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A Review on Cryptography Using SHA Algorithm

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Abstract:
As digital technology continues to expand into every field, ensuring the integrity and authenticity of data has become increasingly essential. Cryptographic hash functions, especially the Secure Hash Algorithm (SHA) family, are instrumental in achieving these objectives. This review presents a detailed study of SHA-1, SHA-2, and SHA-3, discussing their algorithmic design, strengths, weaknesses, and applications in digital security. The paper provides comparative insights supported by research literature and explores recent advances in cryptanalysis and the challenges posed by quantum computing.

Keywords:
SHA, Cryptography, Hash Functions, SHA-1, SHA-2, SHA-3, Blockchain, Digital Signatures, Data Integrity, Post-Quantum Security

I. INTRODUCTION

In this era of technological interconnectivity, information security relies heavily on cryptography. Heavily relied on among the tools of any given set of tools, cryptographic hash functions play an essential role in maintaining data integrity and authentication. The SHA family of algorithms, introduced by the National Security Agency (NSA) and standardized by the National Institute of Standards and Technology (NIST), has evolved significantly to address growing security threats [1]. This paper delves into the design and impact of SHA algorithms, with an emphasis on their real-world cryptographic applications.

II. HISTORICAL BACKGROUND AND EVOLUTION

The Secure Hash Algorithm (SHA) family has evolved significantly over the past three decades to address increasing demands for data integrity, authentication, and security in digital communications. Originally developed by the U.S. National Security Agency (NSA) and published by the National Institute of Standards and Technology (NIST), the SHA standards are integral to many cryptographic protocols including SSL/TLS, digital signatures, and blockchain systems.

A. SHA-1: The Foundation and Its Decline

SHA-1 was introduced in 1995 as a successor to the earlier MD5 hash function, offering a 160-bit output and improved security. It became widely adopted in cryptographic protocols such as TLS 1.0, SSL, PGP, and digital certificate signatures. However, cryptanalysis efforts began to highlight weaknesses. In 2005, Wang and colleagues introduced the first theoretical collision attack, indicating that SHA-1 could be compromised more efficiently than through brute-force techniques [2]. This theory was later validated in 2017 when Google, in collaboration with CWI Amsterdam, successfully produced two distinct PDF documents sharing an identical SHA-1 hash—an event that underscored the algorithm's vulnerability and marked a pivotal step toward its deprecation [3].Consequently, NIST abandoned SHA-1 and recommended upgrading to more secure hash algorithms.

B. SHA-2: A Strong Advancement

Introduced in 2001, the SHA-2 family comprises six distinct variants: SHA-224, SHA-256, SHA-384, SHA-512, SHA-512/224, and SHA-512/256. While these versions vary in terms of output size and internal structure, they all rely on the Merkle–Damgård framework. Among them, SHA-256 and SHA-512 are the most widely adopted, playing a crucial role in areas such as digital signature authentication, secure boot processes, software integrity checks, and blockchain systems—most notably in Bitcoin [5]. SHA-2 addressed SHA-1's vulnerability to collision and length extension attacks to a great extent, although it still inherits structural limitations from the Merkle–Damgård framework. As of now, there have been no documented practical attacks successfully targeting the SHA-2 algorithm [4].

C. SHA-3: A Paradigm Shift in Hash Design

In response to growing concerns about the structural limitations of SHA-2 and the need for diversity in secure hash algorithms, NIST initiated a public competition in 2007 to develop a new standard. This process ultimately led to the selection of the Keccak algorithm, which was officially standardized as SHA-3 in 2015 [6]. Unlike its predecessors, SHA-3 employs a sponge construction and uses a permutation-based approach, providing enhanced security against length extension, collision, and differential cryptanalysis. SHA-3 integrates SHA3-224, SHA3-256, SHA3-384, SHA3-512, in addition to extendable output functions (SHAKE128 and SHAKE256) which permit outputs of varying lengths.SHA-3 is not meant to replace SHA-2 but to complement it as a cryptographically diverse alternative [7].

D. Impact and Adoption Timeline

- In 1995 SHA-1 was standardized as FIPS PUB 180-1.
- FIPS PUB 180-1 was later updated in 2001 to include the SHA-2 family which was published as FIPS PUB 180-2.
- In 2005, SHA-1 was considered theoretically weakened.
- 2012: The Keccak algorithm is chosen as the winner of the NIST hash function competition, paving the way for its designation as SHA-3.
- 2015: SHA-3 is formally adopted as FIPS PUB 202.
- In 2017 Google validated the practical collision of SHA-1.
- From 2020 onward there was a growing reliance on SHA-2, and there was increased focus on post quantum hash algorithms alongside SHA-3.

The progression from SHA-1 to SHA-3 highlights the continuous advancement and strengthening of cryptographic standards over time. This evolution reflects a continuous response to cryptanalytic advances and the practical needs of digital security. As of today, SHA-2 dominates, but with the rise of quantum computing and lighter IoT devices, SHA-3 will shift focus towards the futuristic problems it will need to tackle.

III. WORKING MECHANISM OF SHA ALGORITHMS

SHA algorithms operate in well-defined stages to convert arbitrary input data into a fixed-size hash output. The internal design ensures that small changes in input produce significantly different outputs (avalanche effect), while preserving performance and resistance to attacks.

A. Message Preprocessing and Padding

The input message undergoes a padding process first, taking care to set its length to a specific multiple of 'K' known as the block size. The block size for SHA-1 and SHA-256 is 512 bits; for SHA-512, it is 1024 bits. Padding begins with a single '1' bit, followed by enough '0' bits, and concludes with a 64-bit representation of the original message length. This structure ensures consistent processing and mitigates length-extension vulnerabilities [8].

B. Parsing and Message Schedule Expansion

In SHA-256, each 512-bit message block is initially split into 16 words, each consisting of 32 bits, with each word subsequently processed and expanded into additional segments for further computation. These are expanded to 64 words using specific bitwise operations such as right-rotate, XOR, and shift operations. The expansion allows the algorithm to use both the original message and its transformed components across multiple rounds [9].

C. Initialization and Compression Function

Every SHA variant starts with a set of initial hash values, which attributes them to certain mathematical constants. For example, barrel-sha256 employs eight 32-bit words which treats parts of the square roots of the first eight prime numbers as its constituents. These initial values are iteratively updated through a series of rounds.

Each round applies a compression function, which mixes the expanded message schedule with the current hash values using modular addition, logical functions (Ch, Maj), and constants known as round constants. The functions are designed to ensure diffusion and non-linearity in the output. For SHA-256, there are 64 such rounds, whereas SHA-512 has 80 [9].

D. Final Digest Computation

As an example, in sha256 the eight 32 bit state words are combined to create a 256 bit hash, which achieves the utmost value-of-state expectation. The resulting digest serves as the final output, acting as a unique cryptographic fingerprint of the input data.

E. SHA-3 Specific Mechanism

SHA-3 employs a distinct method rooted in the Keccak sponge construction, setting it apart from the Merkle–Damgård-based designs of its predecessors. The input message is absorbed into a state of 1600 bits, which is updated through permutations and XOR operations. The necessary length of the document can be altered by squeezing the output from the state which produces the document hash after the message has been received. The sponge construction enhances cryptographic resilience by mitigating and removing the inherent weaknesses found in the Merkle–Damgård design [10].

IV. CRYPTOGRAPHIC STRENGTH AND SECURITY ANALYSIS

Cryptographic hash functions must uphold three essential properties to be considered secure: preimage resistance, second preimage resistance, and collision resistance. The SHA family of algorithms has undergone thorough analysis by the cryptographic community to evaluate their effectiveness in satisfying these properties and their resilience against emerging threats.

Algorithm	Hash Size	Collision Resistance	Preimage Resistance	Known Attacks	Status
SHA-1	160-bit	Weak	Moderate	Collision (Wang et al., Google 2017)	Deprecated
SHA-2	224-512-bit	Strong	Strong	None practical	Widely Used
SHA-3	Variable	Very Strong	Very Strong	None practical	Secure

A. Collision Resistance

Collision resistance guarantees that finding two different inputs that produce the same hash output is computationally infeasible. SHA-1 has been broken in this regard, as demonstrated by Wang et al. [2] and later by Google's SHAttered project [3], which proved practical collision attacks. SHA-2 and SHA-3, however, have withstood extensive cryptanalysis without any known feasible collision attacks, making them safe for use in high-security applications [4][6].

B. Preimage and Second Preimage Resistance

Preimage resistance ensures an attacker cannot reconstruct the original message from its hash. Second preimage resistance relates to the challenge of identifying a second input that results in the same hash as a specified input.SHA-2 and SHA-3 provide strong security against both, with no practical attacks reported. SHA-1 shows moderate resistance, but its known weaknesses make it unsuitable for cryptographic operations requiring long-term integrity [11].

C. Resistance to Length Extension Attacks

Since SHA-1 and SHA-2 rely on the Merkle–Damgård construction, they are susceptible to length extension attacks, where an attacker can append additional data to a hashed message and produce a legitimate hash output without having knowledge of the original data.SHA-3 overcomes this with its sponge construction, which inherently prevents such exploits by design [7].

D. Implementation Security

While theoretical security is critical, practical implementation also plays a vital role. Side-channel attacks, such as timing analysis, power consumption monitoring, and electromagnetic emissions analysis, exploit physical characteristics of cryptographic operations to uncover sensitive information. Secure coding practices, constant-time implementations, and hardware-level protections are necessary to mitigate such risks [9].

E. Quantum Vulnerabilities

The emergence of quantum computing introduces new threats. Grover's algorithm, for instance, can reduce the complexity of brute-force attacks from O(2^n) to O(2^(n/2)), theoretically halving the effective strength of a hash function. Thus, SHA-256 could be reduced to 128-bit security in a quantum scenario. Although no quantum computer is currently capable of such an attack at scale, this threat has accelerated interest in post-quantum secure hash functions and digital signature schemes [12].

F. Summary of Cryptographic Strengths

- SHA-1 is banned and must not be utilized in any secure applications.
- SHA-2 remains robust for current use, with 256 and 512-bit variants offering scalable security.
- SHA-3, with its unique architecture, provides excellent resistance to modern and theoretical attacks and is suitable for future-proofing security systems.

The robustness of SHA algorithms stems from a foundation in advanced mathematical principles, extensive peer-reviewed evaluation, and thorough analysis through real-world implementations. Continuous evaluation is necessary to maintain trust and adaptability in the face of evolving attack models and technological advancements.

V. APPLICATIONS OF SHA IN SECURITY

A. Digital Signatures

Used with RSA and ECDSA, SHA functions verify message integrity. A hash's signature is derived from the private key and validated through the public key[13].

B. Password Protection

SHA-2 combined with salting and stretching algorithms (e.g., PBKDF2, bcrypt) secures passwords against rainbow table attacks [14].

C. Blockchain Technology

Bitcoin relies on SHA-256 for hashing block headers and implementing its proof-of-work consensus mechanism. This ensures immutability and secure consensus [15].

D. Secure Communication Protocols
Data in motion is protected from unauthorized access or modification using SHA-2 within SSL/TLS for establishing secure connections[16].

E. Data Integrity Checks
SHA functions help verify software integrity using hash-based checksums distributed along with downloads [17].

VI. FUTURE DIRECTIONS AND CHALLENGES

A. Post-Quantum Security
Researchers are exploring hash-based signature schemes (e.g., SPHINCS+, XMSS) to counteract quantum threats [18].

B. Lightweight Hash Functions
Emerging IoT applications require efficient, compact hash algorithms that retain strong security (e.g., SHA-3 variants, KangarooTwelve) [19].

C. Standardization and Compliance
Ongoing NIST efforts aim to ensure SHA compliance with evolving international standards and interoperability demands [20].

VII. CONCLUSION

SHA-based cryptographic algorithms continue to serve as a fundamental pillar of today's digital security framework. Though SHA-1 is defunct SHA-2 still reigns in day-to-day usage and SHA-3 serves as a trustworthy alternative with a novel approach. As threats evolve, especially with the emergence of quantum computing, further research and development are essential. Lightweight and post-quantum hash functions will define the next frontier in secure cryptographic design.

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