Visually Guided Flow Tracking in Software-Defined Networking

Tobias Post*
University of Kaiserslautern

Thomas Wischgoll
Wright State University

Adam R. Bryant
Wright State University

Bernd Hamann
University of California (UC Davis)

Paul Müller
University of Kaiserslautern

Hans Hagen
University of Kaiserslautern

Abstract

Software-defined network/ing (SDN) is a novel configuration technique that has the potential to become the future backbone of computer networking. In contrast to conventional networking techniques, SDN utilizes controller elements to configure groups of networking nodes, resulting in a hierarchy. SDNs have to be simulated and analyzed to identify applicable configuration settings for real world applications. To determine the quality of a SDN configuration, its packet flow is an important indicator for the analysis.

This work presents an interactive system for the analysis of SDN data. An intuitive overview of the SDN hierarchy and the underlying packet flow is provided. The ability to track packets through the SDN and to interlink multiple views of the SDN forms an interactive analysis tool that is successfully applied to a simulated SDN dataset.

Keywords: Software-defined Networking, Flow Visualization, Linked Views

1 Introduction

The constantly increasing digitalization of the modern society raises problems in conventional networking, such as high complexity, inconsistent policies and scalability issues [15, 3]. To tackle these problems, new networking methodologies such as software-defined network/ing (SDN) are required. In contrast to conventional networks, where each networking node is configured separately, SDNs provide controller elements that are able to administrate groups of nodes. This work considers each networking node being administered by exactly one controller element, resulting in a hierarchy for the SDN.

The indirect administration of networking nodes enables SDNs to separate the control plane and the data plane of a network. Although, this concept holds the potential to be the future backbone of networking, it also raises new challenges in the field of network segmentation and security, traffic engineering as well as network provisioning and configuration [12]. Due to these challenges, SDNs are not yet widely applied in real world scenarios. Instead, network analysts run SDN simulations with different settings in order to understand the effects of SDN design choices to the resulting network behavior. An important factor that indicates the quality of the SDN settings is the resulting flow of packets through the network [11].

To analyze the flow of a network, visualization is a common tool. Although various successful network and flow visualization techniques are available, they cannot be applied directly to review a flow in a SDN (see Section 2). This is mainly caused by a combination of two effects: First, current approaches do not cover the hierarchical structure and the resulting packet flows of SDNs. Second, current approaches that utilize videos for time-dependent data often result in a phenomenon called change blindness [21].

*E-Mail: tpost@rhrk.uni-kl.de

This work presents a case study of visualizations forming an interactive analysis tool for SDN data in Section 3. A linked view system is presented that relates the hierarchical overview of a SDN to the resulting packet flow through selected elements of the network. By utilizing an interactive brushing and linking approach, network analysts can select nodes or packets of the network and visually track them in a static flow view. This view is designed to identify coherences of packet paths throughout the SDN while avoiding change blindness. Additional, interlinked tabular views help in displaying node and packet properties.

Therefore, this paper contributes:

- Intuitive visualizations of SDN data
- Visually guided flow tracking in SDNs

To show the applicability of the visualizations presented in this case study, the analysis of a simulated SDN dataset is tackled in Section 4. This work is concluded and future research directions are given in Section 5.

2 Related Work

The following section will discuss the recent work targeting the visualization of SDNs as well as network flow visualization techniques.

An overview of network visualization techniques can be found in the work of Guimares et al. [4]. Also, several tools [2, 10, 14] are suitable to review SDN controller nodes and their connections. Unfortunately, these tools focus only on the topology of the controller elements within a SDN. In contrast to that, this paper presents visualizations enabling the analysis of all network nodes within an SDN.

To visualize the flow in a network, statistical methods such as graphs, showing the amount of network traffic per node [18] or node connectivity matrices [23, 8], can be used. Although these techniques provide a suitable overview, they do not make use of a network layout technique. A spatial flow visualization can be achieved by utilizing particles that flow between nodes in a network [22] or utilizing a space-time cube [1]. Although this gives a visual representation of the flow in a network, it introduces visual clutter and can cause change blindness due to animations. In contrast, this work presents a static flow visualization that resolves change blindness while relating to the underlying network layout.

To reduce visual clutter, edge bundling [6, 17] summarizes similar connections between nodes. This concept can be extended to distinguish between flow directions [20] or bundle time-varying flow data [16]. As SDNs induce a hierarchical structure (see Section 3), classical edge bundling methods cannot be used in this case. Instead, hierarchical edge bundling is required [5]. This technique was already successfully applied to time-varying data [9]. In [7] connections between hierarchically organized structures are bundled. These techniques are used as a starting point for the visualization of SDN in this work. Also, the technique of visualizing a storyline with respect to a hierarchy as shown in [13, 19] is extended and adapted to SDN.

3 METHODS

The following section presents an interactive analysis tool to examine the topology of a given SDN and the flow of packets within. The user is able to specify a temporal interval of interest, referenced as the window. Additionally, networking nodes or packets of interest can be monitored or tracked within the SDN.

3.1 Overview

In SDN, controller elements administrate groups of networking nodes. This work considers each networking node being administered by exactly one controller element. This leads to a hierarchical tree representation for the SDN. The root node represents the whole SDN. The children of the root node represent the individual controller elements, referred to as logical nodes in the following. The children of a specific controller element (logical node) are the nodes in the network that are administered by this controller, referred to as physical nodes, referenced by their IP addresses. The children of one administered node (physical node) are the port nodes of this specific IP node.

So the logical path of a transmitted packet follows this hierarchical tree by ascending from the sending port, IP and logical node and by descending to the receiving logical node, IP and port. In contrast to that, the real physical path of the transmission is only between physical nodes/ports. Still, it is beneficial to understand the logical processes and paths, and to examine the hierarchical nature of the underlying logic. To achieve this, a suitable visual representation like shown in the following is required.

This work provides a visualization for an overview of a SDN. In this overview all active nodes in the selected time window are visualized. An active node is a leaf node of the SDN tree that is receiving or sending a network packet within the given time window. To visualize all active nodes in the SDN and the induced hierarchy, the active nodes in the SDN hierarchy are drawn recursively. Here, each node is surrounded by its child nodes in a circular manner as shown in Figure 1.

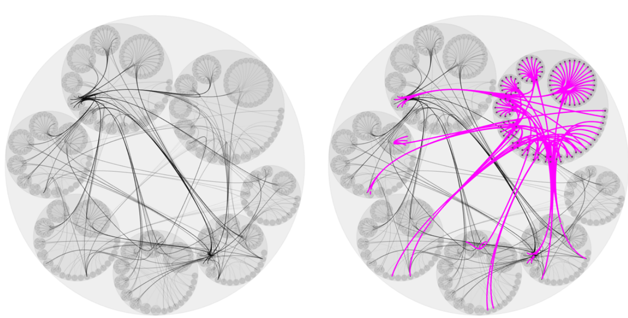

Figure 1: Overview of a SDN simulation for a selected time window. Left: All active nodes in the selected time window are visualized according to the SDN hierarchy. A connecting spline is drawn between each sending and receiving node. Right: Visual enhancement of user selected nodes and links by highlighting.

As only active nodes are shown in the network overview, there exist at least one sending or receiving event for these nodes in the user selected time window. Therefore, sent packets are visualized by a spline connecting the involved active nodes. The displayed logical path of a packet passes through the different hierarchy levels of the SDN. All nodes that are passed by a packet on its logical path are used as sampling points for the drawn spline. As a result, the logical path of a packet through the hierarchy of the SDN is visually encoded. In order to avoid visual clutter, the splines are summarized through a hierarchical edge bundling approach [5]. This results in a fast and intuitive visualization of packets and their way through the SDN hierarchy.

It is possible to select groups of nodes or connections in the overview of the SDN as shown by a magenta color in Figure 1 (right image). Here, the selected elements are visually highlighted. Selecting a node that is not a leaf node in the SDN hierarchy results in selecting the whole sub-tree of this inner node. Also, different detail levels of a SDN can be shown. For example, it is possible to only visualize the root node and the logical nodes of a SDN. Therefore, it is possible to focus on specific aspects of the network.

Although this gives a suitable first overview of nodes and their connections in a SDN, it is important to understand the amount of incoming and outgoing traffic for the considered nodes. Also, a tracking of packets to find common source or destination nodes as well as the identification of equal or diverging physical or logical paths is desired. Therefore, the presented overview is extended by a flow tracking view in the following.

3.2 Flow Tracking

The packet flow in a network is an important feature that helps analysts to determine the quality of the used SDN settings. Although the presented overview of the SDN is a suitable starting point to understand a SDN's hierarchy, the highlighting in Figure 1 cannot distinguish between incoming and outgoing packets of a node. Also, a selected edge between nodes only shows a small part of the path that packets passing through this selected connection travel.

To address these challenges, the overview can be extended by using different highlighting colors for incoming (red) and outgoing (blue) packets, as seen in Figure 3. Packets related to the selected SDN elements (nodes or edges) can be tracked through their content ID. For a specific packet, a selected node or edge is passed at a certain point in time. Other nodes or connections in the SDN are passed at an earlier (red) or later (blue) point in time by this packet. This results in a visually guided flow tracking of packets through the SDN. Arrows, color gradients or diverging colors can further improve an intuitive visualization while the line width could be used to display the amount of accumulated network traffic.

Although this improves the highlighting in the overview, the disability to directly compare the path of packets remain an unsolved problem. As shown in Figure 1, distinguishing single edges becomes challenging due to visual clutter when an increasing number of edges is selected. This is caused by the effect of an increasing number of highlighted edges intersecting each other in the view.

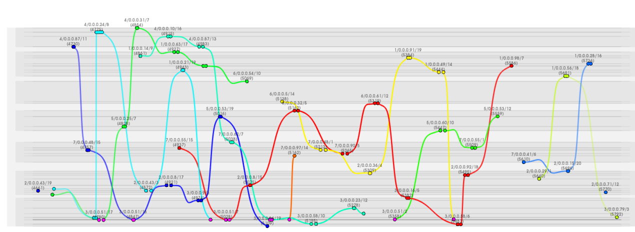

Figure 2: Flow tracking view for selected SDN nodes and their links. Time is used as the x-axis and each active node is represented by a horizontal line. The hierarchy of the SDN is indicated by boxes containing each other. Packets that flow through the SDN are visualized by a uniquely colored spline connecting the visited nodes.

To tackle the mentioned problems, the presented system presents an additional view shown in Figure 3 that displays the selected SDN elements (magenta color) and the network packet traffic passing through them. This flow tracking view is inspired by subway maps. In subway maps, different stations of a train are sorted by their destination order, and their visual representation is connected through a spline. As subway maps form a successful visualization to understand the differences and similarities of multiple subway lines, the goal is to apply this concept to packet flows in SDN data, as

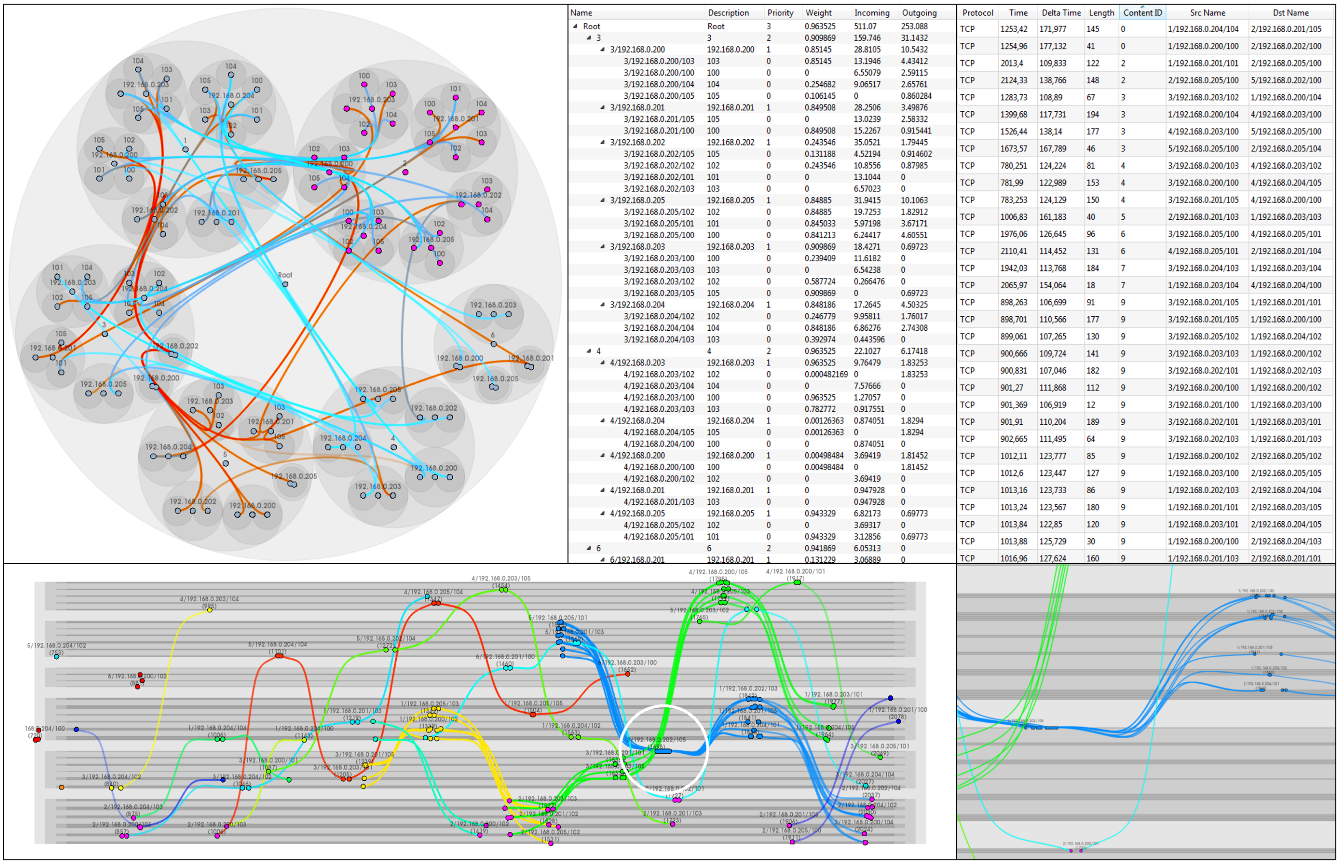

Figure 3: Application of the presented system to a simulated SDN dataset. Upper left: Overview of the SDN hierarchy. Nodes selected by the user are highlighted. Red and blue lines indicate incoming and outgoing packets, respectively. Upper middle: Tree view of active nodes and their properties. Upper right: List of all tracked packets and their properties indicated by the user's selection. Lower left: Flow view of the tracked packets. Lower right: Closeup (white circle) of the bottleneck identified by the flow tracking view.

shown in Figure 2. In the case of a SDN a "train" is a packet and its "stations" are the nodes the packet visits in the SDN. To integrate the different time steps selected in the current time window, time is used as the x-axis of the visualization.

In this visualization each active leaf node obtains a horizontal line that is aligned in parallel to the x-axis. To incorporate the hierarchy of the SDN into the visualization, the line representation of these active leaf nodes are sorted by their logic within the SDN. For each inner active node a box is drawn that includes its active child nodes, meaning that the whole active sub-tree of the node is included. This is done for all active nodes and all hierarchy levels recursively. For each selected node, all related sent and received packets are traced over the user defined time window. This is achieved by tracking the individual packet's content ID, thereby identifying different packets representing the same content. So in general, for each packet's content passing through a selected element in the SDN, the flow graph of visited nodes is displayed.

To visualize the tracked packets, the path of each packet is visualized by a spline connecting all nodes a packet is visiting. Circles are used to mark the points in time when a packet visits a networking node. A hierarchical edge bundling approach [7] is used to bundle edges with regard to the SDN's hierarchy to avoid visual clutter and identify coherent paths for multiple packets. As before in the overview visualization, transparency is used to blend out tracked packets at the borders of the given time window. Each spline is colored by a unique color depending on the content ID of the respective packet to distinguish individual packets and flows in the visualization.

This visualization provided the ability to monitor user selected elements within the SDN and to track individual networking packets over different hierarchy levels in the SDN. Low level physical flows in addition to high level logical flows can be tracked and analyzed and coherent flows and bottlenecks in the SDN design can be identified.

4 Results and Discussion

The presented system was tested with a simulated SDN dataset. As mentioned in Section 1, the concept of SDN is quite novel and not yet applied in many scenarios. Resulting from that, suitable real world datasets are not widely available. Instead, this work uses a simulated SDN dataset generated by the method presented by Nandi [15] to gain insight and show the effectiveness of the presented visualization methods for SDN.

The results in Figure 3 show how the presented system can be used to visualize and analyze SDNs. The overview shows the active nodes in the selected time window of the dataset and a highlighting of nodes that are selected by the user (upper left image). In addition to that, the flow through these nodes is tracked and shown by the a red/blue highlighting. Based on the user's selection, the all views are updated. The tree view (upper middle image) shows the SDN hierarchy and all active networking nodes with their accumulated properties. All packets involved in the flow tracking are shown in the tabular view (upper right image). These views help in analyzing and configuring the SDN.

The flow tracking view (lower left image) presents a static visualization of packet paths. Although the source and destination of some packets (yellow splines) vary in this example, the view indicates that these packets all follow the same logical path. Through the intuitive design of the flow tracking view, the common logical nodes can easily be detected. Furthermore, the visualization is able to visually highlight bottlenecks in the SDN design. As Figure 3 (lower left image) demonstrates, a larger number of packets (blue splines) is sent through only one networking node (white circle). The lower right image shows a closeup of this feature where individual port nodes/boxes become visible. Therefore, this visualization helps identifying security issues or unequal packet distributions in the SDN design through this visually guided flow tracking.

The overview of the system forms an easy to understand visualization that represents the hierarchy of the SDN. Pairs of sending and receiving nodes are connected through a spline that indicates a packet's flow through the SDN hierarchy. This representation allows to easily understand the connection between nodes in the SDN hierarchy. The used hierarchical edge bundling avoids clutter while giving the user a suitable overview of the SDN hierarchy and its packet flow. Focusing, highlighting or color shifting can help in identifying individual paths and countervail obfuscation.

For a further investigation of user selected nodes and packet paths, the flow tracking view is presented. The use of the subway map methodology allows a visually guided tracking of packet paths through the SDN. The box representation with connecting splines provides the possibility to track packets throughout the network and therefore visually highlight common paths in different hierarchy levels. Using small circles to represent networking nodes being visited at certain points in time prevent the recognition of false intersections. As all time steps in the selected time window are visualized simultaneously, the user is not confronted with change blindness problems that often occur in dynamic visualizations. Also, the used edge bundling enables the identification of similar packet paths an helps network analysts in adjusting their configuration design.

The presented approach is highly interactive as the user can select nodes or edges in each presented view while the remaining views are updated accordingly. So all views are interlinked dynamically. In its entirety, the presented system offers a suitable solution to analyze SDN data, allow a visually guided tracking of packet flows and therefore assist network analysts in identifying problematic settings in the SDN.

5 Conclusion

The SDN technology is an immature but upcoming networking technique that requires further investigation through simulations by network analysts to become applicable in real world scenarios. Therefore, this paper presents a linked view system to allow network analysts to review SDNs, their hierarchies and the flow of packets within. The latter is known to be an important factor for the quality of SDN settings. The presented system is capable of of visualizing a SDN's hierarchy and the packet flow through this hierarchy. For further investigation of the flow, the system contains a flow view to analyze and compare the paths of different packets, find coherences and identify weak spots in the SDN design.

As future work, an interactive selection of network elements through user defined security properties is planned. Furthermore, a system able to suggest nodes or points in time of interest to the user is envisioned.

Acknowledgments

This research was funded by the German Research Foundation (DFG) within the IRTG 2057 "Physical Modeling for Virtual Manufacturing Systems and Processes".

References

[1] B. Bach, P. Dragicevic, D. Archambault, C. Hurter, and S. Carpendale. A review of temporal data visualizations based on space-time cube operations. In *In USENIX LISA*, pages 305–317, 2000.

[2] M. Bastian, S. Heymann, and M. Jacomy. Gephi: An open source software for exploring and manipulating networks, 2009.

[3] O. N. Foundation. Software-defined networking (sdn) definition. "https://www.opennetworking.org/sdn-resources/sdn-definition", July 2016.

[4] V. T. Guimares, C. M. D. S. Freitas, R. Sadre, L. M. R. Tarouco, and L. Z. Granville. A survey on information visualization for network and service management. *IEEE Communications Surveys Tutorials*, 18(1):285–323, 2016.

[5] D. Holten. Hierarchical edge bundles: Visualization of adjacency relations in hierarchical data. *IEEE Transactions on Visualization and Computer Graphics*, 12(5):741–748, Sept. 2006.

[6] D. Holten and J. J. van Wijk. Force-directed edge bundling for graph visualization. In *Proceedings of the 11th Eurographics / IEEE - VGTC Conference on Visualization*, EuroVis'09, pages 983–998. The Eurographs Association, 2009.

[7] D. Holten and J. J. V. Wijk. Visual comparison of hierarchically organized data. *Comput. Graph. Forum*, 2008.

[8] C. Humphries, N. Prigent, C. Bidan, and F. Majorczyk. Elvis: Extensible log visualization. In *Proceedings of the Tenth Workshop on Visualization for Cyber Security*, VizSec '13, pages 9–16. ACM, 2013.

[9] C. Hurter, O. Ersoy, S. I. Fabrikant, T. R. Klein, and A. C. Telea. Bundled visualization of dynamicgraph and trail data. *IEEE Transactions on Visualization and Computer Graphics*, 20(8):1141–1157, 2014.

[10] Hyperglance Inc. hyperglance. "https://www.hyperglance.com/", July 2016.

[11] M. Jammal, T. Singh, A. Shami, R. Asal, and Y. Li. Software defined networking: State of the art and research challenges. *Computer Networks*, 72:74 – 98, 2014.

[12] D. Kreutz, F. M. V. Ramos, P. E. Verssimo, C. E. Rothenberg, S. Azodolmolky, and S. Uhlig. Software-defined networking: A comprehensive survey. *Proceedings of the IEEE*, 103(1):14–76, 2015.

[13] S. Liu, Y. Wu, E. Wei, M. Liu, and Y. Liu. Storyflow: Tracking the evolution of stories. *IEEE Transactions on Visualization and Computer Graphics*, 19(12):2436–2445, Dec. 2013.

[14] LiveAction. Netflow visualizations. "http://www.liveaction.com/netflow-visualization/", July 2016.

[15] S. K. Nandi. Topology generators for software defined network testing. *International Conference on Electrical, Electronics, and Optimization Techniques*, 2016.

[16] Q. Nguyen, P. Eades, and S.-H. Hong. Streameb: Stream edge bundling. In *Proceedings of the 20th International Conference on Graph Drawing*, GD'12, pages 400–413, 2013.

[17] V. Peysakhovich, C. Hurter, and A. Telea. Attribute-driven edge bundling for general graphs with applications in trail analysis. In *2015 IEEE Pacific Visualization Symposium (PacificVis)*, pages 39–46, 2015.

[18] D. Plonka. Flowscan: A network traffic flow reporting and visualization tool. In *In USENIX LISA*, pages 305–317, 2000.

[19] K. Reda, C. Tantipathananandh, A. Johnson, J. Leigh, and T. Berger-Wolf. Visualizing the evolution of community structures in dynamic social networks. In *EuroVis'11*, pages 1061–1070, 2011.

[20] D. Selassie, B. Heller, and J. Heer. Divided edge bundling for directional network data. *IEEE Trans. Visualization & Comp. Graphics (Proc. InfoVis)*, 2011.

[21] D. J. Simons and D. T. Levin. Change blindness. *Trends in Cognitive Sciences*, 1(7):261 – 267, 1997.

[22] Uncharted. Torflow. "https://torflow.uncharted.software/", July 2016.

[23] L. Xiao, J. Gerth, and P. Hanrahan. Enhancing visual analysis of network traffic using a knowledge representation. In *IEEE VAST*, pages 107–114. IEEE Computer Society, 2006.