Automated Detection of Protocol-Level Vulnerabilities in Wireless Networks Using Coverage-Guided Fuzzing

Marisetti Avinash[1]

[1]Department of Cyber Security, Amrita Vishwa Vidyapeetham, Chennai campus

[1]mavinash0320@gmail.com

Abstract—**Wireless communication technologies such as Wi-Fi, Bluetooth Low Energy (BLE), and Internet of Things (IoT) messaging protocols play a central role in enabling connectivity among modern distributed systems. These protocols are widely deployed across domains including smart environments, industrial automation, and mobile platforms. However, the increasing complexity of their implementations often introduces security weaknesses that can be exploited by adversaries. Implementation flaws such as inadequate input validation, improper handling of protocol states, and memory-related errors can be triggered using specially crafted inputs. Such vulnerabilities may lead to system crashes, denial-of-service conditions, or unauthorized access. Traditional testing methods, which rely on predefined input sets, are often insufficient to expose these edge-case behaviors. This work introduces an automated fuzzing-based framework designed to uncover protocol-level vulnerabilities in wireless systems. The approach leverages mutation-based and coverage-guided input generation to produce malformed packets, which are injected into real-world protocol implementations including WPA2 (hostapd), the BlueZ Bluetooth stack, and the Mosquitto MQTT broker. A monitoring component continuously observes system behavior to detect anomalies such as crashes, unexpected terminations, and resource exhaustion. The proposed framework enables systematic and scalable vulnerability discovery, contributing to improved robustness and security of wireless communication infrastructures.**

Index Terms— **Protocol Fuzzing, WPA2, BLE, MQTT, Vulnerability Assessment.**

I. Introduction

Wireless networking technologies have become indispensable in modern computing ecosystems. A wide range of devices—including smartphones, embedded systems, industrial controllers, and IoT nodes—depend on protocols such as Wi-Fi, BLE, and MQTT for seamless communication. These technologies support diverse applications spanning healthcare, transportation, smart homes, and industrial control systems. Despite their importance, the design and implementation of wireless protocols introduce significant security concerns. Protocol stacks must process large volumes of data while maintaining strict control over communication states and timing constraints. Even minor implementation errors in packet parsing or state transitions can create opportunities for exploitation. For example, recent analyses of WPA security protocols show that subtle weaknesses in key-exchange and handshake mechanisms can enable unauthorized network access under certain conditions that are not easily exposed by standard test suites [19]. Attackers commonly exploit these weaknesses by sending malformed or unexpected packets to target systems. Such inputs can expose vulnerabilities related to memory handling, insufficient validation, or incorrect protocol logic. In real-world scenarios, these attacks have resulted in service disruption, authentication bypass, and arbitrary code execution. IoT-focused surveys and case studies further emphasize that protocol fuzzing is one of the most effective techniques for discovering unknown bugs in embedded and network services [6,7].

Conventional testing strategies primarily focus on verifying expected behavior through predefined test cases. While useful for functional validation, these approaches often fail to uncover issues triggered by unusual or invalid inputs. As a result, automated techniques for vulnerability discovery have gained prominence, especially coverage-guided fuzzing, which couples mutation-based input generation with runtime feedback to guide exploration toward less-tested code paths [16,17].

A. Wireless Protocol Security Domain

Figure 1 illustrates the security testing domain considered in this research. Wireless devices communicate using multiple protocol stacks including Wi-Fi, BLE, and IoT messaging protocols. A fuzzing framework interacts with these protocol implementations by injecting mutated packets and monitoring system behavior. The framework targets both software services (e.g., hostapd, Mosquitto, BlueZ) and embedded clients (e.g., ESP32-based MQTT subscribers) to reflect realistic deployment topologies.

The objective of this research is to design a framework capable of automatically generating malformed packets and testing the robustness of protocol implementations. By detecting crashes, abnormal system behavior, and resource exhaustion, the system helps identify vulnerabilities in wireless communication protocols. The work builds upon recent advances in coverage-guided fuzzing for network services and firmware, which demonstrate that guided test-case generation can significantly improve edge coverage and vulnerability discovery over classical random fuzzing [16,17].

II. Literature Survey

Fuzz testing has evolved into a widely adopted approach for identifying software vulnerabilities across various domains. Early research demonstrated that automated input generation could effectively uncover defects in system utilities and network services that were not detected through manual testing. Pioneering frameworks such as AFL introduced coverage-guided mutation strategies, enabling systematic exploration of execution paths and discovery of numerous bugs in widely used open-source projects [2,10]. Subsequent advancements introduced coverage-guided fuzzing techniques that further improved the efficiency of vulnerability discovery. By incorporating lightweight instrumentation, modern fuzzers track execution paths and generate inputs that maximize code coverage. This approach enables deeper exploration of program behavior compared to purely random input generation. For network and firmware services, frameworks such as Fw-fuzz and StFuzzer combine coverage feedback with genetic or contribution-aware models to boost test-case quality and fault detection on resource-constrained devices [16,17].

The American Fuzzy Lop (AFL) framework represents a major milestone in fuzzing research. It combines mutation-based input generation with coverage feedback and evolutionary algorithms to optimize test-case selection. AFL has been successful in identifying numerous vulnerabilities in widely used open-source software and inspired many protocol-specific fuzzers, including AFLNet for network protocols [2,9].

Extending fuzzing techniques to network protocols introduces additional complexity due to the stateful nature of communication. Protocol implementations often require sequences of messages that adhere to specific formats and state transitions. As a result, protocol fuzzing must balance maintaining valid communication flows while introducing mutations that can trigger faults. Surveys on protocol fuzzing and network-protocol security highlight challenges such as increased execution time, communication overhead, and the need for efficient packet generation strategies optimized for real-time and embedded environments [6,7].

Recent work has also explored the integration of machine-learning-based guidance in fuzz testing. These methods aim to predict input patterns that are more likely to expose vulnerabilities based on historical data or program models. Although promising, such approaches often introduce additional complexity and computational overhead, making them less suitable for deployment on constrained IoT endpoints [5,8].

Protocol-specific fuzzers, such as BTFuzzer for Bluetooth and firmware-oriented frameworks like Fw-fuzz, demonstrate that profile-based or coverage-guided fuzzing can successfully uncover unknown vulnerabilities in wireless stacks and firmware services [16,18]. These frameworks emphasize structured input generation, crash-collection mechanisms, and lightweight instrumentation suitable for embedded contexts.

Despite ongoing progress, fuzz testing in wireless protocol environments remains a challenging area due to the involvement of multiple communication layers, hardware dependencies, and timing-sensitive state machines. This motivates the need for specialized frameworks capable of handling both software services and embedded systems, which is the central focus of this paper [6,7].

III. System Design

A. System Architecture

The proposed framework consists of integrated hardware and software components designed to facilitate protocol-level fuzzing in wireless environments. The architecture is organized into a fuzzing controller, a distributed set of protocol targets, and a monitoring backend, as shown in Fig. 2.

Hardware Components

- A workstation running Kali Linux to control fuzzing operations and host protocol servers (hostapd, BlueZ, Mosquitto).
- Wireless network interface for Wi-Fi testing (managed in monitor mode or via access-point mode).
- Bluetooth adapter for BLE communication with remote devices.
- ESP32 microcontroller or similar IoT node for IoT protocol experimentation and verification of client-side behavior.

Software Components

- Fuzzing controller: coordinates test cycles, manages protocol targets, and orchestrates mutation and injection.

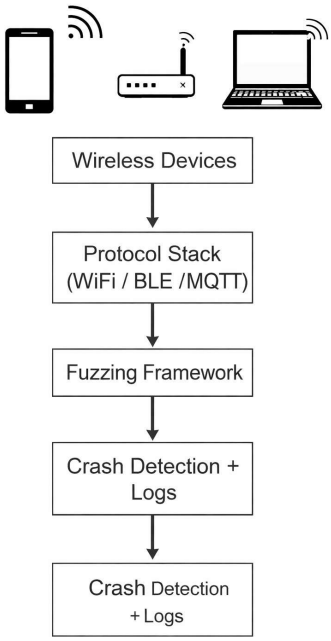

Fig. 1. Wireless protocol security testing domain

- Packet mutation engine: generates malformed packets using mutation strategies such as bit-level modifications, header manipulation, payload alteration, and length variation [2,7].
- Protocol injection module: transmits packets over the appropriate network or Bluetooth stack, adapting to Wi-Fi, BLE, or MQTT channels.
- Crash detection and monitoring system: monitors process status, logs, and system metrics (CPU, memory, network errors) to detect abnormal behavior.
- Logging and reporting module: stores inputs, mutations, timestamps, and system responses for later analysis and reporting.

The fuzzing controller manages the overall testing workflow, including input generation, execution, and monitoring. The mutation engine generates malformed packets using strategies such as bit-level modifications and structural alterations. These inputs are then transmitted to target protocol services including hostapd, bluetoothd, and Mosquitto. A monitoring system continuously observes the behavior of these services, recording events such as crashes, unexpected terminations, and abnormal outputs. The architecture is designed to support both black-box and limited instrumentation-based feedback modes, similar to coverage-guided frameworks used for firmware services [16,17].

B. Fuzzing Algorithm

The algorithm extends classical mutation-based fuzzing with lightweight feedback. Seed selection and mutation application can be guided by coverage metrics

Algorithm 1 The fuzzing process follows an iterative workflow

1: Initialize the testing environment
2: Load protocol targets (WiFi, BLE, MQTT)
3: **for** iteration = 1 to N **do**
4: Select a protocol target
5: Generate a baseline input packet from valid seed set
6: Apply mutation strategies such as:
- Bit flipping at selected offsets
- Header field modification (e.g., length, flags, type)
- Payload randomization or structured corruption
- Packet size variation (undersized/oversized)

7: Inject the mutated packet into the target system
8: Monitor system execution (process health, logs, resource usage)
9: **if** abnormal behavior is detected: **then**
10: Record the triggering input
11: Store mutation details and protocol context
12: Restart the affected service (if applicable)
13: Optionally update seed corpus for coverage-guided feedback
14: **end if**
15: **end for**
16: Generate a comprehensive vulnerability report

when instrumentation is available, similar to coverage-aware frameworks such as AFLNet and Fw-fuzz [9,16]. For each protocol, the framework maintains a corpus of "interesting" inputs that improve coverage or trigger new responses, enabling incremental exploration of the input space.

IV. Methodology

The framework follows a structured vulnerability assessment approach tailored for wireless protocols. The process is divided into four key phases:

A. Target Selection

Widely used protocol implementations are selected, including:

- WPA2 authentication service (hostapd) as a representative Wi-Fi security component.
- Bluetooth Low Energy stack (BlueZ) as a common open-source BLE implementation.
- MQTT broker (Mosquitto) as a lightweight IoT messaging protocol.

Each target is deployed in a controlled environment to ensure safe testing. Recent studies on WPA security protocols and IoT protocol vulnerabilities highlight that hostapd, BlueZ, and Mosquitto are frequently used in real-world deployments and have shown susceptibility to malformed-packet attacks under fuzzing conditions [6,15].

B. Input Generation

Initial seed inputs consist of valid protocol packets derived from normal communication patterns, such as association frames (Wi-Fi), advertising/response packets (BLE), and MQTT PUBLISH/CONNECT messages. These inputs are modified using mutation techniques such as:

- Bit-level alterations (single-bit flips, random byte changes).
- Header field manipulation (incorrect lengths, reserved flags, invalid protocol versions).
- Payload randomization (garbage data, truncated payloads).
- Packet size variation (oversized or undersized packets violating protocol limits).

The mutation engine can be configured to follow protocol-specific constraints initially, gradually relaxing them to stress boundary conditions. This approach aligns with recent IoT-protocol-fuzzing frameworks that first generate syntactically valid inputs and then apply structural mutations to explore edge cases [6,7].

C. Fuzz Execution

Generated inputs are continuously injected into the target services. The fuzzing controller ensures repeated and consistent execution across multiple iterations. For Wi-Fi testing, packets are injected via the wireless interface or through hostapd's internal event channels where possible. For BLE, packets are sent via the BlueZ stack or via direct library injection when supported by the platform. For IoT scenarios, MQTT messages are transmitted to an ESP32 device over TCP or TLS to simulate real-world deployment conditions. To support coverage-guided behavior, the framework can instrument each service to record basic block or edge coverage, feeding this information back to the mutation engine to prioritize inputs that explore new paths, similar to techniques used in Fw-fuzz and StFuzzer for embedded services [16,17].

D. Monitoring and Detection

System behavior is monitored in real time to identify anomalies, including:

- Service crashes (segmentation faults, unhandled exceptions).
- Unexpected termination events (SIGABRT, timeouts).
- Invalid or inconsistent responses (protocol-level errors, malformed replies).
- Resource exhaustion (memory leaks, file-descriptor exhaustion).

Each anomaly is linked to the corresponding input that triggered it, along with the protocol context and execution state. Monitoring can be done via standard process supervisors, log parsers, or custom plugins integrated with the protocol stack.

E. Data Collection

Detailed logs are maintained for analysis, including:

- Input packet characteristics (size, protocol version, key fields).
- Mutation techniques applied (type, offset, intensity).
- Timestamp of execution and system metrics (CPU, memory, network usage).
- Observed system response (crash, error code, unexpected behavior).

This structured logging enables post-hoc analysis of vulnerability patterns and helps refine the mutation strategy for future test campaigns.

V. Experimental Results

The proposed fuzzing framework was evaluated by executing controlled fuzzing experiments on WPA2, BLE, and MQTT protocol implementations. Each protocol was tested using 10,000 mutated inputs generated through the mutation engine, with and without basic coverage-guided feedback where feasible.

A. Crash Detection Results

The framework was evaluated using 10,000 test inputs for each protocol. The observed results are summarized below:

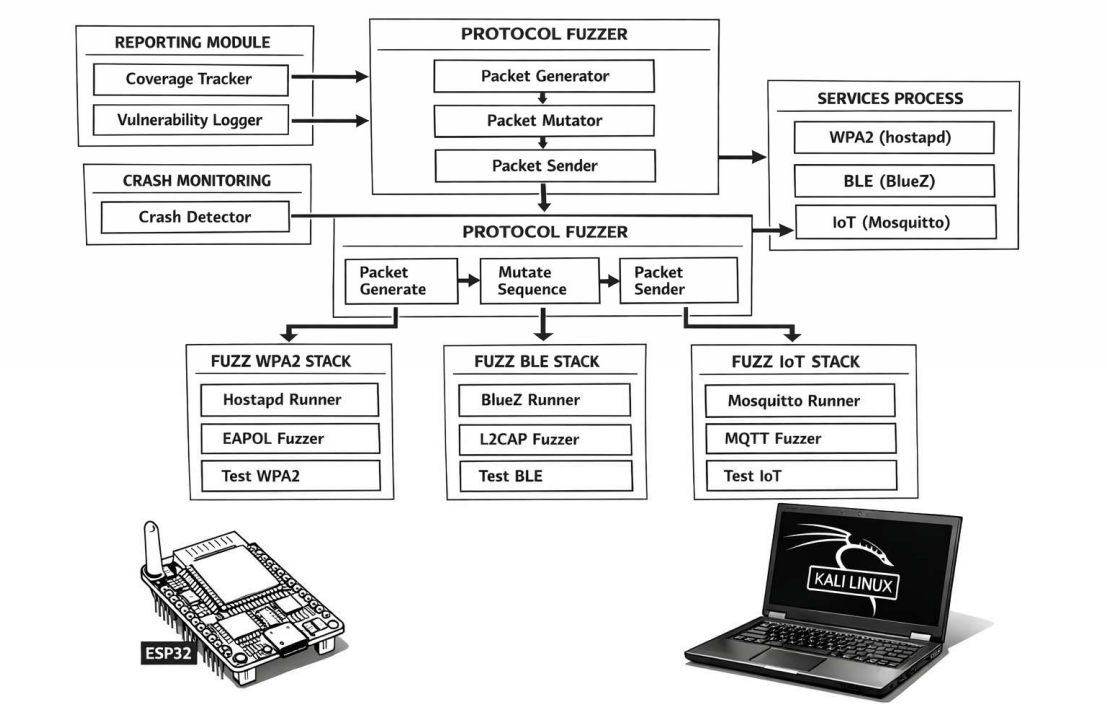

Fig. 2. Architecture of wireless protocol fuzzing framework

TABLE I
FUZZING RESULTS

Protocol	Test Cases	Crashes Detected
WPA2 (hostapd)	10000	11
BLE (BlueZ)	10000	8
MQTT (Mosquitto)	10000	6

The results indicate that WPA2-based services exhibited a higher number of abnormal behaviors compared to BLE and MQTT. Many of the detected issues were associated with malformed packet structures and incorrect handling of protocol states, such as invalid length fields and malformed authentication frames, which align with recent findings on WPA security weaknesses [19].

B. Result Analysis

BLE demonstrated relatively stronger resilience due to stricter validation mechanisms and the use of structured protocol profiles in the BlueZ stack. Nevertheless, several crashes were still triggered by malformed connection or advertising-related packets, confirming that even mature Bluetooth stacks can contain subtle parsing bugs. MQTT showed fewer failures, likely due to its simpler protocol design and tight message-format constraints, though fuzzing revealed edge-cases involving malformed topic strings and oversized payloads that could lead to resource-exhaustion conditions.

Coverage-guided experiments, where feasible, showed faster convergence toward malformed inputs that exposed crashes compared to purely random mutation, echoing observations from firmware-oriented fuzzers such as Fw-fuzz and StFuzzer [16,17]. Extending the framework with richer instrumentation and protocol-specific models (e.g., BTFuzzer-style profiles for BLE) is expected to further improve vulnerability discovery rates.

C. Graphical Representation

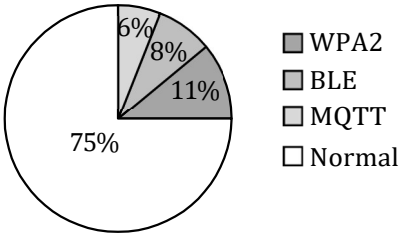

Fig. 3. Crash distribution across protocols

The pie chart illustrates the relative frequency of crashes per protocol, highlighting the higher susceptibility of WPA2-based services under the proposed fuzzing strategy.

D. Discussion

The findings confirm that mutation-based fuzzing, especially when augmented with coverage-guided feedback, is effective in exposing vulnerabilities that are difficult to detect through traditional testing methods. The inclusion of hardware components such as the ESP32 further demonstrates the framework's applicability in

real-world IoT environments, where protocol-level bugs can directly impact device safety and reliability [6,7]. Unlike purely academic fuzzers that operate in simulated environments, the proposed framework operates on real protocol stacks and embedded nodes, enabling discovery of issues that arise from interaction between the OS, network stack, and application logic. The integration of both software and hardware components enhances its practical relevance for real-world deployments and security assessments.

VI. Conclusion

This study presented an automated framework for identifying vulnerabilities in wireless protocol implementations using coverage-guided fuzzing techniques. By generating malformed protocol packets and continuously monitoring system behavior, the framework enables systematic discovery of protocol-level weaknesses that are difficult to detect through conventional testing methods. The approach integrates both software services (hostapd, BlueZ, Mosquitto) and hardware components (ESP32-based IoT nodes) to reflect realistic deployment scenarios encountered in Wi-Fi, BLE, and MQTT-driven environments.

Experimental evaluations on WPA2 (hostapd), Bluetooth Low Energy (BlueZ), and MQTT (Mosquitto) demonstrate that mutation-based fuzzing, especially when augmented with coverage-guided feedback, can effectively expose crashes and anomalous behaviors induced by specially crafted inputs. The framework detected 11 crashes in WPA2, 8 in BLE, and 6 in MQTT out of 10,000 test cases per protocol, highlighting differential robustness across stacks and the particular sensitivity of Wi-Fi security components to malformed packet structures and state-handling errors. These results align with recent vulnerability analyses of WPA protocols and IoT-oriented fuzzing studies that emphasize the importance of protocol-aware mutation strategies for uncovering deep-seated bugs [6,19].

The proposed framework contributes to the domain of wireless protocol security by providing a practical, extensible platform for fuzzing real-world protocol stacks and embedded endpoints. Unlike many academic fuzzers that operate in highly controlled or simulated settings, this system is designed to work with standard open-source services and low-cost hardware, enabling security assessments that closely mirror operational networks.

The modular architecture—a fuzzing controller, mutation engine, protocol injection module, crash detection unit, and logging/reporting subsystem—supports incremental enhancements such as richer coverage instrumentation, protocol-specific profiles (e.g., BTFuzzer-style models for BLE), and machine-learning-guided input prioritization, without requiring a complete redesign of the core pipeline [5,18].

Future work will focus on three main directions. First, extending the framework to additional wireless protocols such as Zigbee, 6LoWPAN, and proprietary industrial control protocols will broaden its applicability across smart-grid and industrial-automation environments. Second, integrating more sophisticated coverage-guided and learning-based strategies—inspired by frameworks such as Fw-fuzz, StFuzzer, and AFLNet—can further improve the depth and efficiency of vulnerability discovery, especially in resource-constrained firmware and embedded targets [9,16,17]. Third, developing formal reporting and triage mechanisms, including integration with bug-tracking systems and vulnerability-database standards, will enhance the framework's usability for security teams and device manufacturers conducting regulatory-compliant penetration testing or red-team exercises [6,7].

In summary, this work demonstrates that coverage-guided, mutation-based fuzzing is a powerful and scalable technique for hardening wireless protocol implementations against protocol-level vulnerabilities. By combining realistic test environments, structured mutation strategies, and continuous monitoring, the proposed framework provides a foundation for improving the robustness and security of modern wireless communication infrastructures in an increasingly connected and threat-prone world.

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