Automated Testing of Stateful Network Protocol Implementations in the IoT

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Motivation

Background: IoT nodes exchange data via network protocols

- Protocol implementations often contain software bugs
- Some of these bugs (e.g. buffer overflows) are exploitable
- Problematic since IoT operating systems have few exploit mitigations

Goal: Automatically find such bugs in network modules

$\Rightarrow$ Emerging method for this purpose: *symbolic execution*

Background: Symbolic Execution

Idea: Enumerate reachable paths based on specific input source

- SW executed with symbolic values, represent set of concrete values
- Symbolic values are continuously constrained during execution
- Constraints on current path: *path constraints* (PC)

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DSE: *Dynamic Symbolic Execution*

- Concrete execution drives symbolic execution
- Track symbolic constraints alongside concrete execution
- Branches are collected; later negated with an SMT solver

Dynamic Symbolic Execution (1/3)

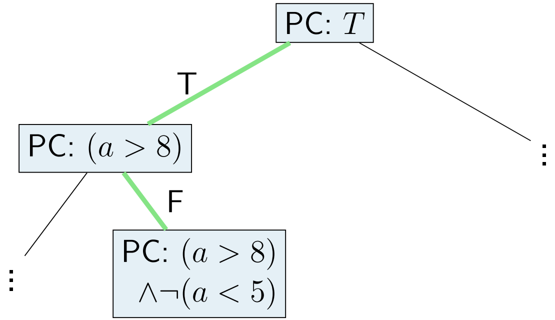
Example:

```
void myfunc(int a) {
  if (a > 8)
    // ...
  else
    // ...

  if (a < 5)
    // ...
  else
    // ...
}
```

Dynamic Symbolic Execution (1/3)

Example: Execution trace for `myfunc` with input $a = 9$

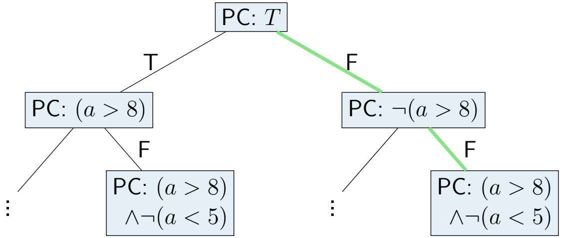
```
void myfunc(int a) {
  if (a > 8)
    // ...
  else
    // ...

  if (a < 5)
    // ...
  else
    // ...
}
```



Dynamic Symbolic Execution (2/3)

Exploration: Negate unexplored branch $\neg(a > 8)$, solve resulting query
$\Rightarrow$ Restart execution with concrete input (e.g. $a = 8$)

```
void myfunc(int a) {
  if (a > 8)
    // ...
  else
    // ...

  if (a < 5)
    // ...
  else
    // ...
}
```

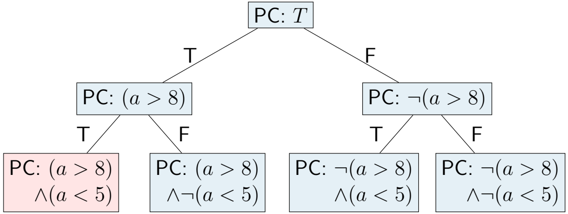


Dynamic Symbolic Execution (3/3)

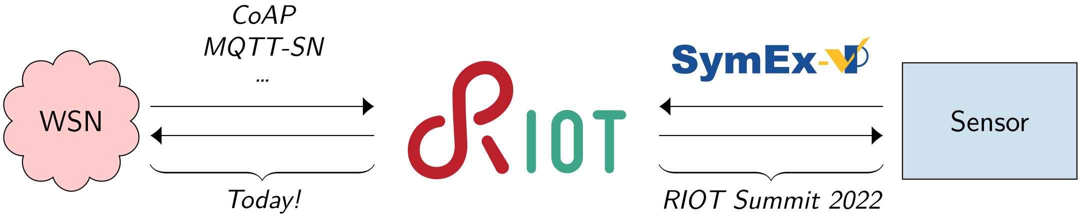
Goal: Ideally discover all execution paths

$\Rightarrow$ Repeat until all branches have been negated

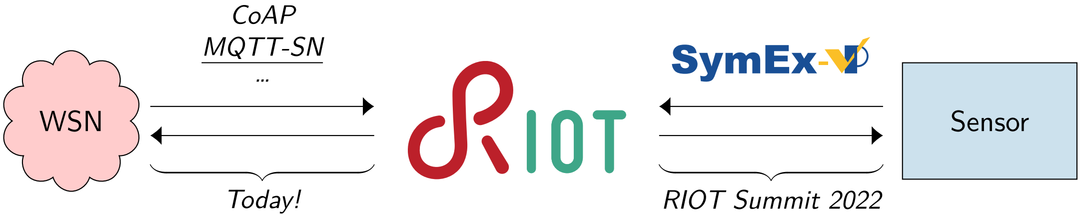
```
void myfunc(int a) {
  if (a > 8)
    // ...
  else
    // ...

  if (a < 5)
    // ...
  else
    // ...
}
```



Input Interfaces in the IoT



Input Interfaces in the IoT



Challenge: State Space Explosion

MQTT-SN: Stateful protocol for data exchange in the IoT

- Certain code can only be tested by establishing a state first
- For example, subscribing to a specific topic
- Results in a large state space for symbolic execution

  $\Rightarrow$ Cannot be fully explored using symbolic execution

Message Format Specification

Goal: Discovering "interesting" execution paths first

⇒ Observation: Many inputs are rejected early on

Approach: Partially specify protocol message format

- Embedded domain specific language (EDSL)
- Based on the Scheme programming language

```
(define-input-format (suback id)
  (make-uint 'len 8 8)
  (make-uint 'type 8 MQTT-SUBACK)
  (make-symbolic 'flags 8)
  (make-symbolic 'topicid 16)
  (make-uint 'msgid 16 id)
  (make-symbolic 'code 8
    `((And
        (Uge ,code 0)
        (Ule ,code 3)))))
```

Figure: Message format for MQTT-SN SUBACK.

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State Machine Specification

Challenge: MQTT-SN is a stateful protocol
$\Rightarrow$ Message format depends on protocol state

Approach: Also describe protocol state machine

- With a separate Scheme-based EDSL
- Advance protocol state based on received messages
- Return new symbolic message depending on state

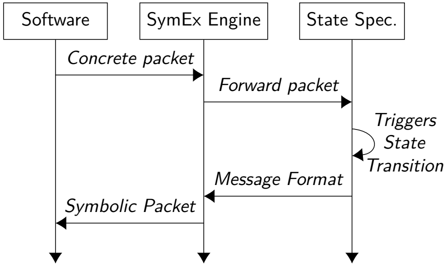


Figure: Overview of message format exchange.

Specification of the MQTT-SN State Machine

Needed: MQTT-SN state machine description

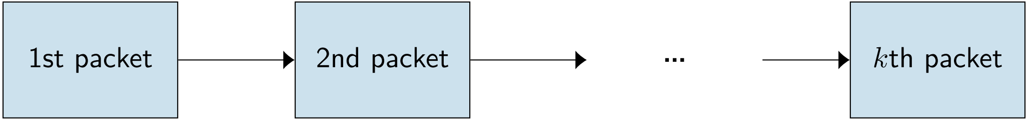
- Described as a finite-state machine
- Transitions based on input packet
- Each transitions returns a response format

```
(define-state-machine mqtt-machine
  (start pre-connected)

  (define-state (pre-connected input)
    ...)

  (define-state (connected input)
    (switch (mqtt-msg-type input)
      ((SUBSCRIBE)
       (-> (make-resp (suback-fmt (msg-id input)))
           subscribed))
      ((DISCONNECT)
       (-> (make-resp disconn-fmt)
           disconnected))
      ...))

  ...
)
```

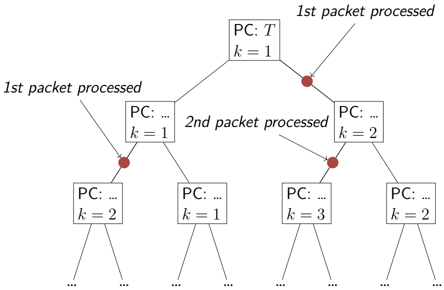
Figure: Excerpt of the MQTT-SN state specification.

Symbolic Packet Sequences

Problem: Need to reason about sequence of packets
$\Rightarrow$ Further increase of state space



Multipacket Exploration



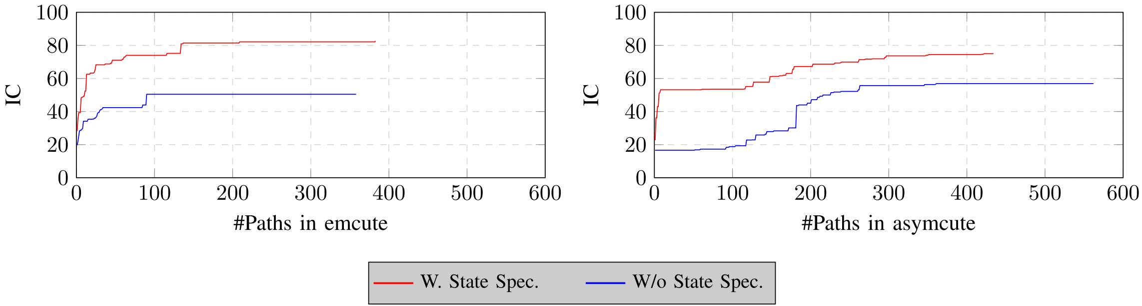
Simplified Algorithm:

1. Explore program up to a sequence length of k
2. Restart execution when packet k was processed
3. When coverage is stagnant: Increment k

$\Rightarrow$ Partially explored paths are re-executed continuously

Evaluation (1/2)

Research Question: Does our symbolic execution approach improve coverage?
$\Rightarrow$ Experiments with RIOT's MQTT-SN implementations



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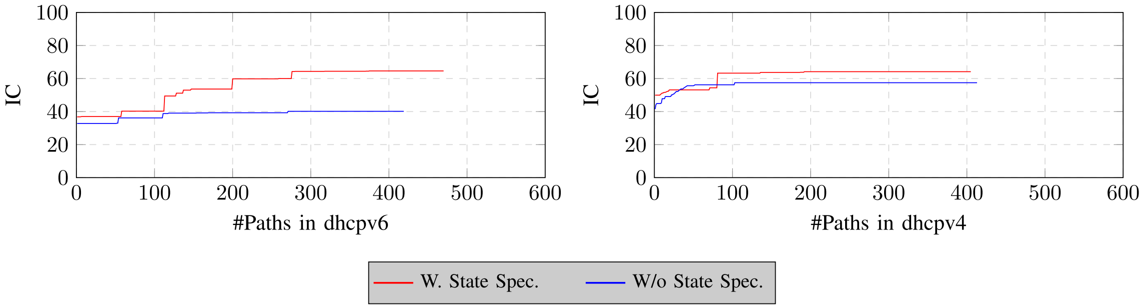
Evaluation (2/2)

Research Question: Is the approach applicable to other protocols?

$\Rightarrow$ Experiments with RIOT's and Zephyr's DHCP implementations



Bugs found in RIOT

Bugs Found:

1. #18307: out-of-bounds read in dhcpv6 module
2. #18289: missing `mutex_unlock` in `asymcute`
3. #18434: null pointer dereference in `asymcute`

Future Work:

- Integrate protocol rules into specification?
- Assessment of created protocol specifications
- ...

Summary

Key Insight: High coverage in complex network modules via symbolic execution
⇒ With comparatively little manual effort

Contributions:

1. Input specification language for message formats[1]
2. Specification language for protocol state machines[2]
3. Enhanced version of SymEx-VP with new exploration engine[3]

More Information: Sören Tempel, Vladimir Herdt, and Rolf Drechsler. *Specification-based Symbolic Execution for Stateful Network Protocol Implementations in the IoT*. IEEE Internet of Things Journal, 2023.

[1] `https://github.com/agra-uni-bremen/sisl`
[2] `https://github.com/agra-uni-bremen/sps`
[3] `https://github.com/agra-uni-bremen/sps-vp`