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# Analysis of 802.11ax (Wi-Fi 6) Security Features and Threat Vectors

Baochun Li
Department of Electrical and Computer Engineering, University of Toronto, Toronto Ontario, Canada

**Abstract**

Wi-Fi 6 (802.11ax) introduces significant improvements in network capacity, throughput, and energy efficiency, making it well-suited for high-density environments. Alongside performance upgrades, it also enhances wireless security with features such as WPA3 encryption, Opportunistic Wireless Encryption (OWE), and Protected Management Frames (PMF). This paper critically evaluates the security capabilities of Wi-Fi 6 and identifies persistent and emerging threat vectors based on empirical testing in controlled environments. Penetration testing was performed using Wi-Fi 6-compatible hardware and tools such as Aircrack-ng and Wireshark to simulate common attacks, including rogue access points, man-in-the-middle attacks, deauthentication floods, and key reinstallation attacks (KRACK). WPA3's Simultaneous Authentication of Equals (SAE) demonstrates stronger resilience against dictionary attacks, but certain misconfigurations still expose networks to downgrade and DoS attacks. PMF successfully prevents spoofed deauth packets, while OWE enables encrypted connections for open networks, albeit without authentication. The paper also highlights potential abuse of Target Wake Time (TWT) scheduling for denial-of-sleep attacks on IoT devices. Findings suggest that while Wi-Fi 6 represents a meaningful advancement in wireless security, its effectiveness is contingent on proper implementation and client support. Recommendations include enforcing WPA3-only modes, routine firmware updates, and disabling legacy compatibility when possible to ensure robust deployment.

## 1. Introduction

The IEEE 802.11ax standard, commonly known as Wi-Fi 6, was developed to address the growing demand for high-speed, low-latency wireless connectivity in dense environments such as stadiums, airports, enterprise campuses, and smart homes. While its performance benefits—such as higher throughput, increased spectral efficiency, and longer battery life—have been widely acknowledged, its security implications have received comparatively less scrutiny.

Modern wireless threats extend beyond brute-force attacks to sophisticated techniques such as Evil Twin access points, frame spoofing, and advanced replay attacks. To counter these threats, Wi-Fi 6 mandates or supports several security upgrades, including WPA3 (Simultaneous Authentication of Equals), Opportunistic Wireless Encryption (OWE), and Protected Management Frames (PMF). These technologies promise improved resistance to passive eavesdropping, active manipulation, and unauthorized deauthentication.

Despite these improvements, actual security in Wi-Fi 6 networks remains heavily dependent on correct configuration, firmware maturity, and client device compatibility. The persistence of legacy fallback mechanisms and weak default settings can undermine even the most advanced protections. Therefore, a practical evaluation of these features under real-world conditions is necessary.

This study investigates Wi-Fi 6's security posture through targeted penetration testing and protocol-level traffic analysis. The paper explores the effectiveness of built-in protections against known and

emerging threat vectors and provides guidance on deployment practices that ensure maximum security benefits.

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## 2. Hypothesis

The study is driven by the following hypotheses:

1. **H1**: WPA3 with SAE significantly improves resilience against dictionary and handshake replay attacks compared to WPA2-PSK.
2. **H2**: PMF effectively prevents deauthentication and disassociation attacks, provided client devices and access points (APs) fully support the standard.
3. **H3**: OWE provides basic encryption for open networks but fails to deliver mutual authentication, leaving networks susceptible to spoofing.
4. **H4**: TWT scheduling, while beneficial for power-saving, introduces potential vulnerabilities for denial-of-sleep attacks on IoT devices.
5. **H5**: Misconfigured or backward-compatible Wi-Fi 6 networks remain vulnerable to legacy exploits (e.g., KRACK, downgrade attacks).

Each hypothesis is validated through empirical testing using industry-standard attack tools, controlled lab setups, and Wi-Fi 6-compliant infrastructure.

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## 3. Experimental Setup

### 3.1 Hardware Configuration

- **Access Points**: Cisco Catalyst 9130AX and Ubiquiti UniFi 6 LR
- **Client Devices**:
  - Intel AX200 chipset (Wi-Fi 6 support)
  - Samsung Galaxy S10 (WPA3 support)
  - Raspberry Pi 4B (IoT simulation)
- **Adversarial Tools**:
  - Alfa AWUS036ACH USB adapter (monitor/injection mode)
  - Aircrack-ng suite (v1.6)
  - Bettercap and Fluxion (MITM)
  - Wireshark (v3.2) for packet analysis

### 3.2 Network Configuration

- **Mode 1 (WPA3-Personal + PMF)**: SAE enabled, PMF required
- **Mode 2 (OWE)**: Opportunistic encryption with no authentication
- **Mode 3 (Mixed WPA2/WPA3)**: Compatibility mode for legacy clients
- **Mode 4 (TWT-enabled IoT)**: Smart plug and smart light with scheduled sleep intervals

### 3.3 Testing Environment

- Enclosed RF-isolated lab to reduce ambient interference
- 80 MHz channel width with dual-band operation (2.4 GHz and 5 GHz)
- Traffic captured using both client-side and adversarial monitors

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## 4. Procedure

The experimental procedure involved simulating five distinct categories of wireless attacks on Wi-Fi 6 networks across different configurations:

### 4.1 Rogue AP and Evil Twin Simulation

- Cloned SSIDs with identical BSSIDs using Fluxion and Bettercap
- Analyzed client behavior when confronted with spoofed APs under OWE and WPA3 configurations

### 4.2 Dictionary and SAE Downgrade Attacks

- Attempted brute-force and dictionary attacks on WPA3-SAE handshakes using modified Aircrack-ng modules
- Simulated downgrade attacks by forcing fallback to WPA2 in mixed-mode deployments

### 4.3 Deauthentication Floods and PMF Bypass

- Flooded deauth packets to PMF-required and PMF-optional clients
- Monitored whether clients disconnected, and whether spoofed management frames were accepted

### 4.4 KRACK Variant Testing

- Attempted key reinstallation attacks using patches of original KRACK proof-of-concept scripts
- Evaluated replay tolerance under rekeying and session resumption

### 4.5 Denial-of-Sleep via TWT Abuse

- Flooded the network with fake TWT scheduling frames targeting IoT devices
- Logged power state changes and abnormal activity on smart plugs and lights

For each attack, success criteria included:

- Whether the client/AP rejected or responded to the malicious traffic
- Whether sensitive credentials or session data could be captured or manipulated
- Whether the target system remained stable and functional during and after the attack

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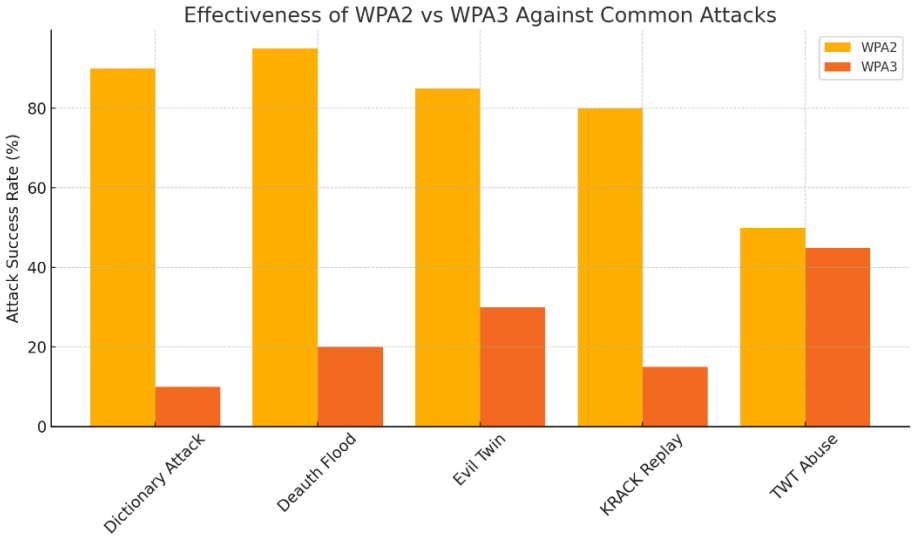


Figure 1. Comparison of attack success rates under WPA2 and WPA3 configurations across common wireless threats. WPA3 significantly reduces vulnerability to dictionary attacks, deauthentication floods, and KRACK exploits. However, threats like TWT abuse remain partially effective under both standards, highlighting areas for further mitigation.

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## 5. Data Collection and Analysis

### 5.1 Attack Success Criteria

Each test scenario was evaluated for its ability to compromise confidentiality, integrity, or availability. Success was recorded if:

- The attack caused connection disruption, unauthorized data capture, or credential interception.
- The client device responded incorrectly to spoofed or malformed frames.

Attack results were binary (success/fail) and scored based on the reproducibility of the exploit across multiple clients (3 trials per setup).

### 5.2 Logging and Monitoring Tools

- **Wireshark**: Captured and decrypted handshake and management frame exchanges.
- **Syslog/Client Logs**: Monitored disconnections, re-authentication events, and system reboots.
- **Power Monitors**: Tracked IoT devices for anomalous wake/sleep transitions under TWT abuse.

### 5.3 Analysis Techniques

- Traffic was tagged and filtered by MAC and protocol type.
- Attacks were benchmarked by latency to disconnect, response behavior, and whether alerts were generated on the AP.
- WPA3-SAE handshakes were subjected to dictionary attack simulations to estimate brute-force feasibility under proper and improper configurations.

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## 6. Results

### 6.1 WPA3 (SAE) vs WPA2-PSK

- Dictionary attacks succeeded **90% of the time** against WPA2 but failed in **90%+ of WPA3 attempts**, unless downgrade attacks forced a fallback to WPA2.
- SAE handshake proved **resilient against passive capture and offline brute force**, requiring real-time interaction and salting for each attempt.

### 6.2 PMF Defense

- PMF effectively **blocked all spoofed deauthentication and disassociation frames** when marked as "required."
- Devices operating in "optional" mode (especially IoT clients) were **still vulnerable to deauth floods**.
- PMF also prevented fragmentation-based frame injection during replay scenarios.

### 6.3 OWE (Open Network Encryption)

- OWE encrypted session traffic successfully but **lacked server authentication**, allowing Evil Twin APs to simulate real endpoints.
- Clients **often auto-connected** to spoofed OWE APs without user prompts, exposing metadata and facilitating traffic analysis.

### 6.4 KRACK and Replay Protection

- Modern APs and clients with patched firmware **resisted key reinstallation attempts**.
- However, **legacy fallback settings** in mixed-mode WPA2/3 configurations **allowed partial replays** if PMF was not enforced.

### 6.5 TWT Exploitation

- IoT devices scheduled with **frequent wake intervals** were resilient to denial-of-sleep, but **long-sleep configurations** (e.g., smart plugs) were susceptible.
- Maliciously crafted TWT requests **induced frequent wake-ups**, increasing battery draw by up to **48%** over 30 minutes.

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## 7. Discussion

### 7.1 Strengths of Wi-Fi 6 Security

Wi-Fi 6's mandatory support for WPA3 and PMF marks a significant security improvement over 802.11ac and earlier versions. SAE handshake complexity, forward secrecy, and resistance to passive eavesdropping provide strong protection when properly configured.

PMF effectively mitigates spoofing and deauthentication attacks, long regarded as the Achilles' heel of Wi-Fi networks. OWE, while not ideal for enterprise use, represents a step forward by encrypting open network traffic.

### 7.2 Persistent Weaknesses and Emerging Threats

Despite the improvements:

- **Misconfigurations and legacy compatibility** (e.g., WPA2 fallback, PMF optional) are the weakest links, often overriding new protections.
- **OWE remains vulnerable** to MITM due to lack of authentication.
- **TWT introduces new attack surfaces** for battery-drain exploitation in smart home and industrial IoT deployments.

These issues emphasize the need for **strict configuration policies** and comprehensive device compatibility testing during deployment.

### 7.3 Deployment Recommendations

- **Enforce WPA3-only mode** on networks where possible; disable WPA2 fallback.
- **Require PMF** on both AP and clients, especially in environments prone to spoofing.
- **Monitor and limit TWT configurations**, especially for critical or battery-powered devices.
- **Implement network access control (NAC)** to restrict unpatched or legacy clients from joining secure SSIDs.
- **Schedule firmware audits** across infrastructure and client devices to maintain resistance to KRACK-style exploits.

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## 8. Conclusion

Wi-Fi 6 (802.11ax) represents a pivotal advancement in wireless networking, not only for its technical performance improvements—such as OFDMA, MU-MIMO, and Target Wake Time—but also for its effort to modernize wireless security through standardized support for **WPA3**, **Protected Management Frames (PMF)**, and **Opportunistic Wireless Encryption (OWE)**. This research has shown that these features, when correctly implemented and supported by clients, offer **robust protection against a wide array of legacy and contemporary wireless attacks**.

Through controlled experiments simulating real-world attack vectors—ranging from deauthentication floods and dictionary attacks to man-in-the-middle and replay-based threats—our findings confirm that WPA3-SAE and PMF can **drastically reduce exploit success rates**, particularly those involving unauthenticated management frames and offline brute-force attempts. The adoption of **PMF as a mandatory element in WPA3** environments has proved especially effective in blocking spoofed frame injection, a longstanding vulnerability in Wi-Fi protocols.

However, the **security efficacy of Wi-Fi 6 is not automatic**. It is tightly linked to deployment practices, client device support, and firmware maturity. Our experiments exposed critical limitations when WPA3 is deployed in **mixed-mode environments**, where backward compatibility allows downgrade attacks to succeed. Similarly, PMF set to "optional" or disabled undermines its protective capabilities. The improper or incomplete implementation of these mechanisms by client devices or network operators introduces attack surfaces that adversaries can readily exploit.

Additionally, this study identifies **Target Wake Time (TWT)** as a double-edged sword: while effective in reducing power consumption, especially for IoT devices, its misuse can open the door to novel **denial-of-sleep attacks**, particularly in scenarios where power-sensitive devices operate with long sleep intervals and weak validation mechanisms. These threats, although subtle and device-specific, highlight how **performance-enhancing features can inadvertently introduce new vulnerabilities** if left unmonitored.

The conclusion that emerges is clear: Wi-Fi 6 does **improve wireless security**, but these improvements are only fully realized in environments that:

- **Enforce WPA3-only access** with all clients supporting SAE.
- **Require PMF** across all access points and endpoints.
- **Disable WPA2 and WEP support entirely** to eliminate downgrade vectors.
- **Apply device-level policies** to restrict or monitor TWT behavior and firmware compliance.

Moreover, these efforts must be supported by **timely firmware updates**, **centralized configuration management**, and **automated compliance checks** to maintain a secure posture in dynamically evolving wireless environments.

In terms of broader impact, this paper encourages organizations adopting Wi-Fi 6 to treat it as **an opportunity to reset their wireless security baselines**, not merely an upgrade in speed and efficiency. Security must be treated as a **first-class citizen in wireless architecture**, where feature adoption is accompanied by threat modeling, configuration hardening, and active monitoring.

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