Survey on Oracle Padding Attacks on Cryptographic Protocols

Anab Leila Abdi
CIISE, Concordia University
Montreal, CA

Tomas Navarro Munera
tomas.navarro@mail.concordia.ca
CIISE, Concordia University
Montreal, CA

Jainil Shah
CIISE, Concordia University
Montreal, CA

Bergen Davis
CIISE, Concordia University
Montreal, CA

Diego Jaramillo
CIISE, Concordia University
Montreal, CA

Md Ashfaque Rahman
CIISE, Concordia University
Montreal, CA

Rogelio Pumajulca
CIISE, Concordia University
Montreal, CA

Shrutibahen Rana
CIISE, Concordia University
Montreal, CA

Juan Soto Chourio
CIISE, Concordia University
Montreal, CA

***Abstract*—Cryptographic protocols play an essential role in protecting information across diverse applications and systems. These systems range from finance, ecommerce, transportation and shipping. The integrity and reliability of these protocols are crucial for safeguarding the confidentiality of the data they facilitate. While modern-day protocols are generally effective in securing systems, there are instances where they can fall victim to malicious actors. These actors employ specially crafted techniques and tools to exploit varipus design flaws within the definiation of the protocols libraries, its implematation etc, effectively bypassing the security mechanisms of cryptographic protocols.**

The Oracle Padding Attack, along with its variants, serves as an example of assaults on cryptographic protocols, padding oracle attacks enable the retrieval of either partial or full content of the original plaintext from encrypted messages. These attacks also impact the prevalent operational method of contemporary cryptographic protocols, particularly the cipher block chaining (CBC) mode. Consequently these attacks have the potential to compromise nearly all online communication channels that rely on such protocols for security In this survey report, we investigate and analyze the Oracle Padding Attack and its variants, along with several other attacks such as CRIME, BREACH, POODLE, DROWN, and BEAST. Our investigation delves into the background information of these attacks, their implementation details, and effective solutions against them

***Index Terms*—Cryptographic protocols, Oracle Padding Attack, systems, confidentiality**

I. Introduction

In today's modern society, a multitude of highly important operations are carried out over the internet or some electronic medium. This dependency on the digital era has correlated with an increase in cybercrimes across the technological industry. Therefore, when communicating, there is a demand for the confidentiality and integrity of components and properties of sent messages over these channels. In the case of the internet, the TLS/SSL protocol has been the conventional standard to secure communication. However, this protocol, among others, is not fully resistant to penetration. Actors can use specific implementations to penetrate and retrieve full or partial recovery of original plaintext messages. These attacks take advantage of unintended side channels revealed by cryptographic protocols. Consequently, they create an oracle that allows making inferences about the underlying plaintext by utilizing easily predictable padding bytes. This is why they are referred to as padding oracle attacks [1]. Therefore, TLS/SSL protocols are not impervious to oracle attacks.

The SSL/TLS protocol has seen a significant change in its security and overall architecture over the last few years, culminating in its termination in 2015. The protocols were rolled out into the market in the early 1990s. However, as time progressed, the protocols were plagued by their insecure design and numerous vulnerabilities. Subsequently, the TLS standard was introduced as the successor to SSL, iterating over versions TLSv1.0 until today's current standard of TLS1.3, which has mitigated vulnerabilities that plagued its predecessors [**?**]

As the SSL/TLS version underwent enhancements for increased security, the Oracle padding attack progressed in sophistication and diversified into various forms. This survey delves into the Oracle padding attack and its multiple variants, presenting an examination of five attacks on the SSL/TLS protocol, encompassing BEAST, POODLE, DROWN, CRIME, BREACH, and LUCKY13.

II. Background

The oracle padding attack, introduced in the early 2000s, has proven to be an intricate attack that operates by utilizing the oracle padding algorithm to carefully examine the integrity of padding on plaintext when given any ciphertext. The padding oracle algorithm was designed to identify cases of valid padding. It operates on the condition that it returns a positive result if the padding is correct; however, it will return a negative result if incorrect. As is common with many standardized formats, this introduces a vulnerability for malicious actors to apply investigative techniques to determine the padding byte of a specific message, which directly results in the collapse of the system and the exposure of the plaintext message [3].

The oracle padding attack is a key attack within the realm of cryptographic attacks, showcasing its prominence by its ability to exploit a server's behavior during the decryption process of messages. Attackers are able to deduce sensitive information through side channel data such as prolonged decryption cycles or error code displays.

In the case of the oracle padding attack, we have designed a scenario where the attacker retrieves the ciphertext through his participation in a man-in-the-middle attack. The server functions as a padding oracle, validating the padding and issuing error messages when incorrect padding is detected. The attacker will perform a series of tests on each byte of the ciphertext, iterating through the set of 0 - 255 until the server validates the padding. Once successfully validated, the attacker will perform XOR computations to reveal the last byte of the plaintext. This process is repeated iteratively to reveal preceding bytes in each instance [3]. The vulnerability within the padding oracle attack underscores the need for well-designed protocols that are regularly revised to protect against security infractions.

A. Padding Oracle History and Emergence of Variants

The earliest version of the padding oracle attack can be traced back to 1998, demonstrated in Bleichenbacher's attack, an adaptive ciphertext attack that victimizes RSA with PKCS 1 v1.5 padding [4]. However, this attack was inefficient and ineffective. This improved in 2002 when Vaudenay made a significant breakthrough in symmetric cryptography, later known as the padding oracle attack [5]. Over the course of the next decade, many faults were discovered in the implementation of security protocols such as TLS and SSL. Regrettably, these weaknesses provided opportunities for cyber assaults to pilfer vital user credentials. Notably, widely-used encryption methods such as CBC are particularly susceptible to such breaches. Surprisingly, the robustness of the encryption doesn't consistently offer protection, as certain attacks can prevail even without the attacker having knowledge of the encryption key. Neglecting this led to the promotion of several variants of the oracle padding attack. These variants include BREACH [6], POODLE, ROBOT[7], LUCKY13, BEAST, and CRIME [8].

B. Overview of Cryptography

In this section, we provide an overview of fundamental cryptographic concepts and terminology to assist readers in understanding attacks more comprehensively.

Encryption and Decryption: Encryption is the process of converting plaintext information into a secret code (ciphertext) to prevent unauthorized access. It is a crucial technique in cryptography for securing sensitive data during storage or transmission. Plaintext messages, denoted as 'm', can be sequences of bytes of any length (m E 0, 18n). The corresponding ciphertext, denoted as 'c', consists of byte sequences that are multiples of 'b', known as the block size. During encryption, a mathematical algorithm (encryption algorithm 'E') and a secret key 'k' are used to transform plaintext into ciphertext. An example of the encryption process is as follows:

E(m, k) = c.

Decryption involves the reverse process of converting encrypted ciphertext back into its original and readable form (plaintext). It is the inverse operation of encryption and requires the use of a key or algorithm to transform the ciphertext back into its original content. During decryption, a mathematical algorithm (decryption algorithm 'D') and the secret key 'k' are used to convert the ciphertext into plaintext. An example of the decryption process is provided below.

D(c,k) = M

III. The Padding Oracle Attack

The Padding Oracle attack exploits weaknesses in modern cryptographic protocols and systems. The attack capitalizes on differences in error messages that occur during the decryption of ciphertexts. Through the investigation and analysis of these errors, malicious attackers can deduce critical data surrounding the validity of padding, allowing them to decrypt and compromise the security of the encryption process. The existence of this attack sheds light on the obstacles and challenges in the realm of securing encrypted communication systems and showcases the importance of robust cryptographic practices. [**?**]

A. Prerequistes for the attack

The success of the Padding Oracle Attack hinges on meeting specific conditions. Typically, the attacker needs access to encrypted communication and the Oracle. This access enables the attacker to discern the validity of the padding generated by the current plaintext. With this crucial information, the attacker can decrypt and reveal the plaintext, regardless of the encryption's strength or the selection of robust keys. [9] The prerequisites for executing the padding oracle attack encompass:

- Availability of an Oracle: Successful execution requires the attacker to have access to a padding oracle, a mechanism indicating whether the decrypted message's padding is correct. This could manifest as subtle error messages or other detectable behaviors.
- Cipher Block Chaining (CBC) Mode: This attack is particularly effective when encryption employs Cipher Block

Chaining (CBC) mode, leveraging the interconnection of blocks to exploit padding.

- Familiarity with Padding Schemes: Understanding the padding scheme used in the cryptographic protocol is essential for the attacker. Various schemes exhibit distinct error patterns that can be exploited. In our demonstration, we'll utilize the PKCS7 padding scheme.

B. Attack Analysis

The Padding Oracle Attack can target symmetric encryption using CBC mode, which employs the PKCS7 padding scheme. Initially, we'll delve into the mathematical principles underpinning the attack. Then, we'll explore the step-by-step decryption process for one byte, followed by subsequent bytes and blocks. Our approach assumes that we can submit any ciphertext to the server, which will indicate whether the decryption yields plaintext with valid padding.

a) Mathematical Foundation: In Cipher Block Chaining (CBC) encryption, each plaintext block undergoes XOR (exclusive OR) with the preceding ciphertext block before entering the cipher. Consequently, during CBC decryption, each ciphertext undergoes decryption by the cipher and subsequent XOR with the preceding ciphertext block to reveal the original plaintext. To decrypt a specific plaintext block Pn, we require both ciphertext blocks Cn and Cn -1 . For instance, to unveil P2, we need access to C2 and C1. In practice, C2 is initially transformed into an intermediate representation, I2, through the block cipher decryption function and the key.

The Padding Oracle attack operates by computing an temporary intermediate representation for each of the ciphertext. This representation holds significance as it facilitates decryption. Understanding I2 is crucial because once we have it, we can derive P2 using the following transformation:

I2 = C1 P2

This equation implies:

P2 = I2 C1 (1)

This equation serves as a compelling motivation to uncover the intermediate representations, which ultimately facilitate complete decryption. In our scenario, since C1 is already known as part of the ciphertext, determining I2 will enable us to readily deduce P2.

b) Computation of the Last Byte:

IV. Variants of the Attack

A. Padding Oracle Attack Against the SCP02 Protocol

The Secure Channel Protocols (SCP) specified by GlobalPlatform aim to secure communication between smart cards (or other secure elements) and external entities (off-card entity) like card readers and servers, some of these specifications are: SCP01, SCP02, SCP03, SCP04, SCP10, SCP11. In this section, the focus is on SCP02 which until today is used and improves upon SCP01 by introducing counter measures against replay attacks and providing more robust security features. SCP02 (based on 3DES) uses dynamic session keys derived from a base key and counters.

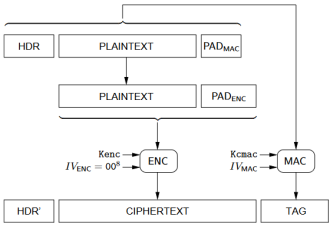

Fig. 1. Encryption and MAC computation of a command data with SCP02

Section Outline: Part 1 describes the SCP02 protocol in detail. Part 2 describes the regular padding oracle attack. Part 3 details how to use the Padding Oracle Attack against SCP02. Part 4 specifies the settings and experimental results. Part 5 lists counter measures and conclusion of the section.

Notation: A byte value is written as 7E. The value 00^i corresponds to the byte string made of i bytes equal to 00. $b_i|b_{i+1}$ refers to the concatenation of the bytes b_i and b_{i+1}. C || B refers to the concatenation of the two DES blocks C and B. ENC indicates a symmetric encryption function, while ENC^{-1} indicates the corresponding decryption function.

1) GlobalPlatform SCP02 protocol:
   The protocol SCP02 is based on symmetric-key algorithms, and it aims at establishing a secure link between an "off-card entity" and a card [23]. The card and the party involved in the communication with the card (from now on "the server") share one or several sets of symmetric keys. Three keys make a set, from this set the session keys are computed every time a new channel is established. The card manages a sequence counter related to a given keyset with an initial value of 0, this value is incremented after each successful session. After the sequence number reaches its maximum value, the card should not start a session with that keyset. The commands sent by the server and the responses sent by the card are encrypted and protected with a MAC tag; although, this depends on the security level negotiated during the key exchange. The lowest security level is data integrity (regarding the commands) and only data encryption in not allowed. The plaintext is padded with a fixed string of bytes [25] where a byte equal to 80 is appended to the plaintext, then it's added as many null bytes as necessary, so the string length is multiple of a DES block. For data encryption is used 3DES in CBC mode with a null IV [24]. The MAC (8 byte) tag is computed on the command header, the plaintext, and a padding data. From figure 1 taken from [26]: The genuine header HDR can be retrieved from the header HDR' of the encrypted command. Besides, IV used for the next command is equal to the MAC tag computed on the previous command. The ciphertext and the MAC tag become then the data field of the server's command.
2) Padding oracle attack
3) Attack Scenario
4) Results

5) Countermeasures and Conclusion

B. Breach

C. POODLE Attack

D. DROWN Attack

a) prerequistes of the attack:

REFERENCES

[1] R. Fedler,"Padding Oracle Attacks,"Supervisor: B. Hof, M.Sc.,Seminar Innovative Internet Technologies and Mobile Communications, SS 2013,Chair for Network Architectures and Services,Department of Computer Science, Technische Universität München,2013.

[2] IETF. The transport layer security (tls) protocol version 1.3, 2018. RFC 8446, Section 1.1.

[3] Rafael Fedler. Padding oracle attacks. Network, 83, 2013.

[4] Daniel Bleichenbacher. Chosen ciphertext attacks against protocols based on the rsa encryption standard pkcs 1. In Advances in Cryptology— CRYPTO'98: 18th Annual International Cryptology Conference Santa Barbara, California, USA August 23–27, 1998 Proceedings 18, pages 1–12. Springer, 1998

[5] Serge Vaudenay. Security flaws induced by cbc padding—applications to ssl, ipsec, wtls... In International Conference on the Theory and Applications of Cryptographic Techniques, pages 534–545. Springer, 2002.

[6] Breach attack website. https://www.breachattack.com/.

[7] Serge Vaudenay. Security flaws induced by cbc padding—applications to ssl, ipsec, wtls... In International Conference on the Theory and Applications of Cryptographic Techniques, pages 534–545. Springer,2002.

[8] Hanno B¨ock, Juraj Somorovsky, and Craig Young. Return of Bleichenbacher's oracle threat. In 27th USENIX Security Symposium (USENIX Security 18), pages 817–849,2018.

[9] Juliano Rizzo and Thai Duong. The crime attack. Retrieved September 21, 2012, via Google Docs: https://docs.google.com/docum.

[10] T. Duong and J. Rizzo. Padding oracles everywhere (presentation slides). In Ekoparty 2010, 2010.http://netifera.com/research

[11] Klima, V., Rosa, T.: Side Channel Attacks on CBC Encrypted Messages in the PKCS 7 Format. Cryptology ePrint Archive, Report 2003/098 (2003)

[12] Cve-2014-3566. NVD. https://cve.mitre.org/cgi-bin/cvename.cgi?name=CVE-2014-3566

[13] Poodle. Wikipedia. https://en.wikipedia.org/wiki/POODLE.

[14] Downgrade attack. Wikipedia. https://en.wikipedia.org/wiki/Downgrade attack.

[15] Poodle. Google Blog. https://www.openssl.org/bodo/ssl-poodle.pdf.

[16] What is the poodle attack? Acunetix. https://www.acunetix.com/blog/web-security-zone/what-is-poodle-attack/.

[17] Poodle implementation. Thomas Patzkes Personal Website. https://patzke.org/implementing-the-poodle-attack.html.

[18] Bodo Möller, Thai Duong and Krzysztof Kotowicz. This POODLE Bites: Exploiting The SSL 3.0 Fallback, 2014.

[19] Abeer E. W. Eldewahi, Tasneem M. H. Sharfi, Abdelhamid A. Mansor, Nashwa A. F. Mohamed, Samah M. H. Alwahbani. SSL/TLS attacks: Analysis and evaluation. 2015 International Conference on Computing, Control, Networking, Electronics and Embedded Systems Engineering (ICCNEEE), 2015. 10.1109/ICCNEEE.2015.7381362.

[20] Nimrod Aviram, Sebastian Schinzel, Juraj Somorovsky, Nadia Heninger, Maik Dankel, Jens Steube, Luke Valenta, David Adrian, J Alex Halderman, Viktor Dukhovni, et al. DROWN: Breaking TLS using SSLv2. In 25th USENIX Security Symposium (USENIX Security 16), 2016.

[21] O. Ivanov, V. Ruzhentsev and R. Oliynykov, "Comparison of Modern Network Attacks on TLS Protocol," 2018 International Scientific Practical Conference Problems of Infocommunications. Science and Technology, Kharkiv, Ukraine, 2018, pp. 565-570, doi: 10.1109/INFOCOMMST.2018.8632026.

[22] Drees JP, Gupta P, Hüllermeier E, Jager T, Konze A, Priesterjahn C, Ramaswamy A, Somorovsky J. Automated detection of side channels in cryptographic protocols: DROWN the ROBOTs!. InProceedings of the 14th ACM Workshop on Artificial Intelligence and Security 2021 Nov 15 (pp. 169-180).

[23] GlobalPlatform. GlobalPlatform Card Specification Version 2.3.1, March 2018. Reference GPC-SPE-034. Available online: https://globalplatform.org/wp-content/uploads/2018/05/GPC-CardSpecification-v2.3.1-PublicRelease-CC.pdf

[24] ISO/IEC 10116:2017 – Information technology – Security techniques – Modes of operation for an n-bit block cipher, available online : https://www.iso.org/obp/ui/iso:std:iso-iec:10116:ed-4:v1:en

[25] ISO/IEC JTC 1/SC 27. ISO/IEC 9797-1:2011 – Information technology – Security techniques – Message Authentication Codes (MACs) – Part 1: Mechanisms using a block cipher, available online: https://www.iso.org/standard/50375.html

[26] Avoine, G., Ferreira, L. (2018). Attacking GlobalPlatform SCP02-compliant Smart Cards Using a Padding Oracle Attack. IACR Transactions on Cryptographic Hardware and Embedded Systems, 2018(2), 149–170. https://doi.org/10.13154/tches.v2018.i2.149-170

[27]