VeriFi: Model-Driven Runtime Verification Framework for Wireless Protocol Implementations

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Abstract

Validating wireless protocol implementations is challenging. Today's approaches require labor-intensive experimental setup and manual trace investigation, but produce poor coverage and inaccurate and irreproducible results. We present VERIFI, the first systematic sniffer-based, model-guided runtime verification framework for wireless protocol implementations. VERIFI takes a formal model of the protocol being verified as input. To achieve good coverage, it first applies state reachability analysis by applying model checking techniques. It then uses a new PACKETSNIPER component to selectively trigger packet losses required to quickly investigate all reachable protocol states. Our results show that the selective packet jamming allows VERIFI to significantly improve the coverage of protocol states. Finally, VERIFI accommodates uncertainty caused by the sniffer when validating traces, allowing it to provide accurate and reproducible results. By modeling uncertainty, VERIFI highlights likely protocol violations for developers to examine.

1 INTRODUCTION

The rapid increase in the number of mobile and custom wireless devices is making wireless protocols increasingly important. Wireless protocols specifications undergo extensive testing, typically through simulations. But a lack of good tools results in protocol *implementations* not being tested as carefully as protocol specifications. Implementations can always introduce bugs, particularly when development is done by parties that did not author the specification. Given the rise of custom wireless devices—such as Apple TVs, XBox controllers, ChromeCasts, and FitBits—effective testing of wireless protocol implementations is more important today than ever before. These devices frequently implement custom and sometimes proprietary wireless protocols. The implementation may itself be proprietary, making source code unavailable to the party performing validation. And they may lack capabilities required to do white-box testing. A series of connectivity flaws in deployed devices and systems—including Apple Watch 3 [24], iOS 8 [11], Google Android Lollipop [17], and the Microsoft Surface Pro 3 [8]—help demonstrate that a new approach to wireless protocol implementation verification is needed.

Formal model checking techniques have been used to verify the correctness of wired communication protocol implementations [25, 14] and distributed systems [15, 9, 22]. But there are several unique features that make verifying wireless protocol implementations more challenging. Wireless protocols confront a more complex and dynamic environment than their wired counterparts. Environment variables—such as attenuation, multi-path, fading, and interference—are hard to control, making reproducible experimentation difficult. To meet tight timing constraints, wireless protocols are often implemented in low level firmware. This makes it difficult to apply source code model checking techniques. Finally, due to closed-source implementations, validation often must be done using external wireless sniffers. Due to the physical nature of the wireless medium, sniffers introduce uncertainty that can sabotage the validation results.

The result of these difficulties is that no systematic testing or verification system for wireless protocol implementations currently exists. Current state-of-the-art industry practices begins with labor-intensive conducted test setup. Manual spot-checking is then used to inspect packet traces collected by the sniffer and validate implementation correctness. The process is tedious, error-prone and time-consuming, but also misses many protocol states resulting in poor test coverage.

In this paper, we describe the design and implementation of VERIFI: the first systematic sniffer-based, model-guided runtime verification framework for wireless protocol implementations. While VERIFI could be extended to study timing-related failures, it currently focuses on implementation bugs caused by packet loss. Factors such as interference and fading make packet loss normal in wireless communications. A core task of wireless protocols is handling packet loss, and VERIFI can help validate that they do so correctly.

VeriFi requires both a *model* of the protocol specification and access to the devices being tested. The model consists of state machines for portions of the protocol that require verification, such as *association*, *rate control*, and *retransmission* policies. During testing, VeriFi manipulates communication with the tested device to ensure that it quickly reaches all reachable protocol states. It accomplishes this using two novel components. A protocol model analyzer determines packet loss sequences that can drive the protocol model into various states. The PacketSniper uses these sequences to determine if a packet currently in the air should be lost to reach an untested state. If so, it prevents packet reception by generating a jamming signal.

Once testing is complete, a trace verifier analyzes recorded packet exchanges to identify protocol violations. VeriFi can distinguish likely implementation bugs from false positions that were probably caused by sniffer uncertainty. This produces a clear work flow for helping developers bring their implementation in line with the specification.

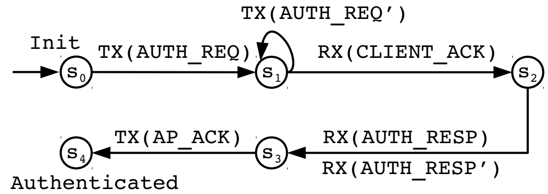
Our work makes the following contributions:

- To the best of our knowledge, VeriFi is the first automatic and systematic framework for end-to-end validation of wireless protocol implementations.
- By formally describing the model of wireless protocols, we use model checking techniques to automatically infer the packet reception and loss sequences that drive the model and implementation into target states.
- We describe the design principles and two prototype implementations of PacketSniper for Wi-Fi systems, which selectively drop the packets specified by the protocol model analyzer.
- We propose a new method of validating sniffer traces under uncertainty (as observed in [30]). By incorporating sniffer as part of our model, the sniffer trace uncertainty can be tackled by an off-the-shelf model checker (instead of a specialized checker [30]).
- We perform an end-to-end evaluation of our framework using the 802.11 link setup protocol. It demonstrates that VeriFi significantly improves test coverage, efficiency, and reproducibility. We also report three implementation issues VeriFi discovered that do not manifest otherwise.

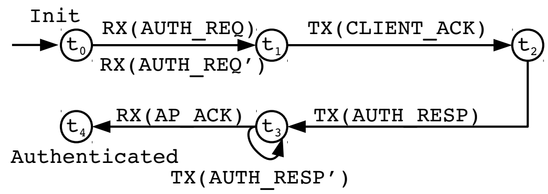
While we believe that VeriFi is a general approach that can validate many different wireless protocol implementations, this paper focuses on Wi-Fi based systems.

2 Validation Framework

We use the Wi-Fi link setup protocol as a concrete example to illustrate the work flow of our validation framework. The detailed protocol is explained in Section 2.1.



(a) **Client State Machine for the Authentication Step.** `PKT'` denotes the MAC layer retransmissions of `PKT`.



(b) **AP State Machine for the Authentication Step.**

Figure 1: **802.11 Link Setup Protocol and State Machines.**

We then describe three key observations from the example protocol in Section 2.2 and show an overview of our validation framework in Section 2.3.

2.1 Example Protocol

The Wi-Fi link setup protocol consists of three phases: authentication, association and 802.11X authentication. Figure 1a shows the client's state machine for the authentication phase. The client first sends `AUTH_REQ` and expects to receive `CLIENT_ACK` ($s_0 \rightarrow s_1$). Either it receives `CLIENT_ACK` and then waits for `AUTH_RESP` ($s_1 \rightarrow s_2$), or it retransmits `AUTH_REQ` and remains at s_1. Once it receives both the `CLIENT_ACK` and the `AUTH_RESP` packet, it moves to the `Authenticated` state s_4. The client then continues to start the association request/response handshake process, the detailed state machines of which are omitted for sake of space.

In Figure 1b, when the AP receives `AUTH_REQ` or its retransmission, it first acknowledges the request ($t_1 \rightarrow t_2$), and then replies with `AUTH_RESP`. Similarly, multiple retransmissions of `AUTH_RESP` may occur before the AP receives `AP_ACK`, and is ready to handle the association request from this client. The AP may have several such state machines running in parallel to handle the authentication requests from multiple clients.

2.2 Key Observations

We make several observations from the example protocol described in Section 2.1. First, wireless protocols can be modeled as a collection of state machines that interoperate with each other via packet exchanges. In particular, each end device can be treated as a black box and the inputs of the state machine are limited to only externally observable events: what (and when) packet is transmit-

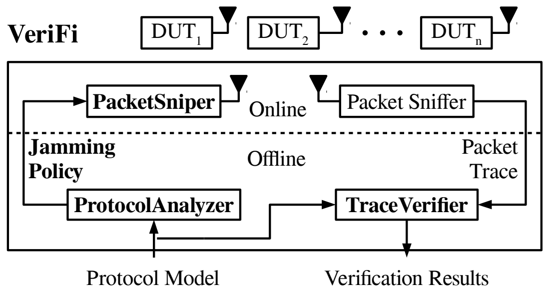


Figure 2: **VERIFI Framework for Verifying Wireless Protocol Implementations.** Components in bold face are proposed and described by this paper. DUT stands for Device Under Test.

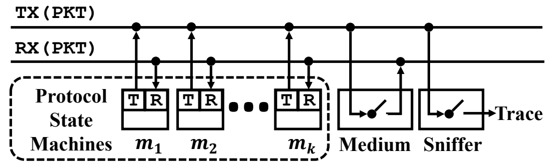


Figure 3: **Model for Wireless Protocols.** `T` and `R` represent common transmitting and receiving modules that are reused at each state machine.

ted. This constraint not only simplifies the protocol analysis and verification, but also has practical benefits. As explained earlier, the implementations of wireless protocols are often proprietary, making observing end-points' internal states extremely difficult if not entirely impossible. Certain wireless protocol aspects, such as the Clean Channel Assessment (CCA) and Distributed Coordination Function (DCF), cannot be modeled in this manner as they require access to the end device's internal states.

Second, packet loss is the key factor that alters the endpoint behaviors in wireless protocols. Other factors, such as out-of-order delivery and queueing delay, are less significant in wireless protocols than their wired counterparts. For instance, the link setup protocol in Figure 1 becomes trivial in the absence of packet loss: each device just iterates through the three stages sequentially before both end-device reach the same associated state. In fact, we argue that a large portion of any wireless protocols is to define how the endpoints cope of packet losses: retransmissions and acknowledgments are required to ensure packet delivery, rate control mechanisms are used to improve the link performance in face of packet loss, etc.

Finally, validating wireless protocol implementations involves driving the system to certain state, and then observe and validate the Device Under Test (DUT)'s behavior. The system state can be represented by a tuple of the model state at each endpoint. For instance, in the state machines shown in Figure 1a and 1b, the system state $\langle Client.s_1, AP.t_3\rangle$ represents the case where the client and the AP disagree with the authentication status: the client thinks it is not authenticated and is trying to retransmit the `AUTH_REQ` packet, while the AP actually receives the `AUTH_REQ` packet and is trying to transmit the `AUTH_RESP` packet.

2.3 Framework Overview

Based on the observations, we propose VERIFI, a model-driven runtime verification framework for wireless protocol implementations. Figure 2 shows main components and the work flow of the framework.

Beginning with a formal model of the protocol, the PROTOCOLANALYZER first uses model checking techniques to infer the edge sequence (packet success/loss) to reach each system state. We describe general principles of modeling wireless protocols and one specific realization using UPPAAL model checker in Section 3.

The packet success/loss information is then fed to PACKETSNIPER—a real-time reactive packet jammer. The PACKETSNIPER drops the packets that are tagged as loss in the policy. We describe the design and two implementations of PACKETSNIPER for 802.11 in Section 4.

Finally, packet traces are collected to verify the system's behavior by the TRACEVERIFIER component. As observed in [30], sniffer trace can not directly be used for verification due to uncertainty. We describe how VERIFI handles sniffer trace uncertainty in Section 5.

3 PROTOCOL ANALYZER

The PROTOCOLANALYZER takes the protocol model which consists of a set of communicating state machines, and outputs the packet success/loss sequences to reach each system state. We first propose a approach to model wireless protocols (§ 3.1) and the algorithm to infer the packet success/loss sequences (§ 3.2). We then describe our implementation on UPPAAL model checker (§ 3.3).

3.1 Modeling Wireless Protocols

Communication in wireless medium is broadcast at physical layer in nature—each transmitted packet can be heard by every devices within the vicinity of the transmitter. The packet contains a destination field to help non-designating devices drop such packets and only the indented receiver delivers the packet to upper layer. Due to factors such as interference and fading, each packet has a non-zero loss probability.

Based on these observations, we propose a *generic model* for wireless protocols, as shown in Figure 3. Transmitting and receiving packets are simulated by sending to and receiving from two shared *synchronous* signal buses: `TX(PKT)` and `RX(PKT)`. The wireless medium is modeled as a *switch* that controls the success or failure of each transmission at per-packet basis. The wireless protocol to be modeled consists of a set of state machines, $m_1, m_2, \ldots, m_k$, that inter-operate with

Algorithm 1 Jamming Policy Generator.

Input: protocol model M, state to reach s.
Output: jamming policy to reach the state s, or *nil* if the state is not reachable.

1: **procedure** JAMMINGPOLICY(M, s)
2: errorState $\leftarrow s$
3: transitions $\leftarrow$ MODELCHECKER(M, errorState)
4: **if** transitions = *nil* **then**
5: **return** *nil* ▷ state s is not reachable
6: **end if**
7: policy $\leftarrow$ []
8: **for** t *in* transitions **do**
9: policy.append($\langle$t.pkt, t.medium_switch$\rangle$)
10: **end for**
11: **return** policy
12: **end procedure**

each other via the two communication buses. The protocol state is a tuple of all the states at each state machine, i.e., $\langle m_1.state, m_2.state, \ldots, m_k.state\rangle$.

Assuming that the protocol itself is deterministic, the only non-determinism in the model lies in the switch inside the `Medium` module. When querying certain properties of the protocol model, such as state reachability, the model checker tool can only manipulate this medium switch for each packet when performing validation. The `Sniffer` module is discussed in Section 5.

Note that there are two common functionalities that are used at each end devices: transmitting and receiving a packet. We use the `T` and `R` sub-modules to provide such abstractions. The packet transmission sub-module (`T`) involves managing sequence number (for de-duplication at the receiver), waiting for acknowledgment and performing retransmission when needed. The packet reception sub-module (`R`) is responsible for sending acknowledgment packet and packet de-duplication. These two sub-modules, together with the `Medium` and `Sniffer` models, are protocol independent and can be provided as part of the verification framework.

The ability of modeling broadcast packets (such as beacons in 802.11) is limited in our current formulation. Since there is only one medium switch for all receivers, the broadcast packet can only be either received or missed by *all* devices. While in reality, the broadcast packet may be received by a subset of devices but missed by others. However, this is not a fundamental limitation, and can be mitigated by extending our formulation and adding a medium switch to each participating device. Without loss of generality, we focus on protocols that only contain single-cast packets in this paper.

3.2 Jamming Policy Generation

The output of PROTOCOLANALYZER is the packet success/loss sequences that drive the protocol model into each state. We call such sequences *jamming policy*, as they provide instructions of which packet to jam or pass for PACKETSNIPER that we will describe in Section 4.

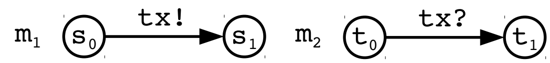


Figure 4: **Channel Synchronization in UPPAAL.**

With our proposed modeling approach, the key idea of inferring jamming policy to reach a target state is to reduce the problem to the well-known model checking problem of determining if an error state s is reachable in a model M [13].

Algorithm 1 shows the jamming policy generator algorithm. In order to infer the jamming policy to reach the target state, we instruct the model checker to verify the property that claims the target state is not reachable (L2). If the state is reachable, model checker will come up with a counter example which consists of the state transitions from the initial state to the target state. By examining the packet and the state of medium switch associated with the transition (L9), we can infer the jamming policy that drives the system to target state. We then apply Algorithm 1 for each system state, and obtain corresponding jamming policies for each reachable system state.

3.3 Implementation on UPPAAL

The proposed modeling methodology of wireless protocols and algorithm for inferring jamming policies are generic, and can be realized in any model checking tool that provides synchronization capability between interacting models. Next, we describe one implementation on UPPAAL model checker.

3.3.1 UPPAAL *Primer*

UPPAAL [6, 5] is a model checking suite for verifying real-time systems modeled as networks of timed automata [2]. The suite contains the UPPAAL language specification and a model checker implemented using constraint-solving techniques.

UPPAAL provides shared variables and synchronization capability via *channel* variables, making it easy to model packet exchange. An example is shown in Figure 4. A channel variable `tx` is defined to synchronize the transitions in two state machines, m_1 and m_2. In particular, the $s_0 \to s_1$ transition labeled as `tx!` in m_1 synchronizes with the $t_0 \to t_1$ transition labeled as `tx?` in m_2. Therefore, a packet can be "transmitted" from m_1 to m_2 by writing a shared variable in the $s_0 \to s_1$ transition in m_1, and reading the same shared variable in the $t_0 \to t_1$ transition in m_2.

Listing 1 shows the 4 optional components of a state transition in UPPAAL. The *Selection* statement non-deterministically binds a local identifier to a value in a given range. The state transition is enabled if and only

```
// transition from s_i to s_j
s_i -> s_j {
  select i : int [0, 1]; // Selection
  guard c < 5;              // Guard
  sync signal!;     // Synchronization
  assign c = 0;}           // Update
```

Listing 1: **State Transition in UPPAAL.**

if the *Guard* statement is evaluated to true. Transitions labeled as *Synchronization* pairs synchronize with each other. For instance, a transition labeled as `signal!` triggers another transition labeled as `signal?`. The *Update* statements are evaluated when the transition happens. The side-effect of the *Update* statements update the state of the model.

3.3.2 Modeling Using UPPAAL

Next, we show how the `T`, `R` and `Medium` models in our formulation can be implemented in UPPAAL.

Listing 2 shows the UPPAAL encoding of the `T`, `R` and `Medium` model in our formulation. The interface to the `T` model is two synchronization channels for each device (`mac_tx_start` and `mac_tx_done`), together with two shared variables (`pkt_to_send` and `tx_ok`) for passing data. Internally the `T` model handles sequence number assignment, expecting acknowledgments and retransmissions if needed.

Similarly, the interface of the `R` model is one channel (`mac_rx_end`) and one shared variable (`pkt_recvd`) for each device. The `R` model handles sending acknowledgment and packet de-duplication. Both the `T` and `R` model are parameterized with an integer identifier so that they can be reused by multiple device models.

Inside the `Medium` model, for each transmitted packet, it non-deterministically decides whether the packet is lost (L34), and only sends the `phy_rx_end` signal if the packet not lost (L40). Therefore, the `Medium` model acts as a switch between the `phy_tx_start` and the `phy_rx_end` signals.

With the help of the `T` and `R` models, it is easy to encode the up layer state machines in UPPAAL language. For instance, the encoding of $s_0 \rightarrow s_1$ transition in the client state machine is shown in Listing 3. To send the `AUTH_REQ` packet, the client model only needs to set the packet to be sent (L3), then signals the corresponding `max_tx_start` signal. The rest of sending logic is handled by the `T` module.

3.3.3 Jamming Policy Generator

In UPPAAL, the property to be verified is expressed using the TCTL [1] query language. In particular, given a property ϕ, the query `A[]`ϕ asks whether ϕ holds for all possible execution paths. This query can be used to generate the jamming policies.

```
1  const int NUM_DEVICE = 2;
2
3  // interface of the T module
4  chan mac_tx_start[NUM_DEVICE]
5  pkt_t pkt_to_send[NUM_DEVICE];
6  chan mac_tx_done[NUM_DEVICE];
7  bool tx_ok[NUM_DEVICE];
8
9  process T(int id) {
10   // listen for mac_tx_start[id]
11   // and transmit pkt_to_send[id]
12   ... }
13
14 // interface of the R module
15 chan mac_rx_end[NUM_DEVICE];
16 pkt_t pkt_recvd[NUM_DEVICE];
17
18 process R(int id) {
19   // listen for the phy_rx_end
20   // and trigger mac_rx_end[id] on
21   // packet received
22   ... }
23
24 // interface of the Medium module
25 chan phy_tx_start;
26 chan phy_rx_end;
27 pkt_t pkt_in_air;
28
29 process Medium() {
30   bool loss;
31   state
32     s_init, s_got_pkt;
33   transitions
34     s_init -> s_got_pkt
35     { select i: int [0, 1];
36       sync phy_tx_start?;
37       assign loss = i == 0; },
38     s_got_pkt -> s_init
39     { guard loss; },
40     s_got_pkt -> s_init
41     { guard !loss;
42       sync phy_rx_end!; }; }
```

Listing 2: **Modeling `T`, `R` and `Medium` using UPPAAL.** The body of `T` and `R` is omitted for sake of space.

```
1  s_0 -> s_1 {
2    sync mac_tx_start[client_id]!;
3    assign pkt_to_send[client_id].type =
         AUTH_REQ;
4      pkt_to_send[id].dest = ap_id; },
```

Listing 3: **Example Modeling of Client Authentication State Machine Using UPPAAL.**

For instance, the `A[] !(Client.s_4 && AP.t_4)` query asserts that the system state $\langle$`Client.s_4, AP.s_4`$\rangle$ is not reachable. There are two possible outcomes from model checking such a property: either the answer is `yes` and the state is indeed not reachable, or the answer is `no` and UPPAAL will also provide one transition sequence from the initial

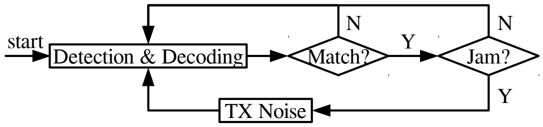


Figure 5: **Work Flow of PACKETSNIPER.**

state to the target state. By examining the value of the `pkt_in_air` and the `Medium.loss` variables at each intermediate state, we can extract the jamming policy in order to reach the target state.

We have implemented PROTOCOLANALYZER for UPPAAL using Python. It first parses the UPPAAL model to extract the models and their states. For every combination of the model states, it generates the un-reachability query described above and runs the UPPAAL model checker. If the query is not satisfied (i.e., the state is reachable), it parses the UPPAAL output and extracts the packet success/failure sequence. The output of the PROTOCOLANALYZER is a list of reachable system states and the packet sequence in order to drive the system to the target state.

4 PACKETSNIPER

With the jamming policy to reach each protocol state, we now describe the design and two prototype implementations of PACKETSNIPER to execute the jamming policy.

4.1 Design Requirements

To ensure the integrity of the transmitted packets, wireless protocols usually include various forms of checksums in the packet to help the receiver to detect bit errors. In wireless protocols such Wi-Fi, packets with checksum errors are discarded by the receiver. The idea of PACKETSNIPER is to detect the beginning of packet transmission in real time, and disrupt the transmission just in time before it ends to cause the checksum to fail at the receiver side. Figure 5 shows the overall work flow of PACKETSNIPER. The PACKETSNIPER continuously monitors the wireless medium, and starts decoding packets upon detection. It then performs matching of the packet with predefined jamming policies and sends jamming signals if the packet is labeled as failure in the policy.

To achieve this goal, the PACKETSNIPER needs to first decode certain packet attributes, such as source, destination and packet type. Therefore, previous physical layer jamming methods [12, 27, 20] are not applicable as they can only blindly jam the wireless medium. The PACKETSNIPER then needs to transmit the jamming signal before the original packet transmission ends in order to disrupt the transmission. This poses very strict timing requirements as the duration of packet transmissions in wireless communication is often in the order of microseconds.

Next, we first describe a set of design requirements and challenges of PACKETSNIPER. We then describe two prototype PACKETSNIPER implementations for 802.11 protocol on Universal Software Radio Peripheral (USRP) N210 and SORA platform.

4.1.1 *Jamming Latency*

The PACKETSNIPER must transmit the jamming signal before the end of packet transmission to jam the packet at the receiver side. This requires the PACKETSNIPER to perform the packet detection, decoding and decision making process within a portion of the transmission duration. There are several MAC protocol implementations on Software Define Radio (SDR) platforms [26, 28]. However, the round trip latency between the SDR frontend and the host PC is usually in order of hundreds of milliseconds, which are prohibitively longer than the requirements. It is clear that the core logic of PACKETSNIPER must be placed as close to the radio frontend as possible to meet the tight timing requirements.

In addition, certain management or action packets, such as the acknowledgment (ACK), Request to Send (RTS) and Clear to Send (CTS) packets in 802.11 protocol, only contains very minimum protocol attributes and no data payloads, making them extremely difficult to jam. The PACKETSNIPER needs to take advantage of certain protocol semantics in order to jam such short packets.

4.1.2 *Protocol Attributes*

PACKETSNIPER needs to decode enough protocol attributes of the packet to help make the jamming decision, yet must stop decoding as early as possible so that the jamming signal can overlap enough with the original transmission. Therefore, the number of protocol attributes to decode represents a trade-off between jamming policy granularity and jamming probability. The more attributes to decode, the more fine granularity the jamming policy can express, yet the probability of successfully jam the packet is lower.

4.1.3 *Decoding Errors*

As wireless receivers, the PACKETSNIPER could also have decoding errors. This may cause the PACKETSNIPER to miss the packets to be jammed, or jam the wrong packets. While the PACKETSNIPER should try its best to execute the jamming policy, such jamming misbehaviors create uncertainty in later verification phase.

4.2 Implementation on USRP

We now describe our prototype implementation of PACKETSNIPER for 802.11 protocol on USRP N210 SDR platform. Because of the tight timing requirements, we choose to implement the core jamming logic in the on-board FPGA to eliminate the long round-trip latency suffered by most SDR implementations.

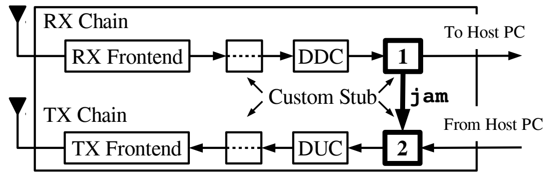


Figure 6: **USRP N210 FPGA Diagram.** Our implementation is in the two bold blocks marked as 1 and 2. DDC/DUC stands for Digital Down/Up Converter.

The USRP N210 platform contains an on-board FPGA for time-sensitive baseband tasks, such as I/Q balance, digital down/up converting. The current resource utilization of the N210 FPGA is only around 25%, leaving enough room for implementing custom logic on board.

Figure 6 shows a simplified diagram of the USRP N210 FPGA. There are two RF chains: one for receiving the RF signals and sending them to host PC (the RX Chain), and the other for transmitting the RF signals from host PC to the air (the TX Chain). On both RF chains, there are stubs reserved for implementing custom logic. By default, these stubs are only pass-through, thus have no effect on the signal processing.

We have modified the custom stubs to implement PACKETSNIPER, as shown in the two bold boxes labeled as 1 and 2. In stub 1, we implemented a full 802.11a/g/n OFDM receiver. The tasks include: short preamble detection [21] and coarse frequency offset correction [31], long preamble detection for symbol alignment and fine frequency offset correction [31], OFDM decoding consists of demodulation, deinterleaving, Viterbi decoding and descrambling.

In addition, there is a jamming filter module in stub 1 that compares the decoded packets with pre-configured jamming policies to determine the jamming decision. The output of stub 1 is a binary signal, called `jam`. When the `jam` signal is asserted, stub 2 starts transmitting pre-configured jamming signals through the TX chain.

The overall implementation includes 4320 lines of Verilog code for FPGA implementation, and 2265 lines of Python code for generating look up tables and cross validation of the FPGA implementation.

4.3 Implementation On SORA

Another promising SDR platform for PACKETSNIPER is SORA [32]. Currently, SORA provides a full implementation of 802.11a/b/g and part of 802.11n up to 2 spatial streams. SORA utilizes real-time threads to meet the strict timing requirements of wireless protocols on general purpose operating system (Windows).

We build our PACKETSNIPER prototype on top of the packet decoder in SORA. More specifically, we instruct the packet decoder to only decode first few bytes of the packet, which are then used to perform jamming filter matching. Once a positive jamming decision is made, we notify the SORA firmware to transmit pre-loaded jamming signal.

Compared to the FPGA implementation on USRP, SORA introduces additional jamming latency due to the data exchange between SORA firmware and host CPU, yet can be potentially used to support latest wireless standards (e.g., 802.11ac) and MIMO operations.

```
Filter ::= "true" | Predicate | Filter &&
     Filter
Predicate ::= x <= const | x >= const
x ::= "length" | "rate" | "header"
```

Listing 4: **BNF Definition of Jamming Filter.**

4.4 Jamming Policy Format

Jamming policy represents the interface between PROTOCOLANALYZER and PACKETSNIPER, and contains two parts: filter and action. The jamming filter defines *what* packets to jam, while the action defines *when* to jam the packet. For each packet success/failure sequence output by PROTOCOLANALYZER, we first convert it into a mapping from packet filter to a list of actions. Next, we describe the format of the filter and action respectively.

We note that wireless protocol attributes typically include certain physical layer properties, such as packet length and encoding rate, and the packet header that contains source and destination information, type, control flags and so on. Therefore, we restrict the jamming filters to these three attributes.

Listing 4 shows the BNF specification of our proposed filter syntax. A jamming filter is a conjunction of predicates, each of which performs filtering on one of the three attributes. The `length` and `rate` attribute are easy to understand. There are two points worth noticing about the `header` attribute. First, as explained earlier in Section 4.1.2, the length of the header represents the tradeoff between filter granularity and jamming latency. Here we do not use a fixed length but instead make the length as an configuration parameter at run time. Second, since the `header` is a continuous chunk of bytes while the actual protocol attributes may scatter in different segments of the headers, a special notation of *don't care* byte is used to skip the non-interested bytes.

The jamming policy also contains a list of actions for the corresponding jamming filter. The possible actions are: `Jam`, `Pass`, and `JamNext`. The `JamNext` action instructs the PACKETSNIPER to skip the current packet but jam the next detected packet. This action is introduced to overcome the challenge of jamming short packets as described in Section 4.1.1. Our observation is that such short packets (such as acknowledgment or CTS packets) are typically the response of certain other packets. Although the short packets themselves are difficult to jam, it is easy for the PACKETSNIPER to predict their transmissions beforehand and sends the jamming signal as soon as detecting the next packet transmission, without needing to decode its content. We acknowledge that this action may not cover all cases for short packets, such as the RTS packet in 802.11.

5 SNIFFER TRACE VERIFICATION

The final step is to validate whether the DUT's behavior is consistent with the protocol model. We first explain the need of using sniffer as vantage point for verification (§ 5.1), then discuss the challenges of sniffer trace verification and our proposed modeling methods (§ 5.2). Finally we show how our modeling can be implemented in UPPAAL (§ 5.3).

5.1 Sniffer as Vantage Point

The broadcast nature of wireless medium makes it possible to observe the DUT's packet exchanges from external devices, or wireless sniffers. Using wireless sniffer as vantage point is more of a requirement of practical constraints rather than a design choice. Due to fine-grained timing requirement in wireless protocols, the implementations are often placed as close as to the hardware in the form of firmwares. Furthermore, these firmwares are usually proprietary, making it difficult to instrument the implementation to collect packet exchange traces or event logs. Even when such instrumentation capability is available, the resource constraints in most embedded or IoT devices make it infeasible to directly collect packet traces from the devices under test.

As shown in Figure 3, the sniffer can be modeled as a passive observer (`Sniffer`[1]) of the `TX(PKT)` signal. Just as regular receivers, the sniffer could also miss packets, thus there is another switch inside the `Sniffer` model. Note that the two switches inside the `Medium` and the `Sniffer` models are *independent* from each other. For instance, a packet could be received by the designating receiver but be missed by the sniffer, and vice versa. Also note that although we model sniffer as one logical entity, in practice it may consist of multiple physical sniffer devices and their time-synchronized traces [10, 4, 23] together form the logical sniffer's observation in our model.

5.2 Verifying Sniffer Trace

Given a sniffer trace that represents the *implementation's* behavior, the verification problem is to check whether it is one of the legal observations of the `Sniffer` model. If the answer is no, then a violation of the protocol can be claimed. On the other hand, however, a complete protocol compliance can not be declared

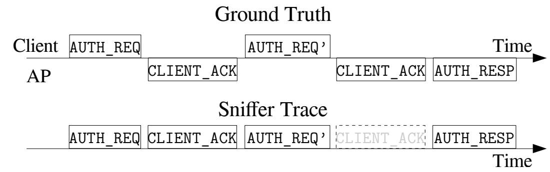


Figure 7: **Example of Sniffer Trace Uncertainty.**

even if the answer of the verification problem is yes. This is because a positive answer only means the implementation *could have* behaved according to the protocol, but it is also possible that the implementation violated the protocol but the violating behavior was missed by the sniffer. This is known as the *sniffer uncertainty* problem first described by Shi *et al.* [30].

More specifically, the sniffer may miss packets that represent protocol violations. Also, the sniffer can not determine whether an observed packet was actually received by the receiver. Figure 7 shows an example of such uncertainty. Note that the first `CLIENT_ACK` packet was missed by the client but was received by the sniffer. A naïve validation of this sniffer trace would report a violation since the client retransmit the `AUTH_REQ` packet after *receiving* the `CLIENT_ACK` packet.

Using sniffer traces for verification, we share the same limitations with [30] caused by sniffer uncertainty. However, in our formulation, the sniffer uncertainty is implicitly explored by the model checker in toggling the two switches inside the `Medium` and `Sniffer` models, whereas it has be to explicitly expressed using the augmented transitions in [30]. More specifically, a ⟨`true, false`⟩ value of the ⟨`Medium.loss, Sniffer.loss`⟩ tuple represents the case when a packet is received by the receiver but missed by the sniffer. Similarly, a ⟨`false, true`⟩ value corresponds to the case when a packet is missed by the receiver but received by the sniffer.

In verifying sniffer traces in our framework, the model checker will try all 4 values of the loss variable tuple for each transmitted packet in the attempt to accept the sniffer trace. We argue that by considering sniffer as part of the model in our formulation, the sniffer uncertainty can be explored in a systematic manner by an off-the-shelf model checker rather than a specialized checker [30].

We also note that the number of sniffer losses that the model checker is allowed to use must be bounded. Otherwise the model checker will either indefinitely infer packets missed by the sniffer without making progress on the actual sniffer trace, or yield artificial traces that contains too many sniffer losses to be practically meaningful. As observed in [30], the number of sniffer losses required for the model checker to accept the trace, denoted as k, is inversely proportional with the confidence of the trace correctness. Intuitively, the larger the k, the more missing packets the model check needs to *guess* to accept the

[1]We use "sniffer" to refer to the physical wireless sniffer devices, and use "`Sniffer`" to refer to the model in Figure 3.

```
1 // sniffer trace to be verified
2 const int LEN = 10;
3 const pkt_t TRACE[LEN] = {...};
4
5 process Sniffer() {
6   bool loss;
7   int idx = 0;
8   state
9     s_init, s_got_pkt;
10  transitions
11    s_init -> s_got_pkt {
12      select i: int [0, 1];
13      sync phy_tx_start?;
14      assign loss = i == 0; },
15    s_got_pkt -> s_init {
16      guard loss; },
17    s_got_pkt -> s_init {
18      guard !loss && idx < LEN &&
19        pkt_in_air == TRACE[idx];
20      assign idx++; }; }
```

Listing 5: **Modeling `Sniffer` using UPPAAL.**

trace, thus less confidence that the trace represents correct protocol behavior.

5.3 Modeling Sniffer in UPPAAL

Next, we show how the `Sniffer` model and the sniffer trace verification can be done in UPPAAL. The key idea is to embed the sniffer trace as a constant array, and assert that the `Sniffer` model must observe the packets sequentially.

Listing 5 shows the UPPAAL encoding of the `Sniffer` model. A constant array of packets, `TRACE`, is defined. The elements and length of the array is populated from the sniffer trace to be verified. The `Sniffer` model taps in the `phy_tx_start` signal (L11) to monitor every packet transmission, and non-deterministically decides whether the transmitted packet was received by the sniffer or not. The `Sniffer` model also maintains an index to the `TRACE` array (L7). If the transmitted packet was received by the sniffer, then it must be the next expected packet in the sniffer trace (L17). This way, we are asserting that the `Sniffer` model should observe the same packet trace as the physical sniffer. The bound on number of sniffer loss, which is omitted for sake of space, can be placed in the guard of the `s_got_pkt`→`s_init` transition (L18).

The verification is then performed by the `E<> Sniffer.idx == LEN` query, which states that there should exist at least one transition path along which the `idx` value eventually reaches `LEN`. If the query is satisfied, then the sniffer trace is indeed one of the possible traces observed by the `Sniffer` model.

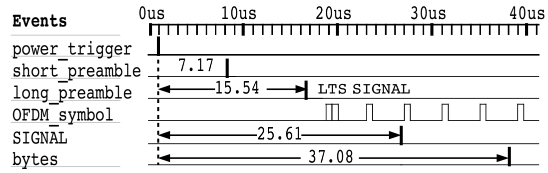


Figure 8: **Timeline of Various Decoding Stages of USRP N210 PACKETSNIPER Implementation.**

6 EVALUATION

In this section, we perform both micro benchmarks on PACKETSNIPER as well as end-to-end evaluation using the 802.11 link setup protocol.

6.1 Micro Benchmarks of PACKETSNIPER

6.1.1 Jamming Latency on USRP

As described in Section 4.1.1, one major challenge of realizing PACKETSNIPER is the critical timing requirement: the decoding and filter matching process must be completed before the end of packet transmission. To quantify this requirement, we define the *Jamming Latency* as the duration between the beginning of the packet and the time when the jamming signal is transmitted. The latency must be shorter than the duration of the packet in order for the jamming signal to overlap with the packet. Next, we evaluate the jamming latency on our USRP N210 prototype implementation of PACKETSNIPER.

Figure 8 shows the timeline of various stages of the decoding a 6 Mbps 802.11a OFDM packet on the USRP N210. The `power_trigger` event is triggered when the receiving power level significantly increases, and marks the beginning of packet transmission. The `short_preamble` and `long_preamble` events are triggered when the presence of short and long preamble are detected respectively. The latency of these two events (7.17 μs and 15.54 μs) corresponds to the fact that the short and long preambles are 8 μs each in duration. For jamming policies that are only interested in the presence of a packet (such as the `JamNext` action), a jamming decision can be made at this stage, and all following decoding steps can be skipped.

The `SIGNAL` field of the packet, which contains physical layer properties such as packet length and encoding rate, is available after 25.61 μs. For jamming filters that only contain these two attributes, their matching results can be concluded, and their jamming decision can be made at this point. No further decoding is required.

The first byte of the packet is available after 37.08 μs from the beginning of the packet transmission. Depending on the header length in the jamming filter, more bytes might be needed to complete the filter matching process. The incurred extra latency depends on the exact encoding rate of the packet. The higher encoding rate, the more

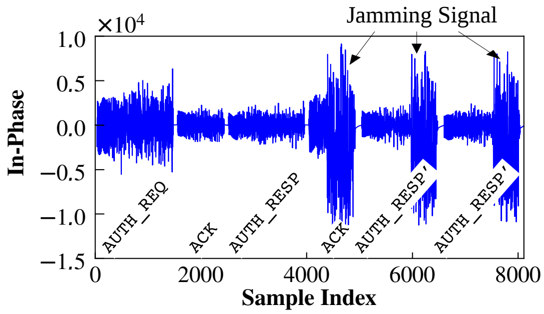


Figure 9: **Jamming in Action.** The first jam signal was sent using the `JamNext` action, while the following two were using the `Jam` action.

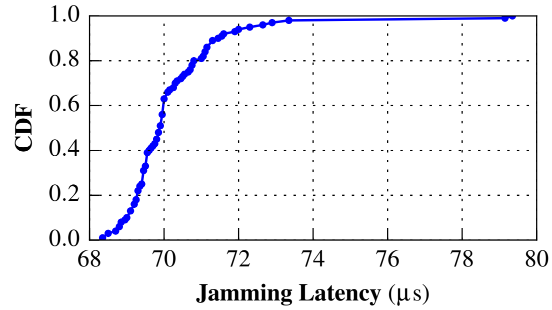


Figure 10: **CDF of Jamming Latency on SORA.**

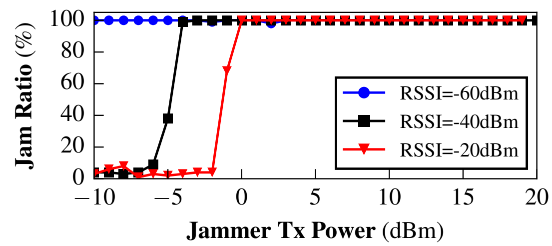


Figure 11: **Jamming Ratio of PACKETSNIPER Implementation on USRP N210.**

data bits each OFDM symbol contains, thus the shorter decoding latency.

To summarize, the jamming latency in our PACKETSNIPER implementation can be as short as 8 μs for certain jamming actions, and as long as 37 μs plus additional decoding time for jamming filters that contain header bytes.

Once the jamming decision is made, the `jam` signal is asserted and jamming signals are transmitted through the TX chain. The RX/TX turn-around time on USRP N210 is negligible (in order of nanoseconds) as the RX and TX chain are independent from each other.

Figure 9 shows the in-phase signals captured during one jamming session we performed for the 802.11 link setup protocol. The particular jamming policy was to jam the acknowledgment packet of the `AUTH_RESP` packet and all following retransmissions of the `AUTH_RESP` packet. Since the acknowledgment packets are short, we utilize the `JamNext` action to jam the acknowledgment of the `AUTH_RESP` packet. As can be clearly seen in Figure 9, the jamming signals, whose magnitudes are significantly larger than the original signals, are transmitted in the middle of packet transmissions. In addition, the jamming latency for the acknowledgment packet is short than the two following `AUTH_RESP`' packets. This is because the jamming decision was made immediately after the `short_preamble_detected` event for the acknowledgment packet. While for the two `AUTH_RESP`' packets, the jamming decision was made after 10 header bytes were decoded.

6.1.2 *Jamming Latency on SORA*

To measure jamming latency on SORA, we leverage another radio hardware to capture the jammed packets over the air. Since jamming signal is LTS, we perform cross-correlation with LTS to detect both the start of a jammed packet and the jamming signal. In our experiment, the data packets are transmitted at 6Mbps.

Figure 10 shows CDF of the jamming latency on SORA for 100 jammed packets. The medium latency is around 70 μs, and is stable within the 70±2 μs range. Occasionally, jamming latency may jump to 80μs, because sometimes SORA thread needs to release the CPU core to prevent from blocking hardware interrupts.

6.1.3 *Jamming Capability*

Finally, we evaluate PACKETSNIPER's capability of jamming packets. We focus on the USRP implementation since our SORA based prototype is still work in progress

We set up a transmitter-receiver pair in a conducted environment, and configure the transmitter to send a constant number (100) of data packets using the `ping` command. The transmitter data rate is fixed at 6 Mbps. The jammer is configured to jam all the non-retransmission packets from the transmitter. There is no path-loss between the jammer and the receiver. We then use three pass-loss values between the transmitter and receiver: 0 dB, 20 dB, 40 dB. In these settings, the RSSIs at the receiver side are -20 dBm, -40 dBm, -60 dBm respectively. We then vary the transmission power of the USRP N210 from -10 dBm to 20 dBm with 1 dBm step.

Figure 11 shows the jamming success ratio under the three path loss settings. As expected, when the RSSI at the receiver side is low, the jammer can easily jam all packets even at lowest transmission power. As the RSSI increases, the required jammer transmission power increases accordingly. After certain cut-off point, the jammer was able to jam nearly all the packets.

6.2 End-to-End Evaluation

We perform an end-to-end evaluation of our framework through a case study of the 802.11 link setup protocol. The results show that our framework can increase state coverage by 2X (§ 6.2.3) and find violations that otherwise do not manifest (§ 6.2.4).

6.2.1 Protocol Modeling

We first give an overview of our modeling of the 802.11 link setup protocol using UPPAAL. As informally described in Section 2.1, the protocol consists of three stages: authentication, association and 802.11X authentication. Listing 3 shows our modeling of the first authentication stage. We have modeled all three stages using UPPAAL. The `Client` model consists of 13 states, and the `AP` model consists of 17 states. The full model consists of 544 lines of UPPAAL code, 275 of which are for the generic `T` and `R` modeling.

We then feed the model to PROTOCOLANALYZER. Among the all possible 221 (13×17) system states, 73 states are reachable, and 40 reachable states involves packet failures in their state transition sequence.

6.2.2 Experiment Setup

We use conducted setup for our end-to-end evaluation to eliminate external interferences. The client and the AP are put inside RF shield boxes, and their only way of communication is via a coaxial cable that connects their antenna ports. We use two TP-LINK WDR3500 routers as testing devices since they have detachable antennas. One router is configured in client mode, and the other is configured in AP mode. Both routers runs OpenWRT 15.05 firmware so that we can remotely control the link setup process. The source code of OpenWRT is available, enabling us to examine any potential implementation bugs we found later.

For each of the 73 jamming policies, we initiate the link setup process on the client for 10 times, and run the PACKETSNIPER with corresponding policy during each link setup session. We utilize the packet log of the PACKETSNIPER as sniffer trace in later verification stage.

6.2.3 State Reachability

We perform verification on the resulting 730 (73×10) traces using the `E<> Sniffer.idx == LEN` query as explained in Section 5.3. A trace is "Accepted" if the query is satisfied, otherwise is "Rejected", which represents potential implementation violations and needs to be further examined. In addition, we also verify if the target system state was reached during the verification ("Reached").

Table 1 shows the verification results for various k values. Recall that k is the maximum number of sniffer missed packets that the model checker would tolerate before rejecting the trace. Overall, we can clearly observe the trend that when k increases, the model checker accepts more sniffer traces, and more traces reached the target system state.

Table 1: **Summary of Sniffer Trace Verification Results.**

k	Accepted	Rejected	Reached
0	155	575 (79%)	289
2	498	232 (32%)	592
4	617	113 (15%)	699
6	641	89 (12%)	723
8	663	67 (9%)	729
10	665	65 (9%)	729

When $k = 0$, which effectively disables the model checker's ability to infer missing packets, 79% of the traces were rejected. This shows the necessity of tolerating sniffer losses in our formulation, as otherwise intensive labor effort is required to examine the rejected traces to prune out false alarms causes by sniffer missing packets.

When $k = 10$, the number of rejected traces reduces to 65. We inspected these traces and found that main cause was the device's internal queueing effect that was not part of our model (this was a design decision to keep the model simple). For instance, the client may enqueue a new round of authentication if the first `AUTH_REQ` packet was not acknowledged but indeed received by the AP. This results an interleaving authentication packet sequence from the same client, which will be rejected by the model checker. We also observe several violations that are potentially caused by implementation misbehaviors, which we report later in Section 6.2.4.

Additionally, when $k = 10$, for 729 out of the 730 traces, the target system state was reached in verifying the sniffer trace. The only failing trace was caused by a violation (discussed in § 6.2.4) in the association stage while the system state is in the following 802.11X authentication stage.

Our framework enables testers to iteratively refine the verification process. Starting with a high k value, the tester can narrow down to a small subset of traces that have high likelihood of violation. After either refining the original model or identifying true protocol violations, the tester can then decrease k and repeat the process.

Finally, we performed a set of baseline experiments without PACKETSNIPER. More specifically, we setup the client and AP (with antennas) in a normal office environment, and performed the association session for 100 times. A regular wireless sniffer was used to collect traces during the experiment. We observed that only 31 out of the 73 reachable states were reached during verifying these sniffer traces. In particular, among the 40 states that require packet losses in their jamming policy, only 6 states were reached in the 100 runs. The results shows that the PROTOCOLANALYZER and PACKETSNIPER together can improve state coverage and also provide validation reproducibility.

6.2.4 *Possible Violations Found*

We now describe several implementation issues that cause the sniffer trace to be rejected. We have reported our findings to the maintainers of corresponding software module, and briefly summarize them here.

Association Without Authentication. We found if the first `AUTH_RESP` packet was received by the client but the acknowledgment and all following retransmissions of `AUTH_RESP` were jammed, the AP still accepted the following `ASSOC_REQ` packet from the client. We originally thought the AP should have rejected the association request since the `AUTH_RESP` packet failed, thus authentication failed as well. After communicating with the maintainer of `hostapd`, we realized this corner case was covered in the latest 802.11 2016 standard, which states the AP considers the client as *authenticated* as soon as receiving the `AUTH_REQ` packet from the client. We were previously referring to the 802.11 2012 standard, which did not describe this case clearly.

Double Association. When the acknowledgment of the `ASSOC_REQ` packet and all of its retransmissions were jammed, the client sent a new `ASSOC_REQ` despite having received the `ASSOC_RESP` from the AP. This is because from the client's point of view, the `ASSOC_REQ` packet failed, thus it restarted the association process. However, the reception of the `ASSOC_RESP` packet indicates that the AP actually received the `ASSOC_REQ` packet, thus should have shortcut client's next association attempt.

802.11X Deadlock. When the acknowledgment of the first `ASSOC_RESP` and all its retransmissions were jammed, the AP claimed the association step failed and would not continue to the 802.11X authentication stage. However, the client actually received the `ASSOC_RESP` packet and was waiting for the AP to initiated the 802.11 authentication step. Thus the client and the AP entered a deadlock state.

7 RELATED WORK

Industry practice: Wireless protocols are typically tested both in a conducted setup and over-the-air. Conducted tests provide a controlled environment. However, even for a conducted setup, we are unaware of any commercially available attenuators that can selectively trigger packet drops. This was corroborated in our conversations with Wi-Fi chip companies. The latency of existing variable attenuators is in the order of 10s of milliseconds, while we need micro-second latencies to trigger single packet drop, as achieved by PACKETSNIPER. Over-the-air tests are run to stress the entire RF subsystem including the antenna in a realistic setup. However, these tests are left running for days to get the appropriate test scenarios to be triggered, and the test time can be significantly shortened by PACKETSNIPER.

Protocol verification: There has been work on model checking network protocol implementations [25, 18]. The problem is different when trying to verify wireless systems, because (i) it is non-trivial to trigger all possible states in wireless systems, and (ii) there is uncertainty in the output captured by the wireless sniffer. Wireless sniffers have been widely used to analyze MAC behavior in enterprise wireless networks [29, 33, 35, 36, 10, 23]. However, this body of research assumes correctness of the protocol implementation while finding anomalies, while VERIFI uses the sniffers to verify the implementation.

Model-based testing and validation: Model-based testing (MBT) is the approach of generating test cases by exploring the model of a system under test [34]. Applications of MBT differ in the modeling approach (UML, Statechart, first-order logic), the use of test-case generation strategies (model checking, theorem proving) and the application domains (automotive, distributed systems etc.). One can view our approach as the first instance of the approach where we use model checker to explore the model to construct jamming policy that is used in conjunction with the PACKETSNIPER to drive the wireless system into interesting states. Our trace validation problem is also more complex due to the presence of uncertainty in observations. Similar problem happens when validating sampled traces in the context of runtime verification [7, 19, 3, 16]. We incorporate the sniffer trace uncertainty problem [30] but our new formulation allows leveraging any model checker instead of a customized checker (as in [30]).

8 CONCLUSIONS AND FUTURE WORK

Testing of wireless protocols is typically cumbersome and incomplete. These systems are left running for several hours to ensure that the system does not exhibit abnormal behavior. This takes a long time, and often bugs are not found until after the product is released. In this paper we present VERIFI, a new automatic framework for validating wireless protocol implementation. We have described the design of VERIFI, and provided implementations based on UPPAAL model checker and Software Defined Radio platforms (USRP and SORA). We have evaluated our system via both micro benchmarks and an end-to-end cast study on the Wi-Fi link setup protocol, and showed that VERIFI can improve validation coverage and reproducibility.

We believe we have only scratched the surface in using formal methods to validate wireless protocol implementations. Our techniques could be further used for other applications as well, such as testing the security aspects of wireless protocols. Moving forward, we are working in two directions in the near term. First, we are extending the approach to detect timing errors. Second, we are extending VERIFI such that it can work for other wireless protocols, such as a frequency-hopping Bluetooth, or a FDD cellular system.

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