Is Your OpenFlow Application Correct?

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ABSTRACT

OpenFlow enables third-party programs to dynamically reconfigure the network by installing, modifying and deleting packet processing rules as well as collecting statistics from individual switches. *But how can we know if such programs are correct?* While the abstraction of a logically-centralized network controller can ease their development, this abstraction does not remove the complexity of the underlying distributed system. For instance, small differences in packet header fields or packet orderings can "tickle" subtle bugs [1]. We argue for the need of thorough, automatic testing of OpenFlow applications. In this paper, we describe our preliminary experiences with taking two state-of-the-art model checkers (SPIN and Java PathFinder) and applying them "as is" for checking an example of OpenFlow program: a MAC-learning switch application. Overall, the preliminary results we report suggest that these tools taken out-of-the-box have difficulties to cope with the state-space explosion that arises in model checking OpenFlow networks.

1 Model Checking OpenFlow

Model checking is an automatic approach for verifying the correctness of a system. Traditionally, model checking operates with a model that describes an abstraction of the system and discovers whether correctness properties asserted by the user are valid on the model. The main idea behind this approach is to systematically explore the space of all global states reachable from an initial state. Depending on the size of the system, the number of reachable states can become too high for current computing resources. Fortunately, a number of general techniques exist that help to mitigate this problem. For instance, partial-order reduction (POR) avoids exploring sequences of transitions when the relative ordering of independent events is irrelevant to determine the final state; so, it explores just one sequence.

ACM CoNEXT Student Workshop, December 6, 2011, Tokyo, Japan.

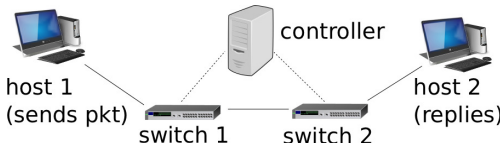


Figure 1: The network model used for model checking.

Modern model checking uses the actual implementation as the model, which has the advantages of making the verification more realistic and not requiring to use a modeling language. However, the sizes of the systems that can be verified are limited because a real program has more states than its abstract model representation.

We believe model checking is a good fit for testing OpenFlow applications because we want to check correctness properties (*e.g.*, absence of forwarding loops) that entail the network state, *i.e.*, states of the controller and switches. Moreover, we expect their violations to be caused by unexpected interleavings of events and corner-case conditions, which are a convenient domain for applying model checking. Therefore, we want to quantify the state-space explosion in this verification problem and investigate the limitations of existing model-checking tools to constrain that explosion.

We consider a small network consisting of two OpenFlow switches driven by a single controller that mimics the functions of a simple MAC-learning switch[1]. As testing requires a closed system, we model two end hosts that behave in this simple way: host 1 sends a packet to host 2; host 2 replies with another packet. Figure 1 shows how these components are inter-connected.

2 Traditional Model-Checking: SPIN

Model. We model the system in PROMELA, the modeling language supported by SPIN[2], a very efficient model checker. This language exposes non-determinism as a first-class concept, making it easy to model the distributed behavior of our simple system. But we found the language to be lacking in expressiveness (*e.g.*, there is no support for procedures and common data struc-

[1]Derived from NOX's `pyswitch` component.
[2]`http://spinroot.com`

tures). Finally, we need to cautiously capture the system concurrency at the right level of granularity. In our case, this means that any event at a single component (e.g., processing a packet on a switch) has to be modeled as a single atomic computation.

Experiments. To understand the scalability challenges in model-checking for OpenFlow, we perform an exhaustive search of the state space and we report on these metrics: memory usage, elapsed time, and number of transitions. We assign exclusive rights to the processes involved in each communication channel so to allow SPIN's implementation of POR to be most effective. The final valid state of our system is when host 1 receives a reply to each packet it sends.

Results. Figure 2a shows the memory usage and elapsed time[3] for the exhaustive search with POR as we increase the number of packets sent by host 1. As expected, we observe an exponential increase in computational resources until SPIN reaches the memory limit when checking the model with 8 pings (*i.e.*, 16 packets).

To see how effective POR is, we compare in Figure 2b the number of transitions explored with POR vs. without POR (NOPOR) while we vary the number of pings. In relative terms, POR's efficiency increases, although with diminishing returns, from 24% to 73% as we inject more packets that are identical to each other. The benefits due to POR on elapsed time follow a similar trend and POR can finish 6 pings in 28% of time used by NOPOR. However, NOPOR hits the memory limit at 7 pings, so POR only adds one extra ping.

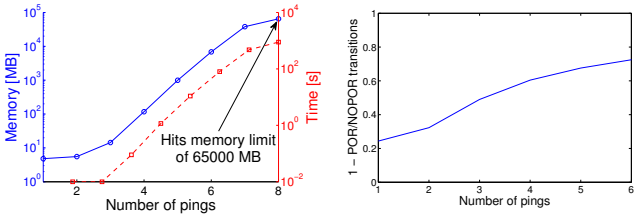
Finally, we test if POR can reduce the search space by taking advantage of one simple rule of independence for the networking domain: *i.e.*, packets involving disjoint pairs of source and destination addresses are completely independent. Unfortunately, we observe that there is no reduction when we inject two packets with distinct address pairs compared to the case with identical packets. This is because SPIN uses the accesses to communication channels to derive the independence of events.

3 Modern Model-Checking: Java PathFinder

Model. Using Java, we follow two approaches to write two models of the system (based on porting the original Python code) for Java PathFinder (JPF)[4], an explicit state model checker. In the first approach, we naively use threads to capture non-determinism. However, in our case, the built-in POR is not very efficient in removing unnecessary network event interleavings because thread interleaving happens at finer granularity than event interleavings. To solve this problem, we tuned this model by using the `beginAtomic()` and `endAtomic()` JPF functions. As this still produces too

[3]The machine where we run the experiments has 64 GB of RAM and a clock speed of 2.6 GHz.

[4]`http://babelfish.arc.nasa.gov/trac/jpf`



(a) Memory usage and elapsed time (log y-scales). **(b) Efficiency of POR.**

Figure 2: SPIN: Exponential increase in computational resources partially mitigated by POR.

pings	time [s]	unique states	end states	mem [MB]
1	0	55	2	17
2	9	20638	134	140
3	13689	25470986	2094	1021

Table 1: JPF: Exhaustive search on thread-based model.

pings	time [s]	unique states	end states	mem [MB]
1	0	1	1	17
2	1	691	194	33
3	16	29930	6066	108
4	11867	16392965	295756	576

Table 2: JPF: Exhaustive search on choice-based model.

many interleavings, we further introduced a global lock.

In a second approach to further refine the model, we capture non-determinism via JPF's choice generator: `Verify.getInt()`. This gives a huge improvement over threads (shown in the results later), mainly because we are able to specify precisely the granularity of interleavings. However, there are several caveats in this case too. For example, explicit choice values should not be saved on the stack as the choice value may became a part of the global state, thus preventing reduction. The vector of possible transitions must also be sorted[5].

Experiments. We perform an exhaustive search with the default JPF settings and report on the following metrics: elapsed time, number of unique states, number of distinct end states, and memory usage.

Results. Table 1 illustrates the very fast exponential explosion when using the thread-based model. Unfortunately, as show in Table 2, the choice-based model improves only by 1 ping the size of the model that we can explore within a comparable time period ($\approx$ 4 hours).

4 Conclusion and Future Work

We presented our experiences with model checking for OpenFlow. While SPIN is fast, the main difficulty lies in writing the model. It took several person-days to implement the model. JPF solves the complexity of model specification but this comes at the cost of significant performance slowdown. To cope with the state-space explosion of OpenFlow networks, our next step will be to supply the model checker with domain-specific knowledge (*e.g.*, independence based on packet header fields) that can reduce non-interesting interleavings.

5 References

[1] M. Canini, D. Kostić, J. Rexford, and D. Venzano. Automating the Testing of OpenFlow Applications. In *WRiPE*, 2011.

[5]We order events by their states' hash values.