Verifying SDN Data Path Requests

Igor Burdonov\textsuperscript{a}, Alexandre Kossachev\textsuperscript{a}, Nina Yevtushenko\textsuperscript{a,b}, Jorge López\textsuperscript{c,}\textsuperscript{a}, Natalia Kushik\textsuperscript{c}, Djamal Zeghlache\textsuperscript{c}

\textsuperscript{a}Ivannikov Institute for System Programming of the Russian Academy of Sciences, Moscow, Russia
\textsuperscript{b}National Research University Higher School of Economics, Moscow, Russia
\textsuperscript{c}SAMOVAR, CNRS, Télécom SudParis, Université Paris-Saclay, Évry, France

Abstract

Software Defined Networking (SDN) is a pillar technology for network virtualization, which currently attracts a lot of attention due to the provided capabilities. In recent years, different works have been devoted to testing / verifying the (correct) configurations of SDN data planes. In general, SDN forwarding devices (e.g., switches) route (stir) traffic according to the configured flow rules; essentially, a flow rule decides which action to take (e.g., forward the received network packet to a set of ports) if the received network packet matches some predefined values. In this paper, we showcase misconfigurations which can occur due to the inherent working principles of flow rules. Namely, we discuss how, when synthesizing a set of data-paths, other data paths (including loops) may be unintentionally configured. Furthermore, we show that for some cases the original set of data paths cannot be implemented (only a superset of it). Additionally, we present a method for detecting such issues and estimate its complexity. The obtained results may be interesting for practical use due to their impact and low (polynomial) time complexity.

Keywords: Interconnecting Networks, Software Defined Networking, Data paths, Verification, Graph paths

1. Introduction

Currently, traditional interconnection networks have evolved into so-called virtual networks. One of the underlying technologies that allow such virtualization is the Software Defined Networking (SDN) technology, that implements various data paths utilizing the common resources and control principles. When using SDN technology the network entities are managed through the controller...
(-s) that works (work) independently of the network equipment and is (are) ‘responsible’ for pushing the necessary rules to the forwarding devices (e.g., switches) [1]. As a result, SDN provides agile controllability and observability by separating the control and data planes.

To guarantee the requested network is configured correctly, various SDN components and compositions need to be thoroughly tested and verified. However, even if the rules are pushed to each switch as requested by the controller (-s), additional verification of the data plane still needs to be performed. Among the main properties to verify in this case are i) the absence of loopholes and packet loss, and ii) security and access control issues. The works on such network verification (not necessarily SDN) have been actively performed in the last decade. Existing approaches mostly employ formal verification and model checking techniques. The underlying formalism covers Boolean functions and their satisfiability [2]; symbolic model checking and SMT solving [3]; algebra of sets [4]. Likewise, a number of works are devoted to the automatic traffic generation where the packets at hosts are stimulated in an active mode [5, 6]. Related works therefore mostly cover the network verification problem when the network is configured, i.e., the rules are pushed and one needs to discover if any of potential network failures can occur. However, such checks are not simple and thus, new approaches for verification could be investigated, which may simplify the above tasks. One of them is to consider the verification of data paths with the same traffic type separately and before the rules are pushed. A traffic type depends on the packet headers; packets with the same traffic type follow the same data paths.

In this paper, we propose a novel proactive approach for checking the network properties. Indeed, given the set of paths to be implemented on the data plane, if this set is not consistent or can lead to potential loopholes then its implementation should be avoided. Let \( P \) be a set of paths which should be implemented on the data plane for packets of a given traffic type. The set \( P \) should be ‘inspected’ before its actual implementation, first to assure that all the paths of the set \( P \) are edge simple (proves the correctness of the path definition) and second whether it is possible to precisely implement the set \( P \) on the data plane or there will be additional (unintended) paths implemented? In the latter case, it can happen that there are implemented paths which are not edge simple and thus, a loophole for packets of a given traffic type can occur. In this paper, we answer the above question by establishing the corresponding necessary and sufficient conditions. In fact, we show that given a traffic type and a set of (requested) paths \( P \), the implementation of \( P \) can induce new paths appearing on the data plane, and moreover, if all the paths of \( P \) are edge simple (no loopholes should occur) it does not guarantee the absence of potential cycles on the data plane. Indeed, the criterion for the absence of those relies on the property of the set \( P \) to be arc closed (see Section 3). Correspondingly, the proposed proactive approach for checking the set \( P \), necessary and sufficient conditions for this check and its complexity (see Section 4) form the main contributions of this paper.
2. Preliminaries

In this paper, the SDN resource topology (data plane) that is used for transmitting packets is represented as an undirected graph $G = (V, E)$ where $E \subseteq \{(a, b)\mid a \in V \& b \in V\}$ without multiple edges and loops. The set $V$ of nodes represents network devices such as hosts and switches; the set $H$ is the set of all hosts while $S$ is the set of all switches, $V = H \cup S$, $H \cap S = \emptyset$. Edges of the graph (the set $E$) represent connections (links) between two nodes in $G$ and each link can transmit packets in both directions. Correspondingly, given an edge between nodes $a, b \in E$, we write $(a, b)$ if a packet is transmitted from $a$ to $b$ and $(b, a)$ when it is transmitted from $b$ to $a$. We reasonably assume that each host is connected exactly with one switch, i.e., $\forall h \in H(\deg(h) = 1) \& \exists s \in S\{h, s\} \in E$ where $\deg(x)$ is the degree of the node $x$. Without loss of generality we also assume that $G$ is connected; otherwise, each (connected) component can be treated as a separate network.

In the SDN architecture, the instructions for the data plane for packets forwarding are provided by SDN applications through an SDN-controller (-s). These instructions are so-called data paths, sets of paths which should carry on corresponding packets, i.e., those paths can have appropriate parameters according to which the packets are then forwarded; in other words, each packet belongs to an appropriate traffic type. When a forwarding rule is installed on an SDN-enabled switch, a data link from and to other node (-s) adjacent to the switch is created, i.e., a packet accepted from adjacent nodes (hosts or switches) is forwarded to a (corresponding) set of ports that are connected to appropriate ports of other nodes.

A host can generate packets that are forwarded to a single switch connected with this host. A switch can only forward packets; moreover, in this paper, we assume that a switch does not modify the packet header, i.e., the packets traffic type and payload are not changed through the network. A switch can forward a packet to several ports, and the set of ports depends on the traffic type as well as on the input port from which it arrives. Every node $a$ of the graph $G$ (a host or a switch) has a set of ports which can be input as well as output and each such port corresponds to some edge at the node $a$ and vice versa, each edge at the node $a$ is associated with a corresponding port. Thus, there is one-to-one correspondence between edges at the node $a$ and the set of its ports. Since $G$ has no multiple edges nor node (self) loops there is one-to-one correspondence between sets of ports of $a$ and the set of neighbor nodes of $a$. Therefore, without loss of generality, we can use a neighbor node instead of the port number.

A path $\pi$ is a sequence of neighboring nodes of $G$, i.e., a path is a sequence\footnote{As usual, we use ‘·’ for denoting the sequence concatenation.} of nodes such that there is an edge between neighboring sequence nodes. A path $\pi = x_1 \cdots x_n$ starts at the node $x_1$, is finished at the node $x_n$, has length $n - 1$, and passes via an arc $(x_i, x_{i+1})$ for $i = 1 \ldots n - 1$. The path is edge simple if it passes via each arc at most one time: $(x_i, x_{i+1}) = (x_j, x_{j+1}) \implies i = j$. The
A path is node simple if all its nodes are pairwise different, i.e., \( x_i = x_j \implies i = j \).

A path is complete if its head and tail nodes are hosts and there are no hosts as intermediate nodes.

An SDN application configures (through the controller) sets of paths which should transport corresponding packets, i.e., those paths can have appropriate parameters (which define their traffic type) according to which the packets are then forwarded. The flow rules of a switch can be written as a mapping of input ports into subsets of output ports. If the subset of output ports is empty then the switch will ‘drop’ a packet that arrived at a corresponding input port.

According to the above, in this paper, we assume that an SDN application configures the switch tables in such a way that each rule determines the set of output ports depending on the traffic type and an input port. As \( G \) has no multiple edges it implies that a rule determines the set of neighboring nodes where a packet has to be forwarded. We also assume that all the switches have in their tables only the information sent by the controller, i.e., no default rules or external interfaces are considered. Switches have forwarding rules and each forwarding rule has a priority, a preamble and a postamble: the header parameters are analyzed in the preamble and the matching rule with the highest priority is determined. Every switch forwards packets according to the rules in its tables. Tables have priorities but in this paper, for the sake of simplicity and in fact, without loss of generality for our purpose, we assume that all the rules have the same priority. For packets belonging to the same traffic type, we can consider every rule as a triple \((a, s, b) \in V \times S \times V\) where \(a\) and \(b\) are neighbors of \(s\). This rule says that getting a packet (with the corresponding traffic type) from neighbor \(a\), switch \(s\) should send it to the neighbor \(b\). If there are several rules which differ only in the neighbor \(b\), then switch \(s\) performs cloning, i.e., the incoming packet is transmitted to several neighbors. The set of rules of all switches is called configuration (for the given traffic type).

3. Implementing the given set of complete paths

The set of complete paths that should be implemented on the data plane, is designed based on methods and tools which process a corresponding user request or predefined configuration. Correspondingly, before setting a switch configuration according to a requested set of paths it would be useful to check whether a given set of paths can be eventually implemented. Three options are possible: 1) The given set \(P\) of paths can be implemented as it is and in this case, the edge simplicity should be checked for the set \(P\). 2) The given set \(P\) of paths cannot be implemented without implementing unintended paths, i.e., a superset of \(P\) is implemented. In this case, the condition of the edge simplicity should be checked for this superset. If the minimal superset of \(P\) that can exist on the data plane has cycling paths, then the set \(P\) cannot be implemented (loops can flood the network) using the given data plane. 3) The given set \(P\) of paths cannot be implemented but the minimal superset of \(P\) that can be implemented satisfies the edge simplicity property. We further discuss
how given set $P$ of paths, a corresponding switch configuration is specified and given a switch configuration, which paths are induced by this configuration.

**Complete paths induce switch rules.** When implementing rules for a complete path (for the given traffic type) $\alpha \cdot a \cdot b \cdot c \cdot \beta$ where $a, b, c \in V$, we need a rule $(a, b, c)$, i.e., a switch $b$ once getting a packet belonging to this traffic type from the neighbor $a$ has to send it to the neighbor $c$. Formally, the set $P$ of paths induces the set $P^\downarrow$ of rules:

\[
\forall a \in V, b \in S, c \in V, \alpha \in V^*, \beta \in V^* \\
\alpha \cdot a \cdot b \cdot c \cdot \beta \in P \iff \text{there is a rule } (a, b, c) \in P^\downarrow.
\]

**Switch rules induce paths.** The rule $(a, b, c)$ induces a path $a \cdot b \cdot c$ of length 2. If there is a path $\alpha \cdot x \cdot y$ and there is a rule $(x, y, z)$ then there is a path $\alpha \cdot x \cdot y \cdot z$. Formally, a switch configuration $P^\downarrow$ induces the set of complete paths, written $P^\downarrow$:

\[
\forall a_1, b_1, c_1 \in V \\
(a_1, b_1, c_1), (c_1, b_2, c_2), \ldots, (c_{n-1}, b_n, a_2) \in P^\downarrow \\
\text{where } a_1 \text{ and } a_2 \text{ are the only hosts in the path, there is a path } a_1 \cdot b_1 \cdot c_1 \cdot b_2 \cdot c_2 \cdot \ldots \cdot c_{n-1} \cdot b_n \cdot a_2 \text{ in } P^\downarrow.
\]

By definition, the set $P^\downarrow$ has only complete paths. By the definition of $P^\downarrow$ and $P^\uparrow$, the following statement holds.

**Proposition 1.** Given a switch $b$, for each rule $(a, b, c) \in P^\downarrow$ of this switch, there is a path $\alpha \cdot a \cdot b \cdot c \cdot \beta \in P^\uparrow$ for some $\alpha$ and $\beta$.

We now discuss the features of the set $P^\downarrow$. If there are two paths $\alpha \cdot x \cdot y \cdot \beta$ and $\alpha' \cdot x \cdot y \cdot \beta'$ in the set $P^\downarrow$ of complete paths, then according to the above rules, there are paths $\alpha \cdot x \cdot y \cdot \beta$ and $\alpha' \cdot x \cdot y \cdot \beta$. Consider the case when $\alpha$ and $\alpha'$ are not empty, i.e., $x$ is a switch. If $\beta$ and $\beta'$ are not empty then according to the prefix of the path, switch $x$, once getting a packet passed the path $\alpha$ or the path $\alpha'$, sends the packet to switch $y$. According to the postfix, switch $y$, once getting a packet from switch $x$, sends it to the starting point of the paths $\beta$ and $\beta'$, and the packet passes the paths $\beta$ and $\beta'$. If $\beta$ and $\beta'$ are empty, then $y$ is a host and the packet passes both paths $\alpha \cdot x \cdot y$ and $\alpha' \cdot x \cdot y$. Therefore, the following statement holds.

**Proposition 2.** Given a switch configuration $P^\downarrow$, $P^\downarrow$ induces the set of complete paths $P^\uparrow$ with the following features:

\[
\forall \alpha, \alpha', \beta, \beta' \in V^* \\
\alpha \cdot x \cdot y \cdot \beta \in P^\downarrow \& \alpha' \cdot x \cdot y \cdot \beta' \in P^\downarrow \implies \alpha \cdot x \cdot y \cdot \beta' \in P^\uparrow.
\]

According to Proposition 2, the set of data paths on the data plane induced by the given set $P$ is exactly $P^\downarrow$, and in fact, is the actual set of paths that gets implemented (when requesting to implement the set $P$).

The set $P$ of complete paths is **closed with respect to a given arc** $(x, y)$ if for each two paths $\alpha \cdot x \cdot y \cdot \beta$ and $\alpha' \cdot x \cdot y \cdot \beta'$ of the set $P$ which have a common arc $(x, y)$, paths $\alpha \cdot x \cdot y \cdot \beta$ and $\alpha' \cdot x \cdot y \cdot \beta$ are also in $P$. The set $P$ of paths is **arc closed** if $P$ is closed w.r.t. each arc over the set $E$. Given a set $P$ of complete
paths, the arc closure of $P$ is the smallest arc closed set of complete paths that contains $P$.

According to the definition of an arc closed set and Proposition 2, the following statement can be established.

**Proposition 3.** Given a set $P$ of complete paths, the set $P\downarrow\uparrow$ is the arc closure of $P$.

**Corollary 1.** The set $P\downarrow\uparrow$ coincides with $P$ if and only if $P$ is arc closed.

**Corollary 2.** If $P$ has only simple edge paths and is arc closed then $P\downarrow\uparrow$ has only simple edge paths.

According to Corollary 1, the set $P$ can be implemented on the data plane (up to the equality relation) if and only if $P$ is arc closed, i.e., Corollary 1 establishes necessary and sufficient conditions for the precise implementation of set $P$ on the data plane (without additional ‘undesired’ paths).

If $P$ is not arc closed then $P$ cannot be implemented on the data plane (up to the equality relation). Moreover, sometimes $P$ cannot be implemented on the data plane at all as its arc closure has some cycling paths. Fig. 1 shows an example when the set $P$ has two edge simple paths $\alpha$ and $\beta$ from initial host $h_0$ to the final host $h_1$ (left), the set of rules induced by this set is shown at the bottom and an induced path $\gamma$ of the set $P\downarrow\uparrow$ is illustrated at the right. The path is not edge simple, and this example illustrates that cycles can occur even when paths of the set $P$ are node simple.

**Figure 1: Induced (cyclic) paths occurrence**

Similar to $P$, all the paths of the set $P\downarrow\uparrow$ are complete paths. However, if $P\downarrow\uparrow$ is a proper superset of $P$ then we have to check whether all the paths of the set $P\downarrow\uparrow$ are edge simple. If it is the case then the set $P$ can be implemented on the data plane up to the set $P\downarrow\uparrow$. If it is not the case then the set $P$ should be modified and this issue is out of the scope of this paper.

From the practical point of view, perhaps the most interesting application is when some set $P\downarrow\uparrow$ of paths is already implemented on the data plane while a request arrives to add new paths to this set. In this case, the same check should be performed before implementing new paths, guaranteeing the implementability of the augmented set of paths.
4. Checking the arc closure

In this section, we discuss an algorithm for checking if a given set of paths $P$ induces unintended paths (a superset of $P$); likewise, we discuss how to detect potential cycles induced by the implementation of $P$.

Given the set $P$ of complete paths in the graph $G$, we construct a directed graph $G(P)$. Vertices of $G(P)$ are all arcs of paths from $P$ and there is an arc $((a, b), (b, c))$ in $G(P)$ iff $P$ has a path $\alpha \cdot a \cdot b \cdot \beta$. Since $P$ contains only complete paths, in the graph $G(P)$, the sources are vertices $(a, b)$ where $a$ is a host, while the sinks are vertices $(c, d)$ where $d$ is a host. The path $(a_1, a_2) \cdot (a_2, a_3) \cdot \ldots \cdot (a_{m-1}, a_m)$ in the graph $G(P)$, starting at the source $(a_1, a_2)$ and ending at the sink $(a_{m-1}, a_m)$, corresponds to the complete path $a_1 \cdot a_2 \cdot a_3 \cdot \ldots \cdot a_{m-1} \cdot a_m$ in the graph $G$. The set of such complete paths in the graph $G$, corresponding to the paths in the graph $G(P)$ from a source to a sink, is precisely the closure of the set $P$. If the number of such paths in $G(P)$ is greater than cardinality of the set $P$, this means that the closure expands the set $P$. To check for (infinite) loops, the absence of oriented cycles in the graph $G(P)$ needs to be checked, which is done through a topological sort (e.g., using depth first search algorithm) \[8\].

The complexity of constructing the graph $G(P)$ is $O(L)$, where $L$ is the sum of the lengths of the paths from $P$. The running time of the depth first search algorithm on the graph $G(P)$ is evaluated as $O(m)$, where $m$ is the number of arcs of the graph $G(P)$, $m \leq |V|^3$. Therefore, the complexity of checking the absence of cycles is $O(L + |V|^3)$.

5. Conclusion

In this paper, we discussed some implementability issues for a given set of paths on an SDN data plane. We showed that for a fixed traffic type, whenever the requested set contains only edge simple paths, more (unintended) paths can still be implemented on the data plane, and some of those can create cycles, i.e., infinite packet loops. We therefore established the necessary and sufficient conditions for a set of requested path to be implemented without any undesired connections and hence, potential loops. Our approach is based on the predefined checking of the set of paths to be arc closed that in fact guarantees its ‘clean’ (exact) implementability; this can be useful for guaranteeing that new (requested) and preexisting paths form valid configurations. The estimated (polynomial w.r.t. the total paths length) complexity of the proposed approach makes believing in its applicability for large scale virtual networks.

As future work, we plan to extend our approach abstracting from a given traffic type, i.e., considering sets of paths that share certain parameters of the packet header. Complexity issues in this case form maybe the main challenge, and thus we plan to study certain properties of various headers partitioning to check the implementability of a given set of paths. Further, we plan to verify different functional and non-functional properties of the set of paths to be implemented, for example, to check security / isolation issues.
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References

[1] S. Sezer, S. Scott-Hayward, P. K. Chouhan, B. Fraser, D. Lake, J. Finnegan, N. Viljoen, M. Miller, N. Rao, Are we ready for sdn? implementation challenges for software-defined networks, IEEE Communications Magazine 51 (2013) 36–43.

[2] H. Mai, A. Khurshid, R. Agarwal, M. Caesar, P. Godfrey, S. T. King, Debugging the data plane with anteater, ACM SIGCOMM Computer Communication Review 41 (2011) 290–301.

[3] M. Canini, D. Venzano, P. Perešini, D. Kostić, J. Rexford, A NICE way to test openflow applications, in: Presented as part of the 9th USENIX Symposium on Networked Systems Design and Implementation (NSDI 12), pp. 127–140.

[4] Y. Boufkhad, R. De La Paz, L. Linguaglossa, F. Mathieu, D. Perino, L. Viennot, Forwarding tables verification through representative header sets, arXiv preprint arXiv:1601.07002 (2016).

[5] H. Zeng, P. Kazemian, G. Varghese, N. McKeown, Automatic test packet generation, in: Proceedings of the 8th international conference on Emerging networking experiments and technologies, ACM, pp. 241–252.

[6] S. K. Fayaz, T. Yu, Y. Tobioka, S. Chaki, V. Sekar, BUZZ: Testing context-dependent policies in stateful networks, in: 13th USENIX Symposium on Networked Systems Design and Implementation (NSDI 16), pp. 275–289.

[7] O. S. Specification, Version 1.5. 0, Open Networking Foundation (2015).

[8] T. H. Cormen, C. E. Leiserson, R. L. Rivest, C. Stein, Introduction to algorithms, MIT press, 2009.