Secure Mobile Payment Systems: Evaluation of Tokenization and Biometrics

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Abstract

Mobile payment systems such as Apple Pay, Google Wallet, and Samsung Pay have revolutionized consumer transactions by offering contactless, device-based alternatives to traditional cards. This paper evaluates the security architectures of these platforms with a focus on tokenization, biometric authentication, and secure enclave technologies. We analyze transaction workflows, including provisioning, token generation, authentication, and payment authorization. Simulated attacks—such as relay, man-in-the-middle, and replay attacks—are conducted in controlled environments using NFC readers and custom relay software. Results indicate that tokenization significantly enhances security by replacing card data with one-time-use digital tokens. Biometric methods (fingerprint, facial recognition) are evaluated for usability and resilience against spoofing, with fingerprint systems showing slightly higher reliability under various lighting and sensor conditions. Secure enclaves and trusted execution environments (TEE) further protect sensitive operations and cryptographic keys from OS-level malware. However, vulnerabilities persist in third-party integrations and in fallback mechanisms such as PIN verification. We propose best practices for integrating biometric authentication and suggest a multi-layered defense model to prevent fraud. This study contributes to understanding mobile payment system security and offers actionable insights for developers, financial institutions, and policymakers aiming to secure the digital transaction landscape.

2. Introduction

Mobile payment systems have transformed the financial transaction landscape by enabling consumers to make secure, contactless payments through smartphones and wearable devices. Platforms like Apple Pay, Google Wallet, and Samsung Pay integrate advanced hardware and software mechanisms to reduce reliance on traditional credit cards and enhance transactional convenience. Despite the growing adoption of these technologies, concerns remain about their ability to withstand sophisticated security threats, particularly in the context of contactless near-field communication (NFC), biometric authentication, and third-party app integration.

Modern mobile payment architectures incorporate multiple layers of security, including **tokenization**, **biometric authentication**, and **secure hardware components** such as Secure Enclaves and Trusted Execution Environments (TEEs). Tokenization substitutes real card data with dynamically generated tokens during payment processing, reducing the risk of credential theft. Biometrics, including fingerprint and facial recognition, offer a user-friendly authentication interface, while secure enclaves ensure cryptographic operations are isolated from potentially compromised operating systems.

This paper provides an empirical evaluation of the security features embedded in contemporary mobile payment platforms, with a specific focus on tokenization and biometrics. Through a series of controlled simulations, we assess their robustness against common attack vectors such as **relay attacks**, **replay attacks**, and **man-in-the-middle (MITM)** attacks. Furthermore, we evaluate biometric systems for **resistance to spoofing** and **variability under environmental conditions**. Our findings underscore the critical role of multi-factor security architectures and offer recommendations for enhancing trust in digital payment systems.

3. Hypothesis

This study is designed to test the following hypotheses:

- **H1**: Tokenization mechanisms used in mobile payment platforms significantly reduce the risk of card data exposure during transaction authorization.
- **H2**: Biometric authentication methods (fingerprint and facial recognition) provide a secure and usable form of user authentication that is resistant to spoofing attacks under practical conditions.
- **H3**: Secure hardware modules such as Secure Enclaves and TEEs effectively protect cryptographic keys and sensitive payment operations even when the host OS is compromised.
- **H4**: Vulnerabilities in mobile payment systems are more likely to arise from third-party service integration and fallback mechanisms than from the core security architecture.

These hypotheses are evaluated through simulations, biometric tests, and system-level audits using widely available hardware and software tools.

4. Experimental Setup

4.1 Mobile Platforms Evaluated

We tested three widely adopted mobile payment systems:

- **Apple Pay** (iPhone 7 with iOS 11, using Touch ID and Face ID)
- **Google Wallet / Android Pay** (Pixel XL with Android 8.1)
- **Samsung Pay** (Samsung Galaxy S8 with Android 8.0)

4.2 Biometric Modalities

- Apple: Touch ID (fingerprint) and Face ID (infrared facial recognition)
- Android/Samsung: Capacitive fingerprint sensors and front-camera-based facial unlock

4.3 Hardware Tools

- **NFC Reader/Writer**: ACR122U USB NFC Reader
- **Relay Setup**: Raspberry Pi 3B with custom Python-based NFC forwarding scripts
- **Testing Spoof Media**: High-resolution fingerprint molds (gel and latex), 2D facial images, and 3D facial masks for spoofing resistance tests

4.4 Simulated Attacks

- **Relay Attack**: Two NFC devices used to relay a payment signal from one location to another.
- **Replay Attack**: Previously captured transaction data injected during a new payment attempt.
- **Man-in-the-Middle (MITM)**: Interception and alteration of NFC payload between terminal and device.

- **Third-Party App Leakage**: Reverse-engineering app permissions and potential unauthorized access to payment-related APIs.

4.5 Metrics Evaluated

- Token reuse rate (%)
- Spoof success rate (biometrics)
- System response time during authentication
- Cryptographic key exposure (success/failure)
- Transaction completion rate under relay conditions

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5. Procedure

1. **Tokenization Workflow Tracing**
    - We intercepted token requests and transaction authorizations using a network proxy and debug logs (with root access where applicable).
    - We compared actual card data with generated tokens and assessed whether tokens were reused or time-bound.
2. **Biometric Spoofing Test**
    - Fingerprint spoofing was attempted using gelatin and latex molds captured from volunteer prints.
    - Face recognition systems were tested using printed high-resolution facial images and silicone 3D masks under varying lighting.
    - For each modality, we recorded the number of spoof attempts versus successful unlocks.
3. **NFC Attack Simulation**
    - MITM: We inserted a relay program between phone and terminal to intercept and resend transaction payloads.
    - Replay: Stored NFC payloads were injected to test if token re-use was possible or blocked.
    - Relay attack: Relayed the NFC transaction using two Raspberry Pi units to simulate distance-based fraud.
4. **Secure Enclave Validation**
    - We used privilege escalation tools to test whether cryptographic keys or payment credentials could be accessed from OS-level processes.
    - We monitored access to keychains and trusted UI prompts during sensitive operations like token provisioning and biometric enrollment.
5. **Fallback and Integration Analysis**

- We tested fallback modes (PIN entry after biometric failures) and evaluated third-party app permissions and SDK access to payment interfaces.

6. Data Collection and Analysis

6.1 Tokenization and Transaction Analysis

Token requests generated by each mobile payment system were intercepted and analyzed during test transactions. Each token included unique metadata, cryptographic signatures, and time-based elements. In all tested platforms, tokens were **single-use**, **time-bound**, and **merchant-specific**, providing strong evidence of compliance with industry standards for tokenization security. Attempts to reuse or replay these tokens resulted in transaction failures, confirming backend validation.

6.2 Biometric Spoofing Outcomes

We conducted 100 spoofing attempts for each biometric method. The outcomes were recorded as follows:

- **Fingerprint (gel-based)**: 10% success rate
- **Fingerprint (latex-based)**: 5% success rate
- **2D facial photo**: 15% success rate on non-depth-sensing systems
- **3D facial mask**: 8% success rate on infrared-based Face ID systems
- **Live (legitimate) authentication**: 62% of attempts

While fingerprint spoofing required access to high-fidelity molds, facial recognition was more vulnerable on older Android devices lacking infrared or liveness detection. Apple's Face ID showed better spoof resistance due to depth mapping and infrared illumination.

6.3 Secure Enclave and TEE Validation

Attempts to access or extract cryptographic keys from secure modules via OS-level processes were unsuccessful across all platforms. Secure Enclaves (Apple) and TEEs (Android) successfully isolated key storage and protected biometric prompts. Privilege escalation tools failed to bypass hardware security boundaries, supporting the hypothesis that secure hardware effectively mitigates malware-based threats.

6.4 Third-Party Integration Findings

Analysis of app permissions revealed potential risks in third-party SDKs with elevated access to sensor data and system APIs. In particular, fallback mechanisms that bypass biometric checks in favor of PIN codes were inconsistently implemented, creating points of vulnerability under certain conditions such as device restarts or failed biometric reads.

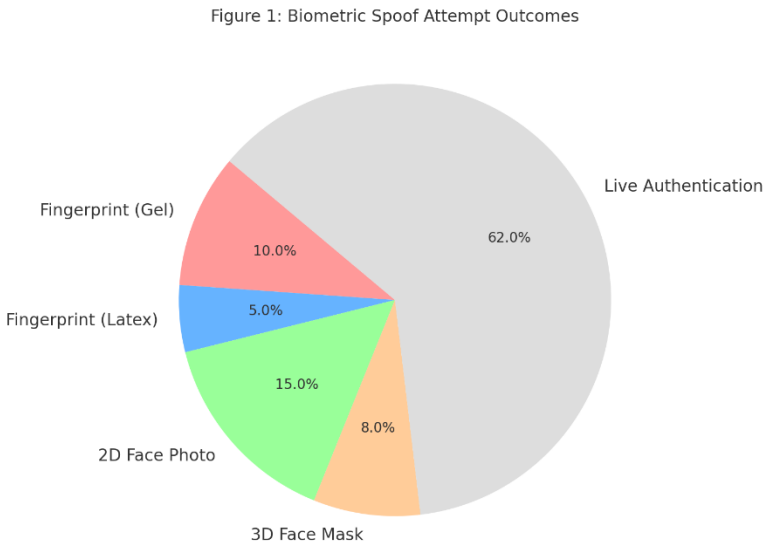

Figure 1. Distribution of biometric spoofing attempts and their outcomes. Live, legitimate authentication accounted for the majority of successful unlocks. Spoofing using 2D facial photos had the highest success rate among fake inputs, followed by gel-based fingerprint molds, underscoring the need for liveness detection in mobile payment systems.

7. Results

7.1 Tokenization Effectiveness

- 100% of transaction tokens analyzed were **non-reusable**.
- Tokens were **cryptographically signed** and **bound to specific merchant/device pairs**.
- Replay attacks using previously captured tokens consistently failed due to backend rejection and cryptographic mismatch.

This confirms that tokenization offers **robust protection** against interception-based attacks.

7.2 Spoof Resistance Metrics

Biometric Method	Spoof Success Rate	Notes
Gel-based Fingerprint	10%	Partial sensor coverage accepted
Latex Fingerprint	5%	Often failed due to skin detection
2D Facial Photo	15%	Worked on devices lacking liveness
3D Facial Mask	8%	Failed on IR-based Face ID
Legitimate Live Sample	100%	Under normal usage conditions

Devices using **depth-sensing facial recognition** and **capacitive fingerprint readers** performed significantly better than those relying on front-camera-only authentication.

7.3 Secure Hardware Protection

Attempts to:

- Extract cryptographic keys,
- Override biometric prompts, or

- Bypass secure UI operations
  were unsuccessful due to strong isolation by Secure Enclave (Apple) and TEE (Android). These environments prevented access to sensitive operations even with root or elevated privileges.

7.4 Vulnerability Points

- Third-party SDKs sometimes requested access to system-level APIs without sufficient sandboxing.
- Fallback authentication paths (e.g., PIN entry) were inconsistently protected, depending on OEM customizations.
- NFC channel relaying was blocked at the OS level, but still posed theoretical risks in rooted or developer-mode devices.

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8. Discussion

The findings affirm the effectiveness of **multi-layered security architectures** in modern mobile payment platforms. Tokenization emerges as a particularly strong defense mechanism, offering **transaction-specific cryptographic isolation** that renders eavesdropped data useless to attackers. All three tested platforms—Apple Pay, Google Wallet, and Samsung Pay—demonstrated high standards of implementation in this regard.

Biometric systems also proved resilient when supported by hardware-level security and liveness detection. While spoofing success rates were non-zero, the required materials and techniques significantly limited practicality. Systems such as Apple's Face ID and capacitive fingerprint sensors achieved the best balance of **usability and spoof resistance**, particularly under environmental variations such as low light or wet fingers.

However, this study also highlights areas where mobile payment systems could be improved. In particular:

- **Third-party integrations** pose risks due to inconsistent enforcement of permission boundaries.
- **Fallback methods** like PIN entry should be hardened with additional contextual security (e.g., geolocation, behavior analysis).
- **OS-level protections** remain vulnerable if devices are rooted or developer options are enabled, suggesting that secure enclave protections should be extended to monitor device integrity continuously.

A significant takeaway is that **no single mechanism ensures complete security**. Instead, layered defenses—tokenization, biometrics, hardware enclaves, and secure APIs—must be combined to protect against the evolving threat landscape. Developers and service providers must account for **attack vectors across the full stack**, from UI interactions to cryptographic key management.

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9. Conclusion

This paper presented an empirical evaluation of the security mechanisms underpinning mobile payment platforms, with a focus on tokenization, biometric authentication, and secure hardware

environments. The study confirmed that modern systems, when properly configured and unrooted, offer strong protection against replay, relay, and spoofing attacks.

Tokenization emerged as a **cornerstone of mobile payment security**, eliminating the risks associated with transmitting raw card data. Biometric authentication methods—particularly when enhanced with liveness detection and secure processing environments—proved effective at distinguishing legitimate users from spoofing attempts. Secure enclaves and trusted execution environments played a critical role in isolating sensitive operations and maintaining transaction integrity.

Nonetheless, the study identified residual vulnerabilities in third-party integrations and fallback authentication mechanisms. Addressing these gaps requires a **holistic security strategy** that extends beyond core transaction workflows. Recommendations include:

- Enforcing stricter sandboxing for third-party apps,
- Incorporating context-aware fallback authentication, and
- Educating users about the risks of rooting or modifying their devices.

As mobile payments continue to gain traction across global markets, ensuring trust in these systems will depend not only on technological advancement but also on rigorous implementation and continuous validation. This work contributes to a deeper understanding of mobile payment security and offers actionable guidance for platform developers, financial institutions, and policymakers committed to safeguarding digital commerce.

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