# Visually guided Flow Tracking in Software-defined Networking

Category: Case Study


## ABSTRACT

Software-defined networking/network (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 physical network nodes, which results in a hierarchy. To promote the use of SDNs for real world applications, they are simulated and analyzed to identify applicable configuration settings. For this analysis the SDN's packet flow is an important indicator to determine the quality of a SDN configuration. To assist network analysts in their tasks, this paper presents an interactive visualization system to review simulated SDN data. An intuitive overview of the SDN hierarchy and the flow of its packets is presented. In addition to that, the system provides a visually guided flow tracking of selected packets through the SDN. Through a brushing and linking approach, the system 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 [19, 6]. To solve these problems, new networking methodologies, such as Software-defined networking/network (SDN) are required. In contrast to conventional networks, where each physical node (e. g. computers, switches and virtual machines) is configured separately, SDNs provide controller elements, that are able to administrate groups of physical nodes. Therefore, SDNs are able to separate the control plane and the data plane of a network. This results in groups of physical nodes with similar behavior, which induces a hierarchy. 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 [16]. Due to this challenges, SDNs are not yet widely applied in real world settings. 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 [14].

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 directly applied to review a flow in a SDN (see Section 2). This is mainly caused by two effects: First, the hierarchical design of a SDN results in packets that flow throughout the different hierarchies in the network. Second, the flow of a network is time-depending, which means, that packets detain in different nodes of the network at different time steps. Although this can be visualized by a video, it often results in a phenomenon called change blindness [1]. Therefore, human brains tend to blend out bigger changes in an image sequence to avoid overwhelming. As studies showed, this effect can lead to a decision blindness [15], where an analyst can not make useful decisions.

To solve these problems, this work presents a case study of a hierarchical visualization for simulated SDN data and its packet flow in Section 3. Therefore, a linked view system is presented to relate the hierarchical overview of the SDN with the flow of selected elements. The system consists of an overview, where a hierarchical visualization of the SDN nodes are shown. Trough an interactive brushing and linking approach, the analyst can select nodes or packet paths 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 hierarchy, while avoiding change blindness problems. In addition to that, the selected nodes and its properties as their IPs, can be reviewed in a tabular view.

Therefore, this paper contributes:

- An intuitive visualization of simulated SDN datasets
- Visually guided flow tracking in SDNs

To show the effectiveness of the presented approach, a simulated SDN dataset is analyzed with the presented system in Section 4. At last, this work is concluded and future goals are stated (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. [7]. Although these techniques are widely used in open source solutions [18, 5, 4, 20] they do not provide a visualization for SDN simulations. In contrast to that, Bastian et al. [3] as well as the products of the Hyperglance Inc. [13] and FlowNetwork4 [17] offer suitable tools to review SDN controller nodes and their connections. As they discard the physical network nodes, this paper presents an visualization for SDN simulations, which includes all nodes of the considered SDN.

To visualize the flow in a network, statistical methods such as graphs, showing the amount a nodes receives and sends per time-unit [24] or node connectivity matrices [27, 11], can be used. Although, this provides a suitable overview over the amount of send and received data packets per node, they do not make use of a network layout technique. A flow visualization using layouts, can be achieved by utilizing particles that flow between nodes in the network [26] or utilizing a space-time cube [2]. Although this gives a visual representation of the flow in the network, it introduces visual clutter and can cause change blindness due to the animation. In contrast to this methods, this paper presents a static flow visualization that resolves change blindness problems while relating to the underlying network layout.

To reduce visual clutter, edge bundling [9, 22] summarizes similar connections between nodes. This concept can be extended to distinguish between flow directions [25] or bundle time-varying flow data [21]. As SDNs induce a hierarchical structure, classical edge bundling methods cannot be used in this case. Instead, hierarchical edge bundling is required [8], which was also successfully applied to time-varying data [12]. This approaches hold a proper opportunity to visualize flow in hierarchical networks, without resulting in clutter. Although this paper uses this work as a starting point, this techniques is further improvement to be able to compare the flow of different nodes in the SDN.

Hurter et al. [12], presented a dynamic edge bundling that can be used to visualize the time-varying flow of a network. Although this is a good starting point for this work, it can lead to change blindness caused by the dynamic visualization. In contrast to that, this paper presents a static flow visualization, that is able to track the flow in a network throughout the different hierarchies of a SDN.

Phan et al. [23] presented a flow visualization, that is able to indicate the distribution of packets to different nodes, by utilizing varying thick lines representing the amount of send packets between these nodes. Although this gives a suitable overview of the network's flow, it does not offer the possibility to track and compare single packets. To solve this problem, this paper present a static flow map, which is able to comparatively visualize the dynamic packet flow in a SDN.

## 3 METHODS

In order to examine a simulated SDN, this paper presents an interactive linked view system to understand the SDN's hierarchy and its packets' flow. In this system, the user can select a time step of the simulated SDN as well as an interval size. The selected time step with its surrounding time interval is referenced as the time window. This time window is consistently visualized in all views of the presented system, as demonstrated below.

### 3.1 Overview

As mentioned before, SDNs form a hierarchical network, where groups of physical nodes with similar behavior can be summarized by a higher order topological node. This implies a tree structure representing the SDN and its contained nodes. The root node of this tree represents the entire SDN. This node's children are the topological components of the SDN, meaning the nodes that represent groups of similar behaving physical nodes. Furthermore, each topological node holds the physical network components he is representing as its child nodes. In addition to that, a physical node can also obtain child nodes if it consists of multiple ports. The resulting tree forms the hierarchy of the observed SDN.

In the considered SDN simulation, the two nodes of a sending and receiving event are always leaf nodes in the presented hierarchy. In contrast to conventional networks, the connection between these nodes is not defined directly. Instead, the packet which is send between these nodes ascends the hierarchy of the SDN tree until it reaches the root node and descends down the hierarchy to its destination node. To understand and examine this process, a suitable visual representation is required.

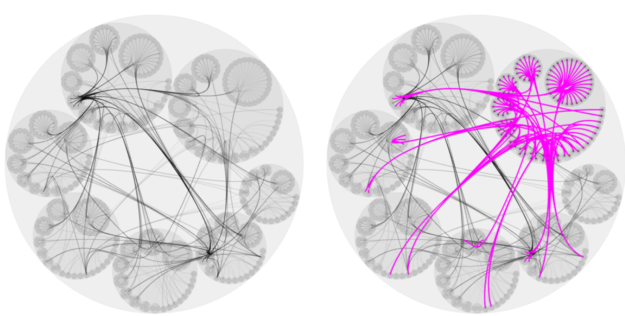

Figure 1: Overview of a SDN simulation for a selected time window. Left: All active nodes in the selected time window are visualized according to the SDN hierarchy. A connecting spline is drawn between each sending and receiving node. Right: Visual enhancement of user selected nodes and links by highlighting.

To solve this problem, an overview of the simulated SDN is provided. In this overview all active nodes in the selected time window are visualized. An active node is a leaf node of the SDN tree, which is either receiving or sending. To visualize all active nodes in the SDN and the induced hierarchy, the active nodes in the SDN hierarchy are drawn recursively. Therefore, each node is surrounded by its child nodes in a circular manner as shown in Figure 1.

As only active nodes are shown in the network overview, there exist at least one sending or receiving event for this node in the user selected time window. Therefore, send packets are visualized by a spline, connecting the involved active nodes. As mentioned before, the path of a packet walks through the different hierarchies of the SDN. To represent this observation, not solely the connection between the involved active nodes is drawn. Instead, all nodes of the packet's path through the SDN hierarchy are used as sampling points for the drawn spline. As a result, the path of a packet through the SDN's hierarchy is visually encoded. In order to avoid visual cluttering, the splines are summarized through a hierarchical edge bundling approach [8]. This results in a fast and intuitive visualization of packets and their way through the SDN hierarchy.

To allow a visual highlighting of nodes and edges through the user, it is possible to select groups of nodes and packets in the overview of the SDN, as shown in Figure 1 (right). In the visualization, the marked elements are visually enhanced by highlighting. If a node is highlighted which is not a leaf node, its entire subtree is selected. 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 packets of the considered nodes. In addition to that, a tracking of packets to find common source or destination nodes as well as the identification of equal sending paths is important. To solve this problem, the presented overview is extended by a flow tracking view.

### 3.2 Flow Tracking

As mentioned before, 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 the SDN's hierarchy, the highlighting in Figure 1 cannot distinguish between incoming and outgoing packets of a node. In addition to that, the selection of a spline only presents one part of the path a packet is using.

To address these problems, the overview can be extended by using different highlight colors for incoming (green) and outgoing (red) packets, as seen in Figure 3. Furthermore, packets related to the selected SDN elements can be tracked through their content ID. As a result, the entire path a packet is taking in the selected time window is highlighted. To visually enhance the selected time step, the alpha value of the highlight color decreases with the distance to the selected time step. This results in a visually guided flow tracking of user selected packets through the SDN.

Although this improves the highlighting in the overview, the paths selected packets are taking cannot directly be compared. Therefore, an additional view is presented, which aims to solve two problems: First, the flow in a SDN consists of dynamic paths between active nodes, which can be hard to track while watching a video. Second, the flow in a SDN is not restricted to one layer. Instead, the flow of a SDN is marching through different layers of the hierarchy. In order to identify similar paths for a group of packets in higher layers of the hierarchy or differentiate the possible physical destination nodes for common flows in the topological layer, a suitable visualization is required.

As shown in Figure 1, if multiple edges are bundled it can be hard to distinguish single ones. In addition to that, the overview can result in clutter if various edges are marked. This is caused by the effect, that more and more highlighted edges are intersecting in this view. Therefore, the presented system requires an additional visualization that displays the selected nodes and their traffic of the overview [10].

Therefore, this paper presents a flow tracking visualization, which 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. If different subway lines are using the same station, their line representations are crossing, respectively. In the case, that subway lines do not share stations, their spline representations do not cross.

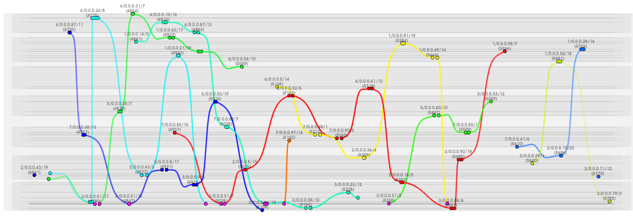

Figure 2: Flow tracking view for selected SDN nodes and their links. Time is used as the x-axis and each active node is represented by a horizontal line. The hierarchy of the SDN is indicated by boxes containing each other. Packets that flow through the SDN are visualized by a unique colored spline connecting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

As subway maps form a successful visualization to understand the differences and similarities of different subway lines, the goal is to apply this concept to packet flows in SDN data, as 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. Each active node obtains a horizontal line, that is aligned in parallel to the x-axis. To incorporate the hierarchy of the SDN into this visualization, the line representation of the active nodes are sorted by their topological node. For each node, which is not a leaf node in the SDN hierarchy, a box is drawn, covering its child nodes. Therefore, the hierarchy of the SDN can be easily identified. For each selected node, all related sending and receiving events are tracked through the user defined time window through the content ID of the packets. To visualize the tracked packets, the path of each packet is visualized by a spline, connecting all nodes the packet is visiting. Therefore, each line representation of a node obtains a circle at the point in time he is visited. These points form the sampling points of the spline representing for the path of the current packet. The result is a spline indicating the packet's path along different nodes in the SDN. As applied in the overview, edge bundling is used to avoid visual cluttering and identify coherences in packets paths.

To distinguish splines, that show the paths of different packets, the color of the packet's spline representation are altered. In order to highlight the currently selected time step, the alpha value of the line decreases the more a time step varies from the selected time step.

With this visualization it is possible to track packets through the different hierarchies in the SDN, find coherences in the paths packets are using and identify bottleneck nodes in the SDN design.

### 3.3 Interaction

In order to create an interactive visualization system, that helps network analysts reviewing the flow induced by a SDN configuration, the presented system uses multiple views, that are connected through brushing and linking.

In each view of the system it is possible to change the selection of nodes. The selected nodes (indicated by highlighting) are updated in all views, which makes the system easy to use and understand. In addition to that, the selection of a node, which is not a leaf node in the SDN's hierarchy, results in the selection of all its child nodes. Furthermore, it is possible to collapse entire levels of the SDN hierarchy in the visualization system. If a level is not enabled, all visualizations neglect the nodes and paths involved in this hierarchical level. This helps users to focus on a depicted layers of the SDN hierarchy.

To allow the system analyst reviewing different properties of selected nodes in the SDN, a tree representation of the selected nodes as well as a table representation of the selected packets with their attributed is offered. The shown attributes can be found in Figure 3.

Through this highly interactive system, network analysts are enabled to review simulated SDN data to understand the effects of network configuration decisions to the packet flow in the resulting SDN.

## 4 Results and Discussion

The presented system was tested with a simulated dataset of a SDN. As mentioned before, the concept of SDN is quite novel and not yet applied to many settings. Resulting from that, real world datasets are not available. Instead, simulated SDN datasets are utilized to gain insights into the SDN technology. The visualized SDN dataset was generated using the method of This paper utilizes the SDN data generation method presented by Nandi [19].

The results in Figure 3 show, how the presented system can be used to visualize and analyze the SDN simulation. 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). In addition to that, the flow related to this nodes is tracked, which is shown by the red and green highlighting. Based on this selection, the remaining views are updated. The tabular view shows the important properties of the selected nodes as their name and weight of received and send packets (upper right). The flow tracking view presents the static visualization of the selected packet paths. As it can be observed, multiple packets are send and received from different nodes. Although the source and destination of the packets always alter, the visualization indicates, that the visualized packets all involve the same topological nodes in their path (yellow). Through the intuitive design of the flow tracking view, the common topological node can be easily detected. Furthermore, the visualization is able to visually highlight bottlenecks in the SDN design. As Figure 3 shows, a high amount of packets are send through one node at one point in time (blue). Therefore, this visualization helps identifying security issues or unequal packet distributions in the SDN design through a visually guided flow tracking.

The overview of the system forms an easy to understand visualization, that represents the hierarchy of the SDN. The chosen circular arrangement directly display which nodes of the SDN behave equally. Pairs of sending and receiving nodes are connected through a spline that indicates the packets flow through the SDN hierarchy. This allows an easy to understand representation of the connection between nodes throughout 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.

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 network. The box representation with connecting splines provides the possibility to track packets throughout the network and therefore visually highlight common paths in different hierarchies. As all time steps in the selected time window are visualized simultaneously, the user is not confronted with change blindness problems as often occurring in dynamic visualizations. Furthermore, similar paths of packets can be identified easily through the used edge bundling, which helps network analysts adjust their configuration design.

The presented approach is highly interactive, as the user can select nodes in each presented view, while the remaining views are updated according to the made selection. In its entirety, the presented system offers a suitable possibility to review SDN simula-

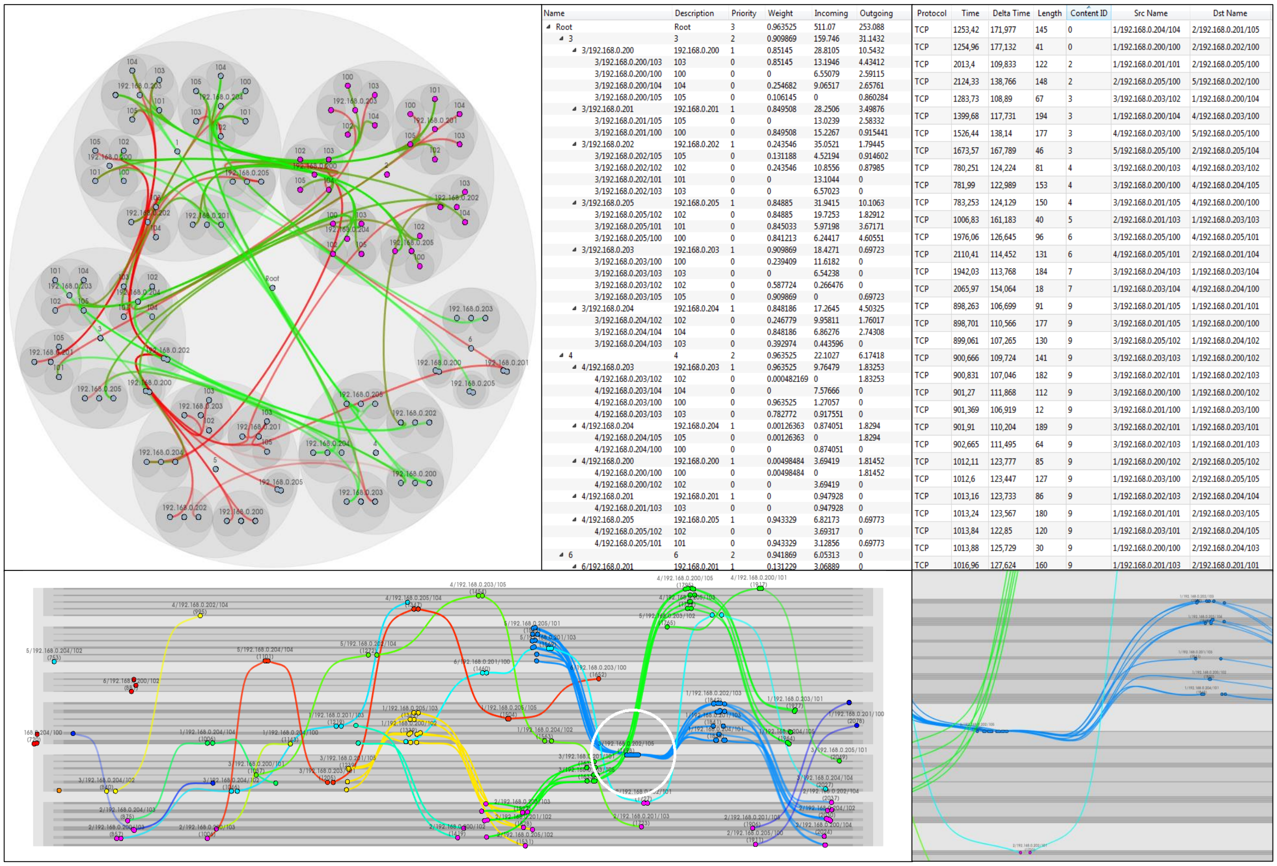

Figure 3: Application of the presented system to a simulated SDN dataset. Upper left: Overview of the SDN hierarchy. Nodes selected by the user are highlighted. Green and red lines indicate incoming and outgoing packets. Upper middle: Tree view of active nodes and their properties. Upper right: List 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.

tions, allow a visually guided packet flow tracking and therefore assist network analysts identify problematic settings of the SDN.

## 5 Conclusion

The SDN technology is an infantile networking technique, which 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 review the SDN's hierarchy and its flow of packets, which is known to be an important factor for the quality of SDN settings. The overview of the system is capable of visualizing the SDN's hierarchy and the packet flow through this hierarchy. For further investigation of the packets' flow in the SDN, 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, the suggestion of nodes that should be further investigated is aimed.

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