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Exploring Cybersecurity in Apple Pay: a Study of Attacks and Vulnerabilities

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Abstract*—In the ever-evolving landscape of e-commerce and payment systems, the profound impact of mobile devices continues to reshape traditional norms. The increasing prevalence of mobile phones has not only driven a surge in online transactions but has fundamentally transformed the way payments are executed. This transformative shift is particularly evident within the realm of mobile payments, with Apple Pay emerging as a prominent player that plays a pivotal role in this ongoing revolution. The widespread adoption of mobile payments, exemplified by platforms like Apple Pay, extends beyond mere transactional efficiency. It has ushered in a paradigm shift in user behavior and expectations, contributing to a more seamless and user-friendly financial experience. However, amidst this pervasive adoption, a critical concern looms large; security becomes paramount as the reliance on mobile payments grows. In this context, this study meticulously scrutinizes the security aspects of Apple Mobile Payments. By delving into the definitions, characteristics, and security policies surrounding Apple Pay, a comprehensive understanding of the subject matter is provided. This investigation unfolds along three key attack vectors: Apple Server breaches, SSL Transaction Traffic manipulation, and Masque Attacks. Navigating through these potential vulnerabilities, this study not only identifies weaknesses but also sheds light on the methodologies, consequences, and mitigation strategies associated with each attack vector. The findings of the research are not only insightful for users but also hold practical implications for developers and policymakers alike. Emphasizing the necessity for continuous research and adaptation, this study underscores the imperative to fortify the security of mobile payment systems. By addressing the identified weaknesses head-on, the aim is to contribute to a more robust and resilient ecosystem for users, developers, and policymakers. In essence, this research calls attention to the ongoing need for proactive measures to ensure the security and integrity of mobile payment systems in the ever-evolving digital landscape.

Keywords—Apple mobile Payments, Attack, Vulnerability, Point of Sale (POS), over-the-air (OTA), NFC (Near Field Communication).

I. INTRODUCTION

The landscape of financial transactions has undergone a profound transformation with the evolution of mobile payments, enabling consumers to conduct transactions without the exchange of physical currency, checks, or traditional bank cards. Rooted in technologies interfacing with mobile devices and point-of-sale (POS) terminals, as well as mobile-to-mobile options, the journey of mobile payments has witnessed significant milestones in recent years [1]. The origins of mobile payments can be attributed to innovative solutions that have surfaced over the past decades. Significantly, in 2011, a conventional retail establishment played a crucial role in reshaping the payment landscape by integrating mobile payments into its app. This allowed customers to conveniently make purchases using their smartphones. This event marked a pivotal moment in the progression of mobile payments, laying the foundation for broader consumer acceptance [2]. As mobile payment technologies advanced, new players entered the scene. During the pandemic, the advent of contactless payments gained momentum with the introduction of NFC (Near Field Communication) technology [3]. Companies like Apple, Google, and Samsung incorporated NFC into their mobile payment systems, contributing to the seamless and secure completion of transactions. Despite initial concerns regarding the security of data during transactions, the popularity of mobile payments has soared in recent years. Statistics indicate a significant increase in mobile payment usage, with platforms like Apple Pay, Google Pay, and Samsung Pay experiencing millions of downloads globally [4]. While the advantages of mobile payments, such as enhanced security, expedited transactions, and simplified financial processes, are clear, challenges do exist. Users may encounter issues like incompatibilities, battery failure, or the risk of theft. Despite these challenges, the popularity of mobile payments has surged in recent years. Notably, Apple Pay has emerged as a frontrunner in ensuring the security of mobile transactions. Through a combination of robust hardware and software measures [5], Apple Pay generates a unique device-only account number for each added card, securely stored in the device's secure element. This ensures that sensitive card information is never shared with merchants or stored. Every transaction generates a unique payment number and dynamic security code, enhancing the confidentiality of the transaction among the consumer, the merchant, and the consumer's bank. Adhering to Apple's encryption guidelines, even the cashier is unable to access the consumer's name, credit card information, or security code [5]. The remainder of this paper is organized as follows: Section II A comprehensive

overview of related work and recent efforts, offering insights into the broader landscape of mobile payments within the mCommerce ecosystem. Section III an exploration of the fundamental definitions and characteristics of Apple mobile payments. Section IV discusses known attacks vectors of Apple Pay and threats. Section V a concise summary encapsulating the key findings and contributions of the paper.

II. Literature Review

In the rapidly evolving landscape of mobile payment applications, security considerations have become paramount. Recent research has delved into the various dimensions of attacks and vulnerabilities, shedding light on the challenges faced by these digital financial platforms. This literature review synthesizes key findings from studies conducted between 2019 and the present, focusing on the security aspects of mobile payment applications and providing a specific examination of Apple Pay. Several studies have underscored the importance of robust security measures to safeguard sensitive user information and financial transactions in mobile payment applications. The dynamic nature of the security landscape is emphasized, with emerging threats such as man-in-the-middle attacks and mobile malware requiring continuous adaptation [6]. Building on this foundation, the attacks on mobile payment applications have been categorized into classes such as unauthorized access, transaction tampering, and identity theft. This typology highlights the multifaceted nature of security risks and emphasizes the necessity of a holistic approach to mitigate potential threats [7]. It been conducted an in-depth analysis of vulnerabilities in mobile payment systems, emphasizing the need to address weaknesses in the design and implementation phases. The implications of these vulnerabilities on user trust and the overall security of financial transactions are discussed, providing valuable insights for developers and policymakers [8]. Turning to the specific case of Apple Pay, the security measures implemented by Apple in its mobile payment ecosystem have been examined. The effectiveness of Apple Pay's security features in thwarting potential attacks was assessed, along with an investigation into reported security incidents related to the platform. This study offers a nuanced understanding of Apple Pay's strengths and areas for improvement [5]. While existing literature provides valuable insights, there is an evident need for further research to address gaps in understanding specific vulnerabilities and evolving attack vectors. This study contributes to the ongoing discourse by conducting a detailed analysis of attacks and vulnerabilities in the context of Apple Pay, offering practical implications for users, developers, and policymakers.

III. Concept of Apple Mobile Payment

In recent years, the landscape of financial transactions has undergone a transformative shift, propelled by the meteoric rise of mobile payments. The growth of this digital payment method has been nothing short of astonishing, marked by a surge in both adoption rates and transaction volumes globally. According to predictions from 2019, the worldwide mobile payments market was anticipated to surpass a staggering $1 trillion, underscoring the unprecedented momentum this technology has gained [9]. A notable player in this paradigm shift is Apple Pay, a mobile payment system that epitomizes the seamless fusion of technology and financial convenience. The allure of Apple Pay lies in its user-friendly features, such as the "one-touch" checkout, eliminating the need for cumbersome card number entry. Moreover, it assures a heightened level of security by avoiding the disclosure of addresses during online transactions and ensuring that sensitive card information remains confidential between the user and the payment service [5]. Delineating the broader spectrum of mobile payments, it manifests in two primary methods; online transactions and physical Point of Sale (POS) interactions. Online transactions represent the virtual realm, where consumers can make purchases through platforms like Apple Pay with unparalleled ease. On the other hand, physical POS transactions, often facilitated by NFC technology embedded in smartphones, provide a tangible bridge between the digital and physical retail spaces [3]. Nevertheless, even with the increasing popularity, mobile payments face significant barriers that impede their widespread adoption. One notable obstacle is the enduring loyalty of consumers to traditional payment methods. The latest data, as of 2021, derived from the PULSE 2016 Debit Issuer study, suggests that despite the heightened availability of mobile wallets, a considerable portion of debit users still exhibits disinterest in embracing this digital payment method [10]. This resistance stems from concerns about the security of mobile payments, a sentiment echoed by 67 percent of respondents in a 2016 survey. Additionally, 47 percent of consumers conveyed a reluctance to adopt mobile payments, citing distrust in the rapid advancements of technology with their confidential information [5]. In the forthcoming exploration of Apple Mobile Payments, we dissect the specific strategies employed by this technology giant to navigate these challenges, redefine consumer trust, and revolutionize the way individuals engage in financial transactions.

A. Definitions and Characteristics of Apple Mobile Payment

Apple Mobile Payments, commonly known as Apple Pay, is a proximity-technology-driven mobile payment platform designed by Apple Inc. It enables users to make secure and convenient transactions using their compatible Apple devices, such as iPhones, Apple Watches, and iPads. At its core, Apple Pay leverages Near Field Communication (NFC) technology, allowing for seamless communication between the user's device and a compatible payment terminal [3]. In the world of digital transactions, mobile payments come in various flavors, each with its own special features. Whether it's the easy tap-and-go of Proximity Payments or the secure versatility of Remote Payments across different systems, each type has something unique to offer [5]. Table I presents a clearer separation between the two payment types. Each type is now outlined, offering concise details on the technology involved, compatibility, popular platforms, usage scenarios, and security features.

TABLE I. TYPES OF MOBILE PAYMENTS.

Type	Technol -ogy	Compatii lity	Popular Platfo- rms	Usage Scenarios	Securi- ty

	Involved				Features
Proximity Payment	Refers to contactless payment.	Works with NFC-enabled devices	Apple Pay, Google Pay, etc.	Point-of-sale purchases, public transportation	Encryption of payment data.
Remote Payment	Mobile device used to authenticate personal information stored remotely.	Compatible with various systems	PayPal,Venmo, etc.	Online purchases, vending machines	Secure remote data storage.

Apple Pay has established itself as a pioneer, redefining the way we approach mobile payments. Beyond its sleek interface and seamless functionality, the true power of Apple Pay lies in its core characteristics.

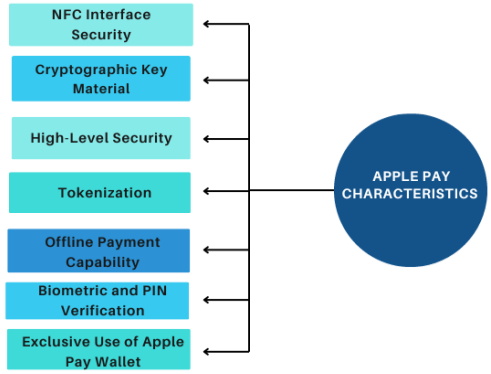

Fig. 1. Relevant characteristics of apple pay.

Fig. 1 provides a visual representation of the diverse security characteristics employed by Apple Pay to fortify transaction foundations against potential threats. Apple Pay employs a robust array of security measures to fortify transaction foundations against potential threats, as illustrated in the accompanying schema. Initially, high-value tokenized Primary Account Numbers (TokenPAN) and cryptographic keys find secure storage within a dedicated Secure Element (SE). This foundational protection ensures the integrity of sensitive transaction data. Subsequently, the payment app within the SE undergoes issuer certification, instilling trust in the transaction process. This trust is further enhanced by the implementation of scheme-controlled tokenization, utilizing a multi-use token approach, as depicted in the schema. Apple maintains comprehensive control over its SE through Apple's SE Management, a critical aspect illustrated in the schema. This control ensures the integrity and security of stored data, enabling seamless implementation and updates of security measures.

To safeguard the NFC interface vital for contactless payments, Apple restricts access solely to the SE, preventing unauthorized entry from other applications, as visually represented in the schema. Additionally, exclusive control extends to payment capabilities, confined to Apple Pay's dedicated wallet app, creating a standardized and secure user experience, as highlighted in the schema. Furthermore, the schema visually represents Apple Pay's offline capability during transactions, offering enhanced convenience in areas with limited or no internet access. Biometric technology serves as a pivotal element, with fingerprint or facial recognition via Touch ID or Face ID ensuring user authentication, as illustrated in the schema. Additionally, the schema captures the alternative security method of a Personal Identification Number (PIN), adding an extra layer of protection to the authentication process. This comprehensive security framework, illustrated in the accompanying schema, underscores Apple Pay's commitment to ensuring the utmost security and trustworthiness in its payment ecosystem.

B. The Transaction Flow of Apple Pay

In the intricate process of an Apple Pay transaction, several key steps unfold seamlessly, orchestrating a secure and efficient payment experience for users. The Fig. 2 outlines the transaction flow of Apple Pay.

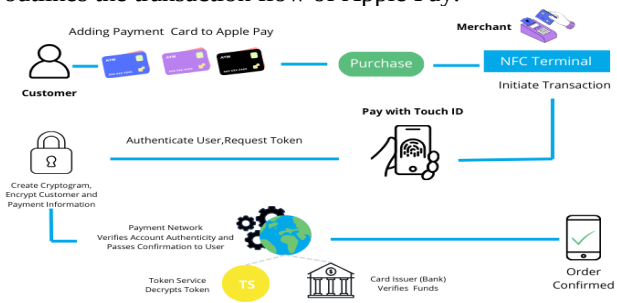

Fig. 2. Apple pay transaction flow: seamless integration and secure processing.

1. Enrolling a Card in Apple Pay: Users commence the process by incorporating a card into Apple Pay, a simple procedure achieved through either scanning the card or manually entering card details. The provided information is then transmitted to Apple servers, initiating the integration process. Following this, Apple transmits the card details to the relevant card network (Visa, MasterCard, etc.), triggering a meticulous validation process with the issuing bank. Serving as a Token Service Provider (TSP), the card network employs advanced tokenization techniques to generate a unique token known as the Device Account Number (DAN). This DAN functions as a secure surrogate for the actual card number. The newly generated token, accompanied by a token key, is subsequently sent back to Apple servers. Upon receipt, this information securely resides within the device's Secure Element (SE), ensuring robust protection of sensitive data [11].

2. Commencing a Transaction with Apple Pay: During the point of sale, when users initiate a payment, the Apple device seamlessly engages with the terminal. If the terminal is compatible with EMV contactless, the secure element orchestrates the creation of a dynamic cryptogram for the transaction. This dynamic cryptogram, accompanied by the token (DAN) and necessary transaction details, commences its journey to the payment processor, where the transaction undergoes meticulous processing. In cases where EMV contactless is not supported, Apple Pay smoothly transitions to Contactless MSD mode as a fallback mechanism. In

this mode, the payment processor receives Track2 data, encompassing the DAN, expiry, service code, and dynamic CVV, facilitating comprehensive transaction processing.

3. Conclusion of an Apple Pay transaction: After finalizing the transaction, the card network receives the transaction request and discerns between tokenized and authentic card numbers. In tokenized transactions, the card network verifies the dynamic CVV using its token key. This process subsequently leads to the detokenization of the Device Account Number (DAN), allowing the retrieval of the original Primary Account Number (PAN). The detokenized transaction request, along with the original PAN, initiates a process that involves forwarding to the issuer (bank or financial institution), where the transaction undergoes meticulous authorization. The issuer's response, carrying the verdict of the transaction authorization, makes its way back, culminating in the completion of the Apple Pay transaction at the point of sale.

In essence, these meticulously orchestrated steps epitomize the sophisticated dance of technology, encryption, and secure protocols that underpin the seamless functionality of Apple Pay transactions, ensuring both security and user convenience.

C. *Apple Mobile Payment: Security and Privacy Protocols*

As the digital landscape continues to evolve, the paramount importance of robust security and stringent privacy policies cannot be overstated. Apple Mobile Payments, epitomized by the widely acclaimed Apple Pay, places a formidable emphasis on ensuring the safety of user transactions and the protection of sensitive personal information [12]. Apple maintains privacy effectiveness through the implementation of two policies:

1) Elimination of Backdoor Access: Upholding a steadfast commitment to security, our software maintains an absolute prohibition against the inclusion of backdoors. These clandestine pathways, which might facilitate malicious activities, are strictly disallowed within any software framework [5].
2) Encryption Protocols: Reflected in the Legal Privacy Policy, Apple employs robust encryption measures across its digital spectrum, encompassing websites, interactive applications like Apple Pay, and online services. Transport Layer Security (TLS) is a pivotal component of our encryption protocols, serving as a non-negotiable imperative in today's digital landscape. This ensures the protection of sensitive information and fosters a secure digital environment for our users [12].

D. *Navigating The Concerns Surrounding Apple Mobile Payments*

In the realm of digital transactions, the advent of Apple Mobile Payments, notably through Apple Pay, has not been without its share of security. While hailed for its transformative impact on the mobile payments landscape, it is imperative to address and analyze the prevalent concerns that have emerged. Here, we delve into the key apprehensions surrounding Apple Mobile Payments, shedding light on the complexities that coexist with the convenience. Concerns about security vulnerabilities and transaction risks in Apple Pay are multifaceted. Firstly, a prominent worry centers around potential lapses in verification during Over-the-Air (OTA) transactions, particularly within the Near Field Communication (NFC) technology, integral to the Apple Pay system. These lapses raise apprehensions about the compromise of sensitive information [11]. Moreover, as the adoption of mobile payments expands, so does the threat landscape. Security researchers highlight the mobile platform's susceptibility to cybercriminal activities, providing an entry point for the theft of credit card details and transaction hijacking. These dynamic challenges cast doubt on the robustness of Apple Pay's security infrastructure [8].

Finally, the lack of consumer knowledge and control is a crucial aspect. Acknowledging the role of consumers in the security equation, it is pointed out that their limited understanding of security standards may contribute to vulnerabilities. Additionally, financial institutions may lack sufficient verification protocols, creating a potential gap in the overall security of Apple Mobile Payments [4]. Apple Pay has revolutionized the landscape of communication and introduced a streamlined approach to conducting financial transactions both online and offline. Consequently, this has played a pivotal role in fostering greater consumer familiarity with mobile payments, leading to increased comfort and acceptance of the conveniences offered by this innovative payment method [5].

IV. Attacks and Threats Targeting Apple's Mobile Payment System

Apple Pay boasts several commendable features that contribute to its positive reputation. The foremost advantages include its user-friendly interface and robust security features. Users appreciate the convenience and simplicity that Apple Pay offers, streamlining the payment process and enhancing the overall user experience. Moreover, the emphasis on security is notable, aligning with Apple's commitment to safeguarding user data and financial transactions [13]. In-depth investigation has revealed multiple forms of attacks and threats, presenting potential avenues for hackers to exploit users of Apple Pay.

A. *Attack 1: Apple Server*

An Apple Server Attack refers to a targeted security breach aimed at compromising the integrity and functionality of Apple servers, particularly in the context of iOS devices that have undergone unauthorized modifications known as "jailbreaking." Jailbreaking involves bypassing Apple's built-in security measures, enabling users to customize their devices and install applications not approved by Apple [14].

In the context of an Apple Server Attack, hackers exploit the vulnerabilities introduced by jailbreaking to compromise the security of both the modified iOS devices and the Apple servers they interact with. The attack typically involves the initial infection of a jailbroken device with malware, allowing the attacker to gain unauthorized access and control over the device [5]. Once the attacker has compromised the jailbroken device, they may exploit the elevated privileges to execute various malicious activities. These activities can include

running tools for runtime analysis, such as Snoop-it, to steal sensitive data from the device. The compromised device may be used as a conduit to intercept and manipulate data in transit between the device and Apple servers, potentially including sensitive information like payment data [13].

In more advanced stages of the attack, the hacker may acquire root privileges, granting them full control over the jailbroken device. This level of access allows the attacker to execute nefarious deeds, such as damaging the device itself, launching attacks on the network through features like FaceTime, and compromising the security of data stored on Apple servers [15].

An Apple Server Attack on jailbroken iOS devices poses serious risks, not only in terms of data security but also in terms of the overall stability and reliability of the Apple server ecosystem. Users are strongly advised against jailbreaking their devices, as it exposes them to potential security vulnerabilities and undermines the robust security measures implemented by Apple to protect user data and maintain the integrity of its servers [5].

B. Attack 2: SSL Transaction Traffic

SSL attack transactions involve exploiting vulnerabilities in the Secure Socket Layer (SSL), a protocol designed to secure data transmission over the internet. SSL ensures the confidentiality and integrity of information by establishing a secure connection through the exchange of public and private keys during the SSL Handshake. This process generates a symmetric session key used for encrypting and decrypting transmitted data [16].

Despite SSL's robust security features, attackers have found ways to compromise transactions, particularly in scenarios involving Apple devices and services like Apple Pay. One method involves intercepting and manipulating SSL traffic before the server can decrypt the symmetric session key. This interception allows unauthorized access to sensitive transaction data [5].

In the context of Apple devices, attackers may exploit vulnerabilities in jailbroken devices to inject malware. By doing so, they can intercept and manipulate SSL transaction traffic associated with Apple Pay. This attack often begins with the theft of the payment token from the victim's device, a process facilitated through tactics like creating fraudulent Wi-Fi hotspots [14].

C. Attack 3: Masque Attack

In 2015, the introduction of iOS 8.4 marked a critical step in addressing vulnerabilities within the iOS system. Among the vulnerabilities rectified were those targeted by two distinct Masque Attacks, identified as CVE-2015-3722/3725 and CVE-2015-3725. These attacks, namely Manifest Masque and Extension, posed significant threats by compromising various applications and resources integral to the Apple ecosystem, including but not limited to Apple Pay, Apple Watch, and Apple Health. Notably, the exploits had the potential to dismantle and corrupt the data containers of affected applications [5].

The table II provides a concise breakdown of various Masque Attacks, their Methodology, and the Vulnerabilities Exploited.

TABLE II. MASQUE ATTACKS.

Attack Type	Methodology	Vulnerabilities Exploited
Manifest Masque	Interfering with OTA installations, potential code injection	Exploits weaknesses in app installation and OTA deployment
Extension Masque	Gaining unauthorized access, exploiting app vulnerabilities	Exploits vulnerabilities in targeted applications
Plugin Masque	Varied methods depending on the sub-attack, involving by passing security measures, manipulating network traffic, and exploiting kernel vulnerabilities	Exploits trust mechanisms, VPN plugin vulnerabilities, and weaknesses in the device's kernel

One specific avenue of attack, known as Plugin Masque, demonstrated the capability to circumvent iOS security protocols. This particular exploit focused on hijacking Virtual Private Network (VPN) traffic, thereby undermining the established security measures [17].

D. Additional Weakness, Risks and Vulnerabilities

1) Apple Mobile Payment Risks to Users

In the realm of mobile payment systems, safeguarding against potential threats is paramount to ensuring the security and integrity of financial transactions. The table III outlines various vulnerability threats that could compromise the security of Over-the-Air (OTA) transmissions between mobile phones and Point of Sale (POS) devices. These threats include the interception of traffic, unintentional installation of malicious software on mobile phones, lack of two-factor authentication, and the potential for user masquerading, which may result in fraudulent transactions [18].

TABLE III. RISKS ASSOCIATED WITH APPLE MOBILE PAYMENTS FOR USERS [5].

Vulnerabilities	Threats	Risks
Over-the-air transmission between the phone and point of origin (PO)	Interception of traffic.	Identity theft, disclosure of information, and relay attacks.
Accidental installation of harmful software on a mobile phone.	Interception of authentication data.	Unauthorized access to authentication parameters, disclosure of information, and repudiation of transactions.
Absence of two-factor authentication	User masquerading	Fraudulent transactions

2) Apple Mobile Payment Risks Upon Service Provider

In the landscape of mobile payment systems, understanding the potential vulnerabilities, associated threats and risks is imperative for ensuring the robustness and security of transactions [5]. The table IV encapsulates various scenarios related to Point of Sale (POS) systems, outlining vulnerability threats and the inherent risks they pose. From the acceptance of Over-the-Air (OTA) transmissions by POS systems to challenges such as malicious flooding leading to Denial of Service (DoS) attacks, each entry sheds light on a specific vulnerability [18]. The associated risks, including tampering, relay attacks, and digital rights management concerns, underscore the importance of implementing effective countermeasures. As we delve into each aspect, it becomes evident that a comprehensive understanding of these

dynamics is crucial for fortifying the security infrastructure of mobile payment systems.

TABLE IV. APPLE MOBILE PAYMENT RISKS TO SERVICE PROVIDER [5].

Vulnerabilities	Threats	Risks
POS system accepts OTA transmissions	Malicious party floods POS system with meaningless requests	Dos
POS devices are installed at merchant premises	Masque attacks, Tampering with POS	Unauthorized use of services, relay attacks, and alterations to messages
Lack of digital rights management on mobile device	Mobile device user illegally distributes content	Unauthorized access to content and breaches of digital privacy threats, and providers face risks related to infringements on digital rights.

V. CONCLUSION

In conclusion, situated within the dynamic context of the evolving digital payment landscape, this paper has explored various attacks targeting the Apple Payment System. It has shed light on potential vulnerabilities within its security infrastructure, aligning with the overarching trend of increased reliance on digital transactions. The examination of specific attack vectors against the widely-used Apple Payment System is particularly pertinent in this broader context. A reminder of the problem underscores the susceptibility of the Apple Payment System to specific attack vectors, raising concerns about the overall security posture of this widely-used platform. The potential risks associated with Apple Server Attacks, SSL Transaction Traffic manipulation, and Masque Attacks highlight the urgency of addressing these vulnerabilities to safeguard users and maintain trust in the platform. In response to this problem, the paper has proposed a forward-looking solution. Future efforts in this domain should prioritize proactive measures to fortify the Apple Payment System against emerging threats. The continuous research and development of robust security protocols, coupled with user education, are pivotal components of this solution. This approach ensures a resilient defense against evolving attack vectors as technology advances. As we reflect on the general context and the reminder of the problem, it becomes evident that the landscape of digital payments will persistently evolve, demanding ongoing efforts to stay ahead of potential risks and vulnerabilities. The conclusion, therefore, serves as a call to action, emphasizing the collective responsibility to maintain the security and integrity of digital payment systems in an ever-changing technological landscape.

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