Automated Verification of Security Chains in Software-Defined Networks with Synaptic

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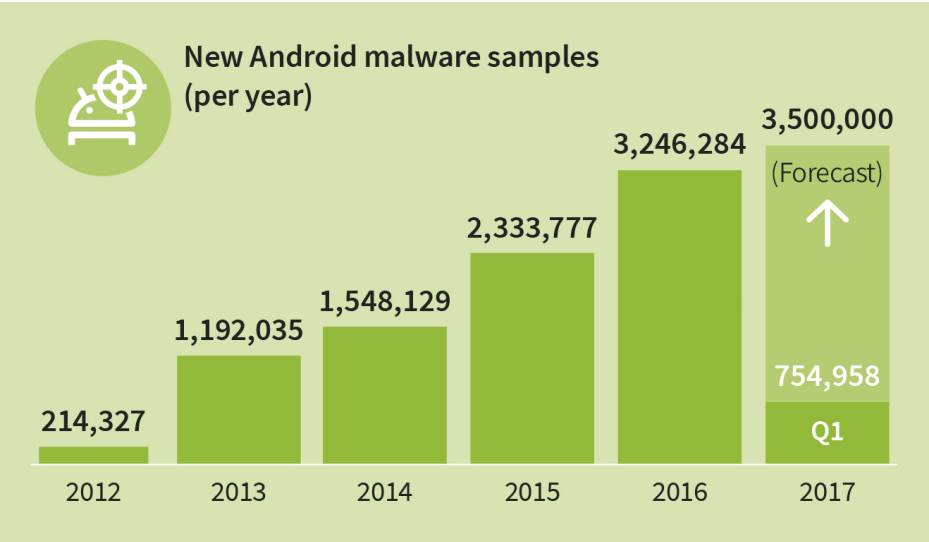
Outline

1. Problem Statement
2. Related Work
3. Automated Verification of Security Chains
4. Prototype and Performance Evaluation
5. Conclusions

Motivations

- Growing number of malicious applications on Android devices
  - 3.25 million malicious applications in 2016 (Gdata Security Labs)



- Limitations of market preventive security methods
- On-device security constrained in terms of resources
- Partial outsourcing through cloud-based security chains
- Can automated verification methods help ensure their quality?

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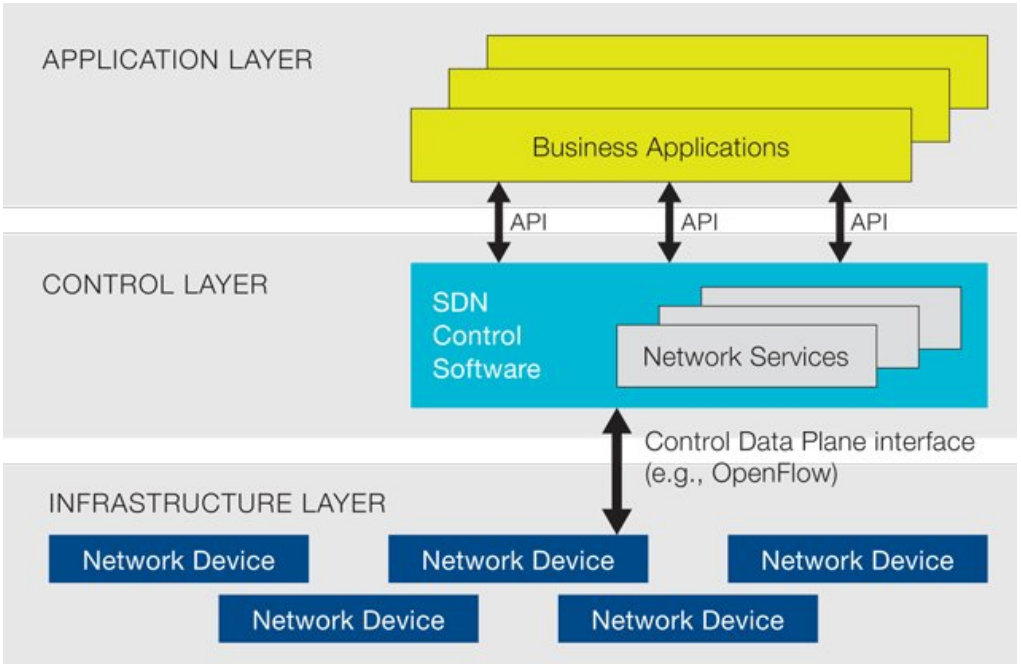
Security middleboxes in cloud infrastructures

- Virtualization and outsourcing of network security functions in cloud infrastructures
- Target: higher flexibility and better manageability

- Uniform middlebox modelling proposed by Joseph and Stoica
- Firewall middlebox specification with *FlowGuard*

- Automating large-scale deployments remains difficult
- Lack of uniform interfaces for these devices
- Formal verification could help validating their correctness

Network programmability as a management enabler



SDN architecture (source: `www.opennetworking.org`)

- Easier automation of middlebox deployment and chaining
- Low level interface needs abstraction and formal methods

Techniques for formal verification

SMT solving

- Representation of systems and properties as logical formulas
- SMTlib: a standard input language for SMT solvers
- Verification based on checking satisfiability/validity

Model checking

- Representation of systems based on finite state automata
- Properties expressed in temporal logics: LTL (Linear Temporal Logic) or CTL (Computation Tree Logic)

Security chains in software-defined networks

Chaining security functions for protecting end users

- Automated building in cloud infrastructures using SDN
- Dynamic and optimized placement of security functions based on available resources

Efforts for formally verifying such security compositions

- Validation of distributed firewall policies: *Al-Shaer et al.*
  - Example: do not simultaneously authorize and block port 5000
- Validation of traffic properties: Vericon *(Ball et al.)*
  - Example: check that a policy blocks incoming connections

The Pyretic language for describing network policies

Pyretic

- Python-embedded domain-specific programming language for writing SDN control programs
- Network data-plane behavior: policy functions
- compiles policies to OpenFlow-based switches

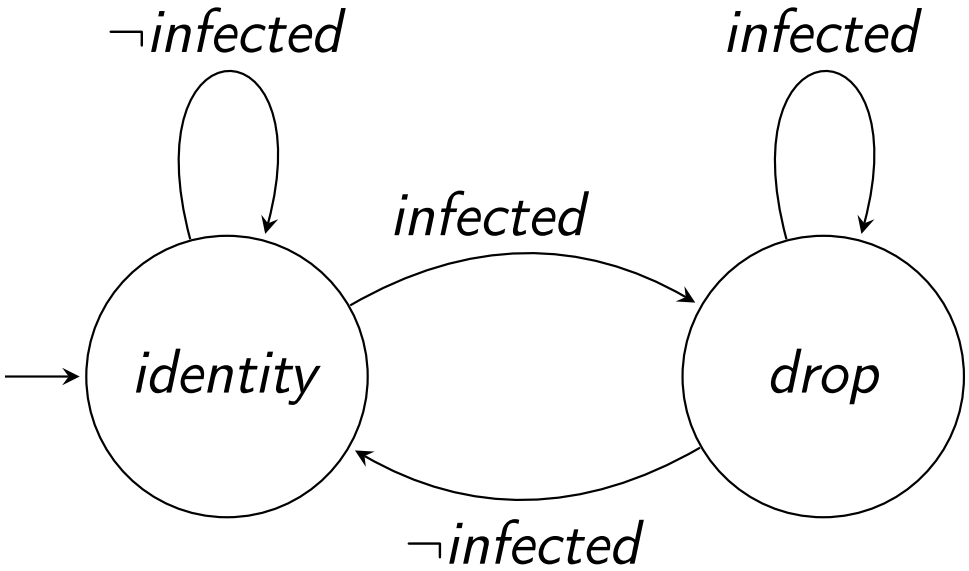
Pyretic rules and compositions

- 4 atomic rules: identity, drop, match and modify
- Sequential composition operator: »
- Parallel composition operator: +

Examples of simple policy chains

- Parallel composition: match(port=5000) + match(port=4000)
- Sequential composition: match(port=5000) » drop

Verifying the control plane of Pyretic chains with Kinetic



- **Kinetic:** represent control dynamics as a Finite State Machine
- Validation by model checking with NuSMV
- Example property: $\mathbf{A}\,\mathbf{G}\,(\mathit{infected} \rightarrow \mathbf{A}\,\mathbf{X}\,\mathit{drop})$
- Objective: extend formal verification to the data plane

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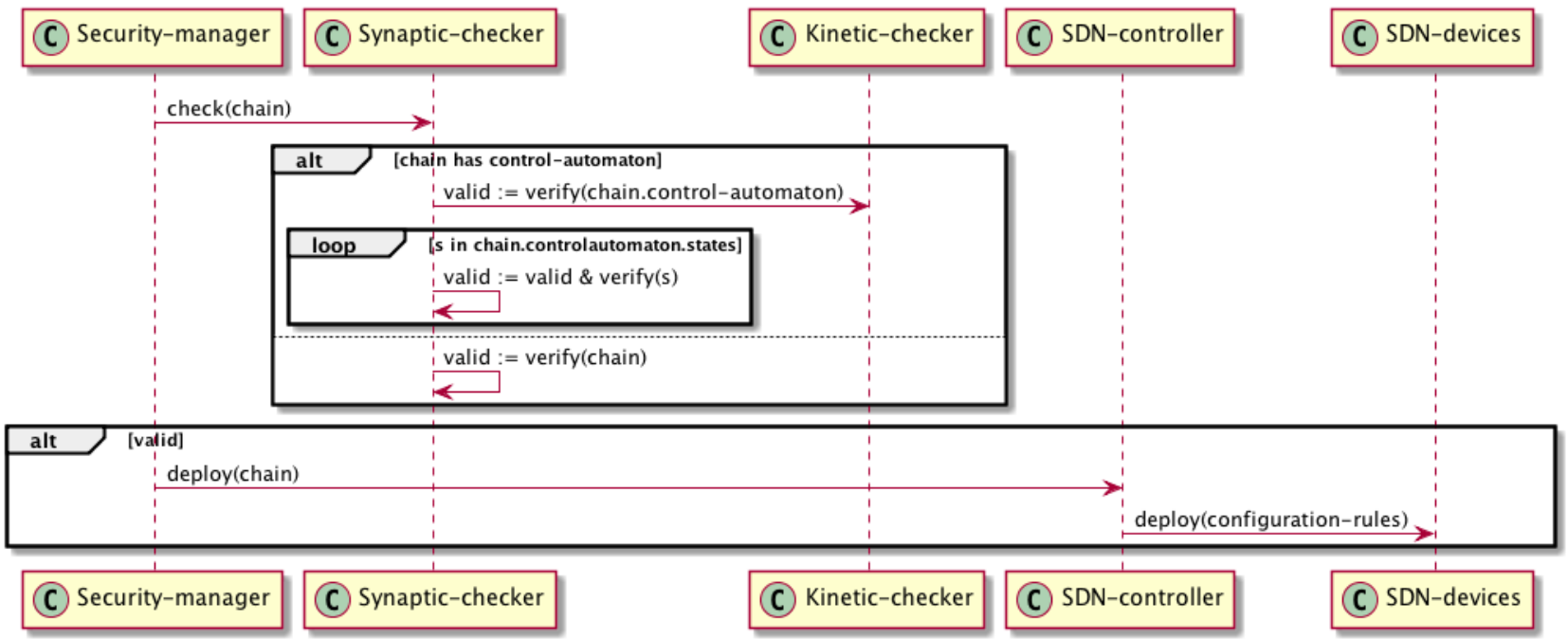
Proposed verification strategy

Verification of both control and data planes of security chains

- Extension of the Kinetic language to the data plane
- Verification using SMT solving and model checking
  - Chains translated to both types of tools
  - Addition of properties to constrain the model



Verifying security chains using SMT solving

Modelling and translation

- Chains and constraints expressed with SMTlib
- Representation based on logical formulas
- Prototype supporting the CVC4 and veriT SMT solvers

Advantages of SMT solving for our strategy

- Pyretic expressions correspond to logical formulas
- Easy to add constraints expressed as equalities
- Example: port==5000 $\rightarrow$ flow accepted

Compilation of a chain for SMTlib

- Atomic rules represented using Boolean values and equalities
- These rules represent the basic building blocks

- Composition operators encoded using Boolean connectives
- Used to build up complex security chains

- Traffic invariants expressed as logical conditions
- Success: the chain validates the constraints

Compilation examples

Compilation of a simple chain

- match(port=5000) + match(port=4000)
  $\rightarrow$ (OR (= port 5000) (= port 4000))
- Production of a packet condition

Compilation of a condition

- ip=192.168.0.15 $\rightarrow$ (= ip 1)
- replacement of network elements by integer values

Verification of security chains using model checking

Modelling and translation

- Represent the network as a finite state automaton
- Express the invariants in temporal logic (CTL)
- Success: the automaton satisfies the invariants

Advantages of model checking for our strategy

- Already used for the control plane (Kinetic)
- Possibility of extending this model to the data plane by using nuXmv instead of NuSMV

Compilation of a chain for nuXmv

- Express the network as a finite state automaton
- Variables represent packet fields

- Strictly sequential policies correspond to automaton transitions
- Join points give rise to states of the automaton

- Traffic invariants expressed as CTL properties
- Authorized traffic accepted by the automaton
- Forbidden packets are blocked

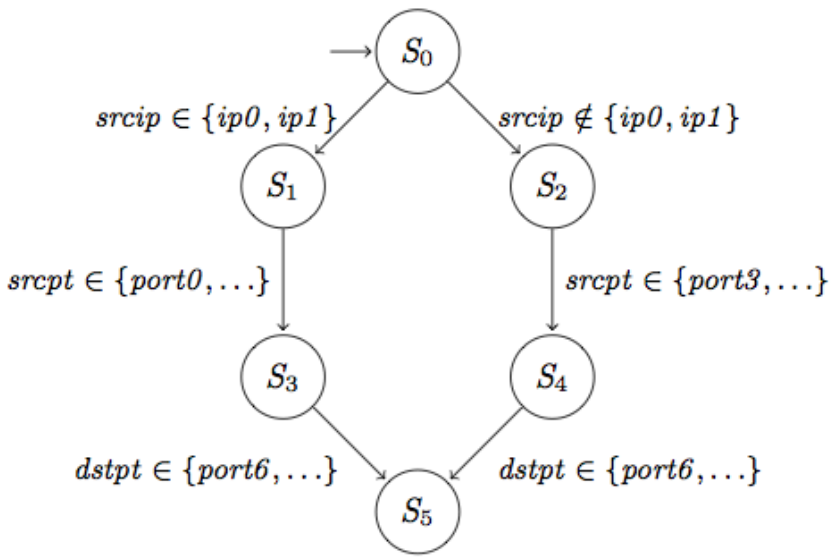
Example of verification by model checking

```
F1 = match(srcip=IP("198.122.37.15")) +
     match(srcip=IP("253.182.3.14"))

F2 = match(srcport=1000) + match(srcport=2000) +
     match(srcport=3000)

F3 = match(srcport=4000) + match(srcport=5000) +
     match(srcport=6000)

F4 = match(dstport=7000) + match(dstport=8000) +
     match(dstport=9000)

chain = ((F1 >> F2)+(~F1 >> F3)) >> F4
```

Pyretic firewall chain

```
AG(((srcip=ip0 | srcip=ip1) &
    (srcpt=port0 | srcpt=port1 | srcpt=port2) &
    (dstpt=port6 | dstpt=port7 | dstpt=port8))
   -> EF state=S5)

AG(((!(srcip=ip0 | srcip=ip1)) &
    (srcpt=port3 | srcpt=port4 | srcpt=port5) &
    (dstpt=port6 | dstpt=port7 | dstpt=port8))
   -> EF state=S5)
```

Chain specifications in CTL



Data plane FSM

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Our prototype: the Synaptic checker

- Checker implemented in Python
- Extension of Pyretic and Kinetic languages
- Implementation of a module dedicated to traffic properties

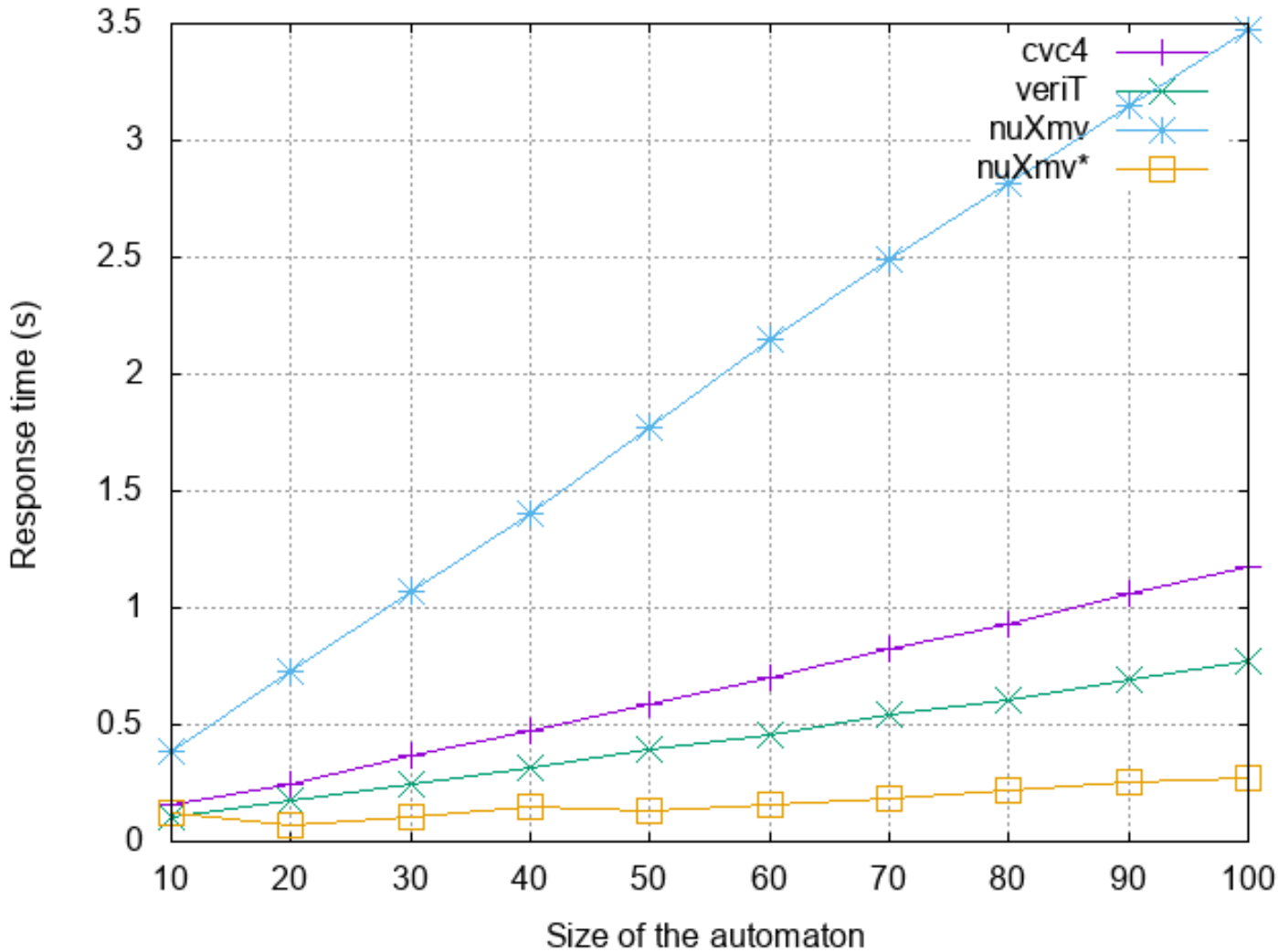
- Integration of formal verification methods
- Use nuXmv or SMT solvers as backend verifiers

Experimental setup and evaluation criteria

Evaluation based on a set of synthetic security chains

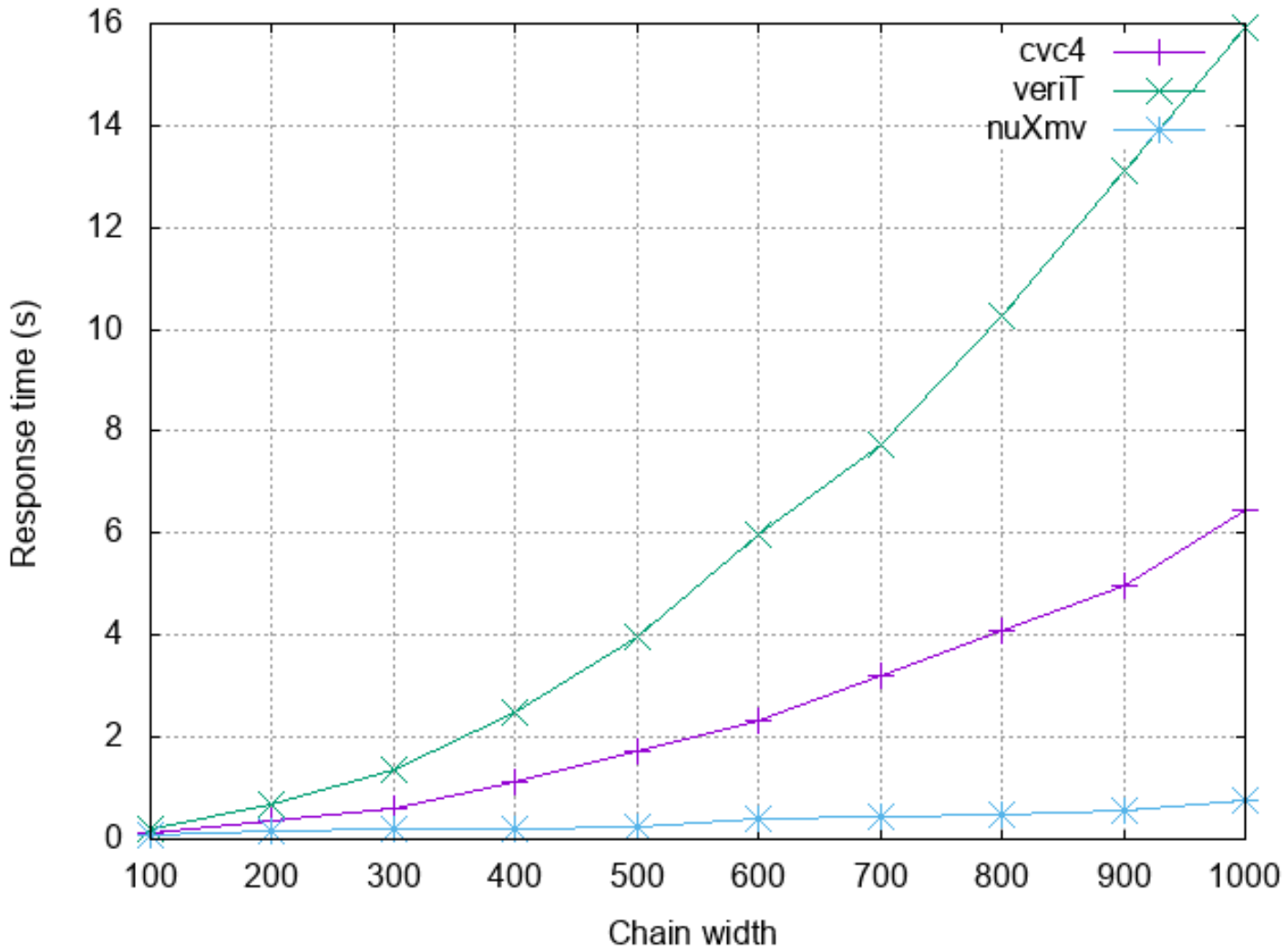
- Impact of several chain-related parameters
  - Size of the control automaton
  - Length and width of a security chain
  - Number of properties to be verified
- Comparison of verification performances
  - Response time
  - Memory space consumption

Impact of the size of the control plane automaton



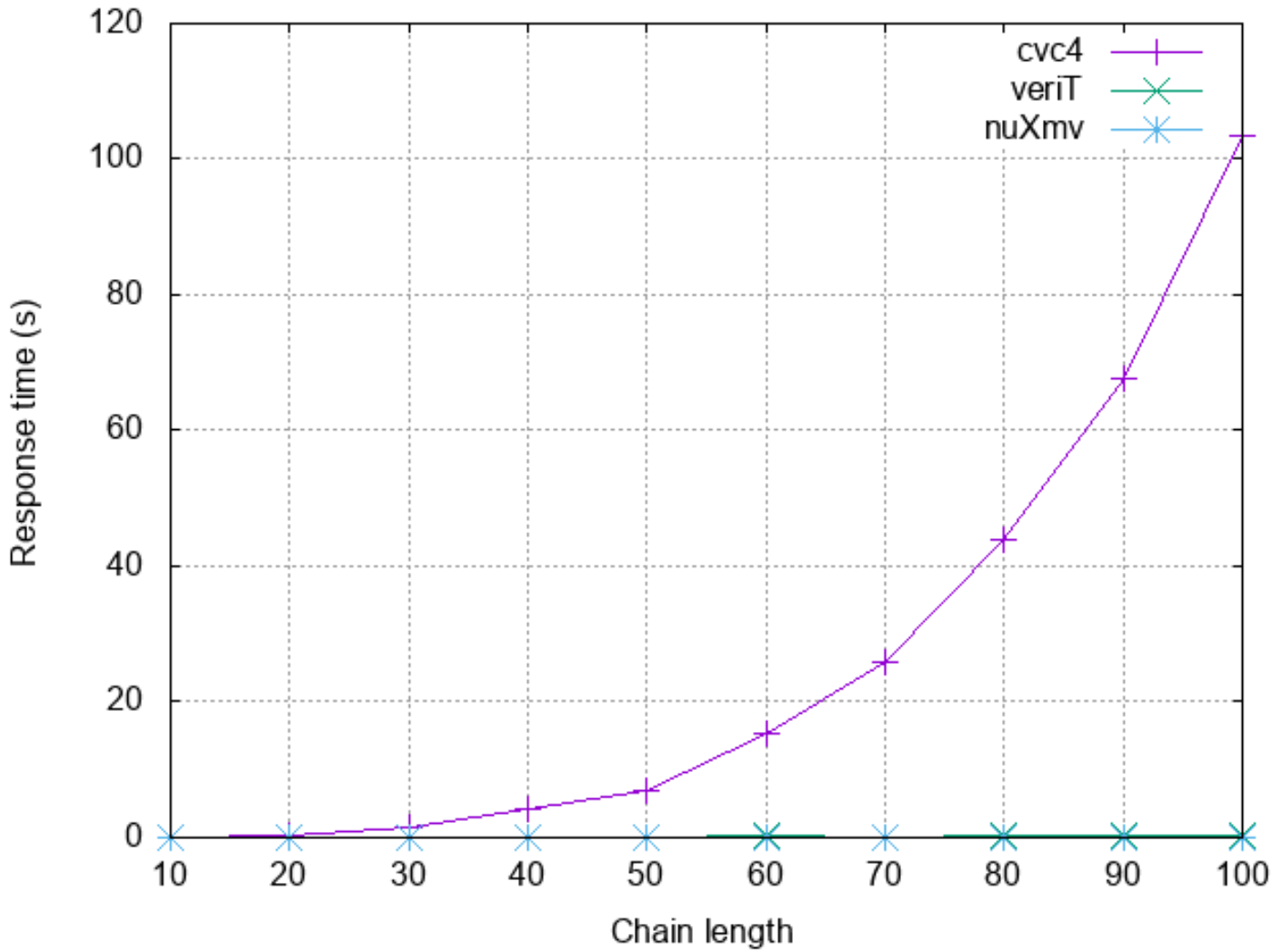
Response time vs. size of the control automaton

Impact of the width of a chain



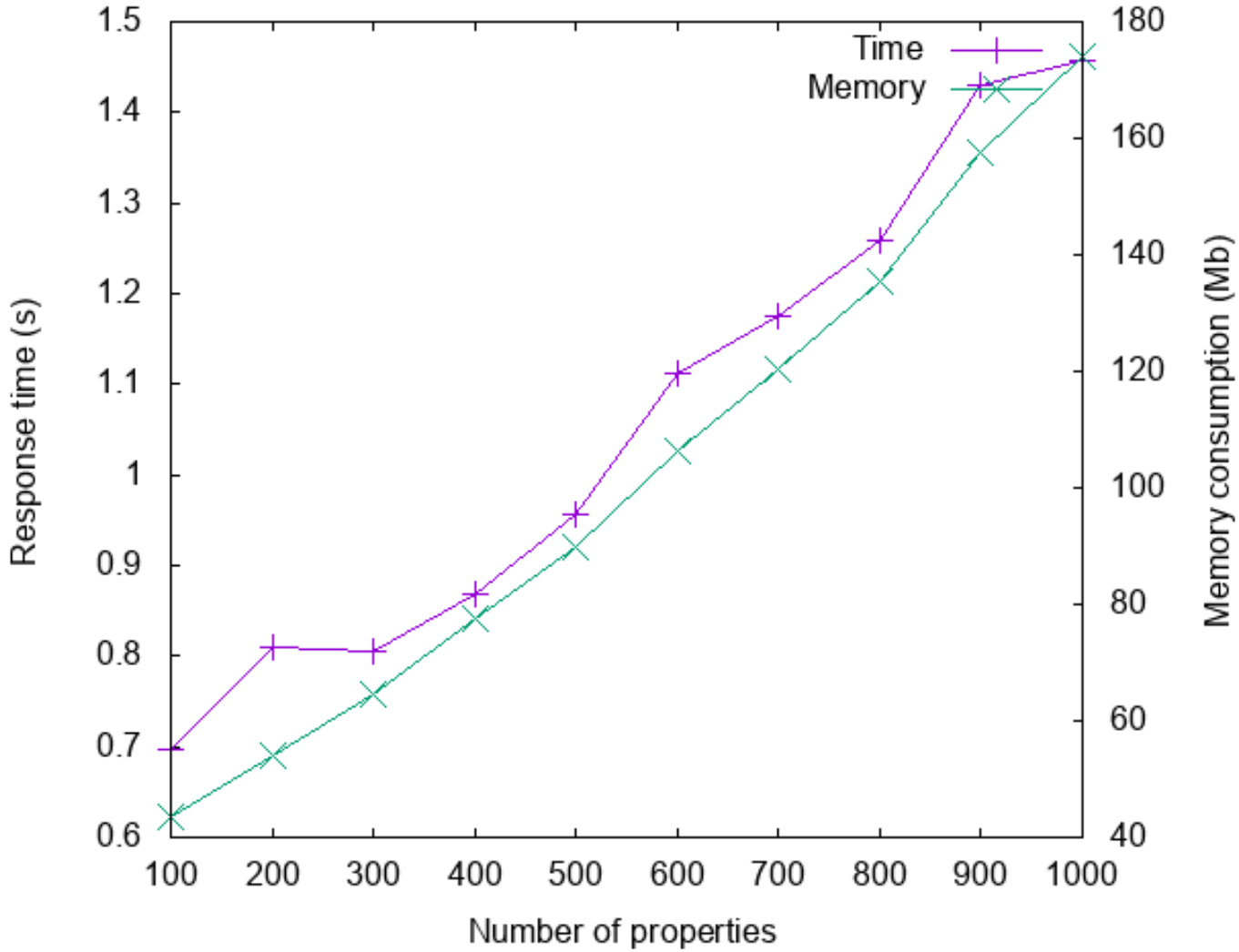
Response time vs. width of a chain

Impact of the length of a chain



Response time vs. length of a chain

Impact of the number of properties to verify



Resource consumption vs. number of properties (nuXmv)

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Conclusions

Automated techniques for verifying SDN security chains

- Checking both the control and the data planes
- Translation of security chains for automatic verification
- Backends based on SMT solving or model checking

Prototyping and performance evaluation

- Development of the Synaptic checker
- nuXmv shows best overall performance in our experiments

Perspectives

- Extensions for more complex and advanced rules
- Further optimization of the encodings into SMTlib and nuXmv
- Integration into an automated security framework