper aims to share the experience for planning and designing a method to monitor BGP routing status initially, identifying the possible issues and challenges for future development.

The remainder of the paper is organized as follows. Section II brings with a brief review of background and related work. Section III has made a discussion of purposes and concerns. Section IV interprets the operation environment, explaining the design of system. Section V shows the initial evaluation results of the implementation. The plan for future developments is presented in Section VI. Finally, the conclusions are given in Section VII.

II. BACKGROUND AND RELATED WORK

This section describes the background knowledge and related work. It explains the concerns for designing and developing issues of SD-Routing Exchange in the OF@TEIN testbed.

A. *Wide-area Routing in SDN*

For reaching a better network architecture with flexibility and adaption, the SDN is recognized as an innovative way [11] for network provision. The most significant different between SDN-enable network and legacy network is that the SDN uses centralized control method to manage the network. It separates the control plan and data plane by utilizing out-of-band control channel to make control communication between network operation system (i.e., controller) and device. While the essence of the control plane in SDN network is more fragile than the legacy network. The reason is that the SDN devices (e.g., switch and router) have to be instructed by the controller to process the packets. Therefore, the design issues for securing the control plane are an important thing in SDN research.

Since the BGP [10] is the most wide-spread protocol for managing wide-area routing operation, to stitch local SDN network with wide-area network, the SDN controller has to recognize and advertise routes from/to the legacy network. The provision is usually called Hybrid SDN [12]. For exchanging routes between SDN and legacy network, there are many researches focusing on SD-Routing issues. For example, the BGPMux [13] in GENI project had delivered a software router in VINI [14] testbed to carry real traffic into experiments. On the other hand, Lin et al. [15], Rothenberg et al. [16] as well as Thai and Oliveira [17] proposed their ideas and practices for integrating BGP and SDN. To determine the convergence time between SDN and legacy network, Gämperli et al. [18] illustrated a testing mechanism for further evaluations. For studying SDN traffic engineering and loading balance issues, Hong et al. [19] proposed a hybrid design to make approaches, and they also presented the evaluation result with discussion.

B. *Trans-Eurasia Information Network and OF@TEIN*

The Trans-Eurasia Information Network (i.e., TEIN) is a high speed network for research and education which connected among Europe and Asia areas [20]. There are more than fifty colleagues have joined the operation and established peering through TEIN. The OpenFlow at TEIN (i.e., OF@TEIN [8]) collaboration community was established to carry out the SDN research and education purposes. It is expected to have further education activities in Cloud computing, SDN, Cyber-Security, WSN, Multi-media, IoT and other networking issues. There is also a federated testbed built for network experiments. The infrastructure of testbed is consisted of the SmartX [21] and domestic systems to provide not only computing but networking resources for creating experiments. Currently, the OF@TEIN testbed is constituted of more than a dozen sites and services on this testbed is free for academic use [22].

C. *Software-Defined Routing Exchange on the OF@TEIN*

Owing to the TEIN is a public network which carries the production traffic, therefore, in the beginning, the FlowVisor [23] and the VXLAN [24] are integrated with OpenFlow switch to deliver the inter-traffic among testbed sites. The VXLAN is able to create tunnels for establishing connections. As the result, this implementation solves the problems of traffic isolation and delivery well, while it also has some limitations. For example, the tunnels make intermediate routes being masked, it is hard to realize the status of underlay network. Especially for some routing experiments required to evaluate the network status closing to real network, this shortcoming is prohibited on their purpose.

To enhance the network control ability and use SDN-ways to establish inter-connections among each site in the testbed, a new development with SD-Routing Exchange method is under development. By designing a routing exchange utilizing ONOS [25] controller and software-based BGP router [26], the experiment network of OF@TEIN testbed is acting as a semi-controlled hybrid SDN, operating as an layer 3 overlay network for inter-connecting testbed sites. The routing exchange allows testbed operators advertise their domestic IP prefixes to the experiment network of the testbed. Due to the TEIN network provides the Internet Exchange service for collaborators, namely, the inter-traffic among OF@TEIN testbed sites is count on it for delivery.

III. Discussion

The prototype development of SD-Routing Exchange in OF@TEIN makes the improvement on emulation for the testbed, while it also brings the demands on supervising and management for testbed operators. There are several concerns about planning and designing the monitoring mechanism for routing status on the testbed. This section makes a brief discussion for illustrating the key research issues.

A. Network Stitching

The PlanetLab [27] is the classic network testbed which runs across the WAN. It uses virtualization techniques to create multiple spaces for users, and the related spaces are linked [28] together as slices. Therefore, PlanetLab users are able to use assigned slices for conducting their experiments. The infrastructure of OF@TEIN testbed is partially similar to the PlanetLab, it also consisted of multiple sites from different countries. While the network architectures of PlanetLab and OF@TEIN testbed are different. First of all, for OF@TEIN testbed, the platform is able to allow testbed users to assign public IP addresses to their nodes in experiments. Second, to link inside (SDN) and outside (legacy) networks, the edge BGP router is directly connected to one or more legacy gateways. By doing this, the edge BGP router is able to forward node packets between production network and testbed network on each site.

B. Network Transparency

For a large-scale network testbed with distributed infrastructure, the testbed network is usually collaborated by following methods: light-path, native VLAN, VPN and layer 3 connection. Owing to the light-path and VLAN are expensive in establishment and maintenance, these two solutions are not considered. By contrast, the VPN is an essential way to build site-to-site connection, while it shields the hop information during packet transmission. Therefore, for providing experiment network with more reality, the OF@TEIN testbed using the layer 3 IP routing for packet transmission among testbed sites. However, due to the network environment, the testbed sites are separated by legacy network. The SDN controller is not able to manage the traffic in the intermediate area. For enhancing the scalability, we plan to use an alternative way to let testbed user configure their cross-site experiment network passively. Since several testbed sites are attached with multiple RENs and domestic ISPs, it might be possible to determinate site-to-site routes by assigning different IP domains on the nodes. By doing this, testbed users are able to select network path among their nodes indirectly. For achieving this, developing a measurement method to realize the possible routes in legacy network is necessary.

C. Measurement and Monitoring

In order to realize the system status, there is an existing health check mechanism [29] for monitoring hardware utilization and availability. It uses active ways (with probe packets) to measure data plane of the OF@TEIN testbed. Due to the method is concentrating on end-to-end test, there is a shortcoming to realize the network status between testbed sites. For this problem, there are already several novel researches use open and flexible ways [30] to design measurement methods in SDN measurement. Even so, since the testbed sites are distributed and semi-controlled with hybrid architecture, deploying a suitable and effective way for observing the traffic with visibility is a challenge. Hence, as stated above, there is a requirement to collect relevant information for presenting the inter-network of sites and sharing the results for management.

IV. System Design and Development

This section provides an overview of monitoring the experiment network in OF@TEIN testbed. The design and development issues are introduced in this section.

A. Network Environment

In the data plane of testbed network, the forwarding policies for experiment traffic can be divided as three parts: LAN traffic, Intra-traffic and Inter-traffic. When a node sends packets to another node in the same LAN, the packets are delivered as directly. On the other hand, when packets are sending to the node located in another local network (sub-net) in the same site, the gateway will forward packets according to its routing table. In this part, the gateway routers are stitching to a OpenFlow switch, and the underlay packet processing action is made by the OpenFlow controller. For inter-traffic, the edge routers is used to manage routing exchange among testbed sites. Their next-hop attributes is forced to set as default gateway addresses of legacy networks. By contrast, the edge router of production network also has to setup reverse routes with IP prefixes used by testbed nodes.

As mentioned above, the testbed network in OF@TEIN testbed acts as layer 3 overlay architecture through TEIN and other domestic RENs. On account of requiting extra devices, there are only three sites in OF@TEIN testbed has been equipped with this new architecture, and the local routes also advertise IP prefixes for routing exchange experimentally. For the time being, the development is implemented on GIST (Korea), UM (Malaysia) and NCKU (Taiwan) sites initially. Figure 1 is an example of routing architecture in one of sites. The deployed SDN controller is inherited from SDN-IP of ONOS [25]. For delivering incoming packets on the local SDN network, the data links of related devices are stitched to an OpenFlow switch, and then the controller setups corresponding flow rules for transmission.

B. Routing Exchange

For inter-traffic among testbed sites, a logical transit AS is developed to exchange route information. Routers in this AS are running with Route Reflector (RR) configuration to provide redundancy, which is shown as Figure 2. Due to the connectivity is relying on the Internet, therefore, the advertised routes are setup with next-hop attribute values as the default

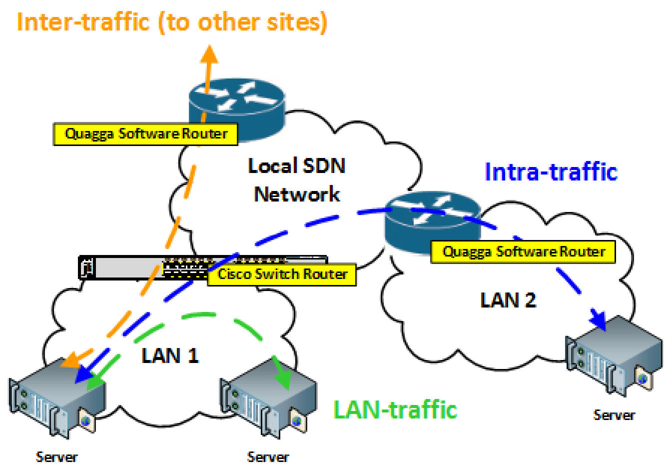

Fig. 1. The traffic forwarding at NCKU site.

gateway. The key point here is that there is no interaction between legacy network and SDN network in this hybrid architecture. The connection established by legacy network can be seen as links among routers in this logical transit AS. By doing this, the packets of testbed network are delivered by production network forcibly in the intermediate areas. In this operation scenario, if the BGP session for one router is abnormal, the routes are still able to be learned from another reflector. By measuring the status of RR routers, the monitoring of overall available routes can be easily made. However, there is no replication to guarantee routing exchange currently. Authors are still finding better solutions to enhance the reliability by adding more failover mechanisms.

C. *Development of Monitoring Schemes*

For monitoring and measurement this SD-Routing exchange, there are several monitoring indexes are required initially in control plane, such as BGP session, advertised IP prefixes, routing information base (RIB) as well as forwarding information base (FIB). Moreover, if the next-hop information can be recorded by the probe packet, it is possible to realize the transparent hops in the intermediate network. There is no way to control the path in the WAN by OF@TEIN testbed, while the routing path can be presented to testbed users, and let them realize more details about the status of experiment network.

Due to most networking devices are supporting standard SNMP-based query, the traffic statistics in data plan are able to be collected easily. For objectively observing the testbed network, the network management system (NMS) is setup at the third-party location to collect data (located at Amazon EC2 ap-northeast-1 region, Tokyo zone). All the routers and OpenFlow switches are required to enable SNMP daemon for pulling information by the NMS. There two common NMS tools are used to gather, analysis and present measured data: Cacti [31] and SmokePing [32]. Some customized scripts are also developed to provide measured data to the tools. We would like to implement different measuring ways to generate various logs as more as possible.

V. Initial Evaluation

To have a quickly view of work-in-progress tasks, this section makes a brief summary of prototyping developments in current stage. For initial evaluation, we focus on several important purposes for managing testbed network: routes advertisement, traffic weathermap, and anomaly notification.

A. *Route Advertisement*

To monitor BGP status, it is commonly and elastically to setup an observer router for receiving advertisement passively. Therefore, the IP prefixes announced from other routers are able to be received by this router, and the route information can also be recorded. However, considering the transit AS for passing advertisements is configured as RR way, it is not able to tracking details for diagnosis advertisement precisely on a single observer. Hence, the designed method is sampling each BGP routers separately. The measured data provides a change for further investigation in future development. By combination with the cacti plugin [33], the monitoring results network can be visualized clearly.

B. *Traffic Weathermap*

Since the original SmartX system already has a mechanism for monitoring the point-to-point throughput among server nodes, therefore, the proposed method in this paper is focusing on the experiment network of OF@TEIN sites. By making combination with the visualization tool [34], a web-based interface for illustrating the statistics of inter-traffic is being built, and the presentation is shown as Figure 3. On this weathermap website, a simple view of inter-traffic is briefly showed tentatively.

C. *Anomaly Notification*

To let site operators of realize of abnormal events, a mailing list is established to forward alert messages to OF@TEIN community members. Currently, the health check of network nodes and BGP session are two major indexes under supervision. If the heartbeat of a network node is unreachable, the detected mechanism will trigger the alert, sending email/SMS to site operators with warnings.

VI. Possible Research Directions in Future Development

On account of that there is only three sites have implemented SD-Routing, the routing topology is simple and clear currently. While there are still many sites in OF@TEIN testbed using the original way for inter-connection. In order to migrate routing functionality as well as develop monitoring schemes to extended sites, several planned and work-in progress tasks are described as follows.

A. *Exchange Centre*

When the number of joined sites grows up, the peering among testbed sites is getting much more complicated. How to manage a reliable routing exchange becomes a crucial task. For elastic and flexible configuration in joining new testbed sites, there is an idea to develop a control centre with automatic

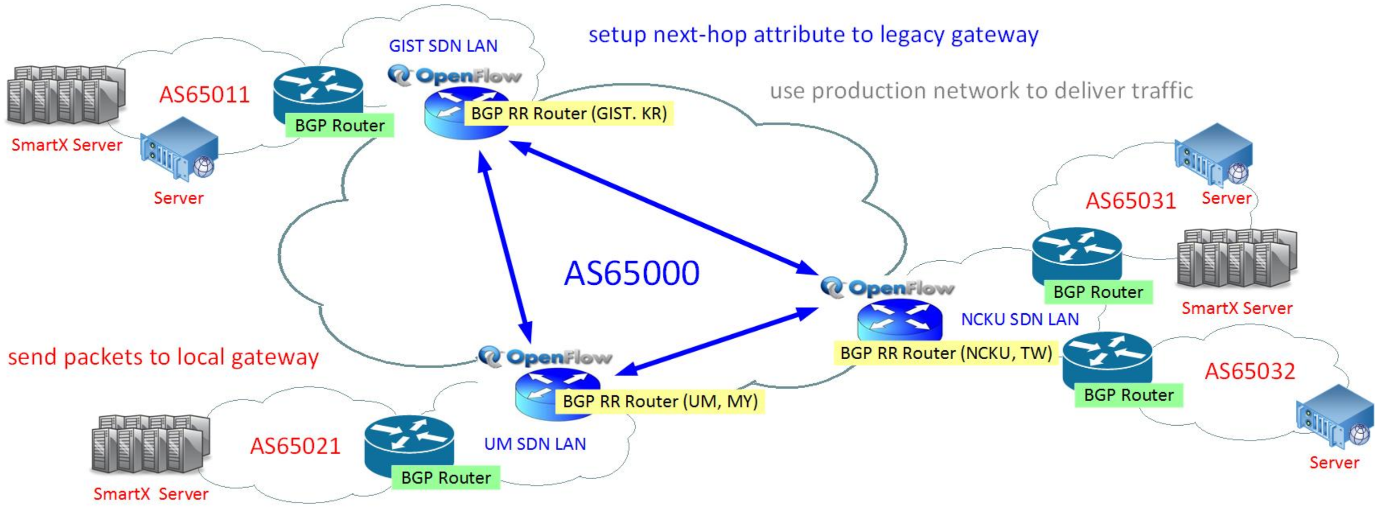

Fig. 2. The BGP routing deployment in OF@TEIN testbed.

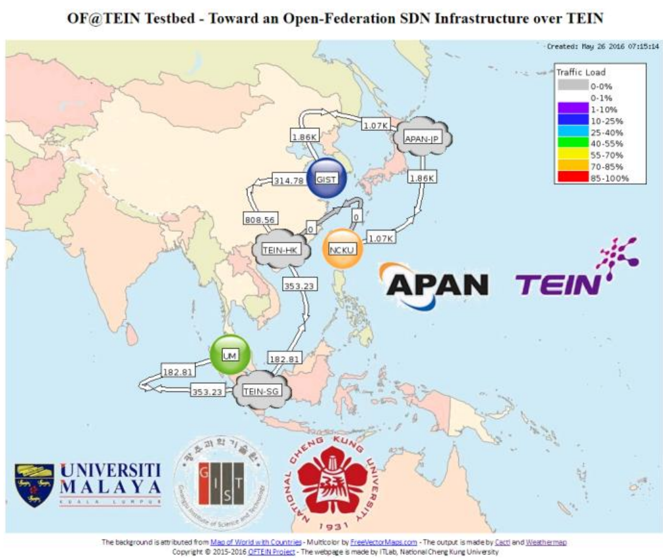

Fig. 3. The output screen of weathermap exported on website.

update ability is a possible solution. After registration, site operators are able to submit their latest IP prefixes and configured policies to the exchange centre, and the exchange centre will push instructions to the routers for updating their configuration periodically. The testbed portal can also have the global view of routing advertisement on the centre.

B. Security

Due to the testbed network in intermediate area is in-band control, the routers are exploited with public access. For securing the system, a classic way is using access control rules to filter irrespective messages for the routers, Furthermore, only the authorized operators are allowed to access the routers, and the configuration of each router should be verified before activated. Integrating security mechanism into exchange centre is probably a choice, the unify authorization and authentication in updating routing configuration can be made with no difficulty.

C. Supporting Multi-layer Monitoring

In current stage, the measurement on the OF@TEIN testbed only watched few entries to satisfy the lowest requirement, such as live ping, traffic statistics, routing advertisement. For better viewing on system status, authors would like to extend the watched layers, collecting measurement data from not only the hardware but software framework. Building a shared database to store from all sites is also a thought. By doing this, the abnormal detection is able to be implemented on all the sites, and the global visibility is easier to make approaches. Furthermore, we would like to consider deploying perfSONAR [35] on each testbed sites, trying to use it for getting more measurement results. It is expected to help us to determine the network status more precisely.

D. User API and Toolkit

To provide testbed users more transparency in their allocated resource in experiments, sharing the measured results in database is a way, there is a plan to organize measured data into some divisions. By using Application Programming Interface (API) and defining query parameters, the authorized testbed users are able to get statistics information about nodes and networks in their experiments. For toolkits on the testbed, they are also able to access the shared database for gathering information. This development is expected to support more exploration for measurement and management issues for testbed users in the future.

VII. CONCLUSIONS

This paper introduces the implementation of SD-Routing Exchange in OF@TEIN testbed, and it also illustrates the management requirements and concerns which met by authors. The proposed method is trying to monitor the networking status of a hybrid SDN architecture with distributed sites. The design considerations and related issues are discussed in the paper, and the possible research directions are also introduced for future development. The aim of this paper is to introduce the experience on evaluation, trying identifying the issues for practicing the monitoring schemes over a federated multi-domain testbed.

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REFERENCES

[1] T. D. Nadeau and K. Gray, SDN: software defined networks. " O'Reilly Media, Inc.", 2013.
[2] A. Lara, et al., "Network innovation using openflow: A survey," Communications Surveys & Tutorials, IEEE, vol.16, no.1, pp.493-512, 2013.
[3] M. Jarschel, T. Zinner, T. Hoßfeld, P. Tran-Gia, and W. Kellerer, "Interfaces, attributes, and use cases: A compass for sdn," Communications Magazine, IEEE, vol. 52, no. 6, pp. 210–217, 2014.
[4] S. Jain, A. Kumar, S. Mandal, J. Ong, L. Poutievski, A. Singh, S. Venkata, J. Wanderer, J. Zhou, M. Zhu et al., "B4: Experience with a globally-deployed software defined wan," in ACM SIGCOMM Computer Communication Review, vol. 43, no. 4. ACM, 2013, pp. 3–14.
[5] C.-Y. Hong, S. Kandula, R. Mahajan, M. Zhang, V. Gill, M. Nanduri, and R. Wattenhofer, "Achieving high utilization with software-driven wan," in ACM SIGCOMM Computer Communication Review, vol. 43, no. 4. ACM, 2013, pp. 15–26.
[6] A. Gupta, L. Vanbever, M. Shahbaz, S. P. Donovan, B. Schlinker, N. Feamster, J. Rexford, S. Shenker, R. Clark, and E. Katz-Bassett, "Sdx: A software defined internet exchange," ACM SIGCOMM Computer Communication Review, vol. 44, no. 4, pp. 551–562, 2015.
[7] S. Sezer, S. Scott-Hayward, P.-K. Chouhan, B. Fraser, D. Lake, J. Finnegan, N. Viljoen, M. Miller, and N. Rao, "Are we ready for sdn? implementation challenges for software-defined networks," Communications Magazine, IEEE, vol. 51, no. 7, pp. 36–43, 2013.
[8] "Web portal of of@tein." [Online]. Available: http://oftein.net/
[9] N. McKeown, T. Anderson, H. Balakrishnan, G. Parulkar, L. Peterson, J. Rexford, S. Shenker, and J. Turner, "Openflow: enabling innovation in campus networks," ACM SIGCOMM Computer Communication Review, vol. 38, no. 2, pp. 69–74, 2008.
[10] Y. Rekhter and T. Li, "A border gateway protocol 4 (bgp-4)," 1995.
[11] D. Kreutz, F. M. Ramos, P. Esteves Verissimo, C. Esteve Rothenberg, S. Azodolmolky, and S. Uhlig, "Software-defined networking: A comprehensive survey," Proceedings of the IEEE, vol. 103, no. 1, pp. 14–76, 2015.
[12] S. Vissicchio, L. Vanbever, and O. Bonaventure, "Opportunities and research challenges of hybrid software defined networks," ACM SIGCOMM Computer Communication Review, vol. 44, no. 2, pp. 70–75, 2014.
[13] V. Valancius and N. Feamster, "Multiplexing bgp sessions with bgpmux,"in Proceedings of the 2007 ACM CoNEXT conference. ACM, 2007, p. 44.
[14] A. Bavier, N. Feamster, M. Huang, L. Peterson, and J. Rexford, "In vini veritas: realistic and controlled network experimentation," in ACM SIGCOMM Computer Communication Review, vol. 36, no. 4. ACM, 2006, pp. 3–14.
[15] P. Lin, J. Bi, and H. Hu, "Internetworking with sdn using existing bgp,"in Proceedings of The Ninth International Conference on Future Internet Technologies. ACM, 2014, p. 21.
[16] C. E. Rothenberg, M. R. Nascimento, M. R. Salvador, C. N. A. Corrˆea, S. Cunha de Lucena, and R. Raszuk, "Revisiting routing control platforms with the eyes and muscles of software-defined networking," in Proceedings of the first workshop on Hot topics in software defined networks. ACM, 2012, pp. 13–18.
[17] P. W. Thai and J. C. De Oliveira, "Decoupling bgp policy from routing with programmable reactive policy control," in Proceedings of the 2012 ACM conference on CoNEXT student workshop. ACM, 2012, pp. 47–48.
[18] A. Gäamperli, V. Kotronis, and X. Dimitropoulos, "Evaluating the effect of centralization on routing convergence on a hybrid bgp-sdn emulation framework," in ACM SIGCOMM Computer Communication Review, vol. 44, no. 4. ACM, 2014, pp. 369–370.
[19] D. K. Hong, Y. Ma, S. Banerjee, and Z. M. Mao, "Incremental deployment of sdn in hybrid enterprise and isp networks."
[20] "The cooperation center of the trans-eurasia information network."[Online]. Available: http://www.teincc.org/
[21] J. Kim, B. Cha, J. Kim, N. L. Kim, G. Noh, Y. Jang, H. G. An, H. Park, J. Hong, D. Jang et al., "Of@ tein: An openflow-enabled sdn testbed over international smartx rack sites," Proceedings of the Asia-Pacific Advanced Network, vol. 36, pp. 17–22, 2013.
[22] T. Na and J. Kim, "Inter-connection automation for of@ tein multipoint international openflow islands," in Proceedings of The Ninth International Conference on Future Internet Technologies. ACM, 2014, p. 12.
[23] R. Sherwood, G. Gibb, K.-K. Yap, G. Appenzeller, M. Casado, N. McKeown, and G. Parulkar, "Flowvisor: A network virtualization layer," OpenFlow Switch Consortium, Tech. Rep, pp. 1–13, 2009.
[24] M. Mahalingam, D. Dutt, K. Duda, P. Agarwal, L. Kreeger, T. Sridhar, M. Bursell, and C. Wright, "Virtual extensible local area network (vxlan): A framework for overlaying virtualized layer 2 networks over layer 3 networks," Internet Req. Comments, 2014.
[25] P. Berde, M. Gerola, J. Hart, Y. Higuchi, M. Kobayashi, T. Koide, B. Lantz, B. O'Connor, P. Radoslavov, W. Snow et al., "Onos: towards an open, distributed sdn os," in Proceedings of the third workshop on Hot topics in software defined networking. ACM, 2014, pp. 1–6.
[26] P. Jakma and D. Lamparter, "Introduction to the quagga routing suite," Network, IEEE, vol. 28, no. 2, pp. 42–48, 2014.
[27] L. Peterson and T. Roscoe, "The design principles of planetlab," ACM SIGOPS operating systems review, vol. 40, no. 1, pp. 11–16, 2006.
[28] A. C. Bavier, M. Bowman, B. N. Chun, D. E. Culler, S. Karlin, S. Muir, L. L. Peterson, T. Roscoe, T. Spalink, and M. Wawrzoniak, "Operating systems support for planetary-scale network services." in NSDI, vol. 4, 2004, pp. 19–19.
[29] "Visibility-tools on of@tein." [Online]. Available: http://oftein.net/projects/visibility-tools/wiki
[30] A. Yassine, H. Rahimi, and S. Shirmohammadi, "Software defined network traffic measurement: Current trends and challenges," Instrumentation & Measurement Magazine, IEEE, vol. 18, no. 2, pp. 42–50, 2015.
[31] "Cacti: the complete rrdtool-based graphing solution," 2010. [Online]. Available: http://www.cacti.net/
[32] T. Oetiker and N. Tyni, "The smokeping website," 2005. [Online]. Available: http://oss.oetiker.ch/smokeping/index.en.html
[33] "Monitoring of bgp session via quagga daemon in linux." [Online]. Available: http://forums.cacti.net/viewtopic.php?f=12&t=51271
[34] "Network weathermap: Open source network visualisation." [Online]. Available: http://network-weathermap.com/
[35] A. Hanemann, J. W. Boote, E. L. Boyd, J. Durand, L. Kudarimoti, R. Łapacz, D. M. Swany, S. Trocha, and J. Zurawski, "Perfsonar: A service oriented architecture for multi-domain network monitoring," in International Conference on Service-Oriented Computing. Springer, 2005, pp. 241–254.

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