HTOTP: Honey Time-based One-Time Passwords

Zixuan Ding and Ding Wang

***Abstract*—One-Time Passwords (OTPs) play a crucial role in Two-Factor Authentication (2FA) and Multi-Factor Authentication (MFA) by adding an additional layer of security. OTPs effectively mitigate the risk of static passwords being intercepted and reused. Nevertheless, both academic schemes and industrial solutions still encounter security threats stemming from server/device compromises and OTP factor forgery. Chain-based asymmetric OTP schemes are a promising approach to addressing server compromise but still face threats from device compromise and pre-generated chain leakage. We emphasize that since devices directly store the OTP seed, OTP authentication is essentially equivalent to verifying device possession. This means that in existing OTP schemes, OTP forgery and device compromise remain prevalent and difficult to overcome.**

In this work, we propose a brand new scheme to address OTP factor forgery and server/device compromises. *For the first time*, our scheme constructs a tightly coupled architecture between the password factor and the OTP factor. The OTP seed is derived from a password and a device-stored salt, preventing OTP seed extraction and OTP forgery even in the event of a device compromise. Through the integration of "honeywords" with the tightly coupled OTP architecture, the server stores decoy OTP seeds generated by decoy passwords, providing resistance against server compromises and partial password guessing from devices. We conduct a comprehensive evaluation of our OTP schemes. The computational overhead is correlated with the number of honeywords, and with the recommended set size of 20, the total verification overhead is approximately 0.24ms. Additionally, we propose formal security properties and application metrics, and rigorously prove our scheme's resistance against server/device compromise attacks and guessing attacks. Our scheme is the first to achieve comprehensive OTP security with low overhead.

***Index Terms*—One-Time Passwords (OTP); Honeywords; Two-Factor Authentication; Two-Factor Security.**

I. Introduction

Password authentication, long relied upon for its simplicity, faces security challenges due to users' difficulty in remembering complex or multiple passwords. Human-chosen passwords follow certain patterns [1], and Wang et al.'s research [2] further reveals that the entropy of passwords typically ranges from 20 to 22 bits, with the distribution adhering to Zipf's law. Moreover, password reuse and similarity heighten the risk of credential stuffing attacks [3] once a password is compromised. One-Time Password (OTP) is a significant solution to the limitations of static passwords. OTPs add an extra layer of security by ensuring that each authentication code is unique, unpredictable, and cannot be reused.

Lamport [4] first proposed the OTP scheme, named S/KEY [5]. Due to inherent flaws, such as the risk of OTP leakage from pre-generation and storage, S/KEY [5] faces challenges in achieving widespread adoption in the subsequent digital environment. Subsequently, the HMAC-based One-Time Password (HOTP) algorithm was proposed as a new standard in RFC 4226 [6], where the server and client share an OTP seed and a counter, using a one-way hash to generate readable OTPs. The Time-based One-Time Password (TOTP) algorithm replaces the counter in HOTP with a timestamp, addressing the issue of desynchronization attacks. HOTP and TOTP are currently the most widely used. However, following the industrial standards of HOTP [6] and TOTP [7], the server stores the OTP seed in plaintext, allowing an adversary who compromises the server to impersonate the user.

To counter server compromise, the strategy shifts from symmetric to asymmetric secret sharing. T/Key [8] improves upon S/KEY [5]. The user device pre-generates a hash chain according to the time interval, and the server stores the tail node of the chain. During verification, the device computes the OTP for the current time by hashing the seed multiple times, and the server hashes the received OTP and compares with the stored node. However, asymmetric TOTP does not address device compromises and comes with shortcomings, including long OTP generation and verification times, the need for regular regeneration of OTP chains, and the fact that used OTPs can be linked and potentially tracked by adversaries.

In addition to security threats of compromises, we highlight crucial issues that affect all OTP schemes. First, the integration of the OTP factor as an additional security layer is loosely coupled with other factors. This loose coupling allows adversaries to independently compromise each component, thereby simplifying attacks. Second, the device possession represented by OTPs is vulnerable to forgery, such as through channel hijacking and OTP (or OTP seed) leakage. A typical example is the use of HOTP [6] and TOTP [7] standards by Google Authenticator [9] and Microsoft Authenticator [10]. These systems implement OTP as a supplementary authentication factor in a loosely coupled manner but do not resolve the issues of loose coupling and vulnerability to forgery.

A. Motivations and Challenges

Emphasize the possession of the second factor: Password combined with OTP is a widely adopted Two-Factor Authentication (2FA) method, where the OTP represents the possession of the device. However, this "possession" can be easily forged, and the verifier cannot determine whether the individual genuinely holds the device or if the secret has been disclosed. We aim to transform the loosely coupled

This work was supported in part by the National Natural Science Foundation of China under Grant (62222208); and in part by the Fundamental Research Funds for the Central Universities, Nankai University (63243154). *(Corresponding author: Ding Wang.)*

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password and device possession (in the form of OTP) into a tightly coupled architecture. This architecture ensures that the knowledge provided by the password is maintained while highlighting the irreplaceable nature of the user's possession of the device. The challenge lies in constructing a tightly coupled architecture for passwords and OTP without altering the user's habit in password-OTP authentication, while ensuring that the verifier recognizes the OTP as proof of the registered user's possession of the device. The construction of the tightly coupled architecture is currently absent but urgently needed in existing OTP academic schemes and industrial solutions, this work represents the first attempt.

Resistance to secret compromise: In the loosely coupled 2FA framework, the server holds complete knowledge for verifying both factors separately (e.g., in password-OTP 2FA [10], [11], the service provider holds the password hash and the OTP seed). Loosely coupled authentication factors cannot provide stronger security beyond adding an extra security layer, allowing an adversary who compromises the data to separately compromise each authentication factor. Besides server compromises, other forms of secret leaks should also be taken seriously. In HOTP, TOTP, or SMS-based OTP, the server distributes OTPs (or OTP seeds) to the device. Due to numerous attacks on SMS [12]–[14], it is not recommended for OTP distribution [15]. Meanwhile, HOTP and TOTP involves the server distributing OTP seeds in the form of QR codes [11], making it possible for terminal recording attacks to compromise both the OTP seed and the password simultaneously. Trusting the login terminal poses risks to the user, it is safer for users to rely solely on their own device.

We aim to construct a tightly coupled architecture for factors. The challenge lies in preventing an adversary who compromises the server from compromising all factors. Specifically, for the coupled two factors, the server should not independently possess the knowledge to verify. Moreover, the task is to modify the OTP seed distribution method without changing password-OTP 2FA habits, ensuring that powerful adversaries, such as those intercepting channels or controlling terminals, cannot obtain the secrets. Users only need to trust their own devices, with no additional trust burden.

Detect leaks and guessing: It is challenging for both service providers and users to detect server data breaches, device compromises, and guessing attacks. We combine honeywords [16] with the tightly coupled OTP-password architecture to construct an alert mechanism for server compromises and guessing attacks. Specifically, the server stores both the real OTP seed and decoy OTP seeds. These seeds are generated by combining salt with honeywords. To ensure security, the server itself cannot distinguish the real OTP seeds unless it interacts with the honeychecker. When an adversary compromises the server and tries to log in with honey seeds, or compromises the device to guess passwords, the honeychecker will detect the breach and guessing attempts, alerting the attacks.

B. Contributions

In this work, we first analyze OTP academic schemes and industrial solutions, highlighting security issues and shortcomings related to secret derivation and leakage in symmetric OTP authentication (e.g., HOTP [6] and TOTP [7]). Asymmetric schemes (e.g., S/key [5] and T/key [8]), suffer from drawbacks including low usability (the OTP length is not user-friendly), limited lifespan, and extended registration and authentication times. *For the first time*, we identify the issues caused by the loose coupling of OTP factors with other authentication factors: the server authenticates the factors separately and holds all the knowledge for independent verification, meaning that a breach compromises all factors. Furthermore, OTP does not equate to the user's possession of the device.

We construct a tightly coupled two-factor architecture combining passwords and OTP. The OTP seed is derived from the password and salt, and the user device stores the salt rather than the OTP seed. Consequently, a correct OTP simultaneously indicates the knowledge of the password and user's possession of the device without forgery. The combination of passwords and OTP resolves issues of device-side leaks and identity forgery associated with OTP authentication. Inspired by honeywords, we accompany the OTP seeds stored on the server with decoy OTP seeds generated based on honeywords. Honeywords include decoy passwords generated from the original password as well as popular passwords. Therefore, compromising the server to log in and compromising the device to guess passwords online will both trigger alerts.

In summary, our contributions are four-fold:

- **Tightly coupled password-OTP two-factor architecture.** We transform the loosely coupled architecture of password and OTP (indicating device possession) into a tightly coupled one. The coupling is achieved by converting the two independent factors into a mechanism where the OTP seed is generated from a salt stored on the device and the user's password. The combination of device storage and user password knowledge reinforces the user's possession of the device. The tightly coupled architecture not only prevents adversaries from simultaneously compromising both authentication factors, but also prevents adversaries from separately compromising each factor or gaining access to both factors in sequence through a breach. The tightly coupled architecture addresses issues of factor compromise and impersonation inherent in loosely coupled architectures.
- **Unforgeability and loss resistance of the second factor.** The device receives OTPs or stores OTP seeds, and the user's possession of the device signifies possession of the second factor. However, this possession is susceptible to forgery. We convert the approach in previous schemes (including implementation standards [5]–[7] and popular schemes [8], [17]) from storing the entire OTP seed on the device to storing only a salt. In our construction, the OTP seed is generated by combining the salt with the password. An adversary who compromises the salt without the password cannot generate correct OTPs, thus preventing the adversary from impersonating the user after compromising the device. Additionally, the salt stored on the device is easy to back up, and its compromise is far less harmful than compromising an OTP seed. Converting the stored content to a separate salt enhances the second factor's resistance to forgery and device-side compromises.

- **Resistance to server compromises and password guessing.** We integrate honeywords into the tightly coupled password-OTP architecture to create a decoy OTP seed mechanism that defends against server compromises and (partial) password guessing attacks. The server stores decoy seeds generated from decoy passwords, alongside the real OTP seed. Since the salt is stored independently on the device, the salted hash stored on the server cannot be used for offline password guessing. Attempting to log in with compromised OTP seeds or guessing the password online after a device compromise will trigger an alert from the honeychecker. The honey OTP mechanism mitigates password guessing attacks resulting from server breaches and partial [1] guessing attacks originating from the device.
- **Some insights.** The entropy of human-chosen passwords is 20-22 bits, while the entropy of a 6-digit OTP is 19.93 bits, and that of an 8-digit OTP is 26.58 bits. Converting a password into a 6-digit OTP does not significantly reduce entropy, thereby not lowering the collision difficulty. Variable OTP lengths balance security and user-friendliness.
  In contrast to the original honeyword mechanism, storing the salt on the device prevents adversaries who compromise the server from brute-forcing hashes and semantically recognizing the real password. Therefore, incorporating popular passwords into decoy passwords is effective in defending against online guessing attacks from the device. In our honey OTP mechanism, flatness can be regarded as $1/k$, where k is the number of OTP seeds.

II. Preliminaries and Related Works

A. Preliminaries

Honeywords: Honeywords is a method that enhances the security of password-based authentication systems by mixing multiple decoy passwords [16]. The system stores both the real and decoy passwords for an account, while the honeychecker stores the index of the real password. As a result, it becomes challenging for an adversary who compromises the server to distinguish between the real and decoy passwords. During authentication, the honeychecker verifies the validity of the password index. If an adversary uses a decoy password, the honeychecker detects the discrepancy and triggers an alert. Next, we introduce the implementation steps of Honeywords and the variant applied in this work.

Assume the i-th user in the authentication system is denoted as u_i, with the password being pw_i. The authentication server maintains a verification table as $(u_i, H(pw_i))$, which generally includes the username and the hashed password (or salted hash $H(pw_i, r)$, the server holds the salt r).

For the password pw_i, the system generates honeywords. The honeywords and the real password pw_i form the sweetwords list $\mathbb{W}_i = (pw_{i,1}, pw_{i,2}, ..., pw_{i,k})$, where k is the number of elements in the list. Let I_c denote the index of the correct password in $\mathbb{W}_i$, that is $pw_{i,I_c} = pw_i$. The correct password is called sugarword, and the remaining $k-1$ passwords in $\mathbb{W}_i$ are referred to as honeywords. The server stores the hashed sweetwords list $\mathbb{W}_i$ as $(u_i, \mathbb{H}_i)$, where for the elements in $\mathbb{H}_i$, $h_{i,j} = H(pw_{i,j})$. Flatness is used to measure the expected probability that an adversary can guess the real secret from the candidate set. When the probability is $1/k$, it indicates that the elements of the candidate set are flat.

[1]The server stores decoy seeds generated from decoy passwords to alert against online guessing attacks from devices. Decoy passwords are typically composed of popular passwords and variations of the real password. We describe online guessing attacks from the device as partially resisted because the number of decoy passwords is limited.

TABLE I: Terms and Definitions Related to Honeywords.

Terms	Definitions
Honeywords	Decoy passwords excluding the real password
Sweetwords	The set of decoy and real passwords
Sugarword	The real password
Index	Indexing the real password in the set
Honeychecker	Storing valid index & verifying candidate indexes

The honeychecker is set up as an auxiliary server that stores the index I_c. Its purpose is to ensure that unless an adversary compromises both servers simultaneously, it is impossible to know which sweetword hash corresponds to the real password. Compromising both servers simultaneously is challenging for the adversary. Please note that in the worst-case scenario, even if the honeywords system is compromised, the security of the passwords will only degrade to the level they would have had if the system did not include honeywords. The brief terms and definitions are shown in Table I.

We make the following adjustments to the honeywords architecture to suit this work. The salted hashes stored on the server are no longer used for password authentication but rather as seeds for generating OTPs. Additionally, the salt is stored on the device side instead of the server. In this case, even if an adversary compromises the honeywords system in this work, she/he can obtain the OTP seed but do not have an advantage in offline password guessing.

Time-Based One-Time Password (TOTP): TOTP is widely used in 2FA, generating a temporary password using the current time and a shared secret key [7]. OTPs are generated based on fixed time intervals (e.g., 30 seconds) and the HMAC-SHA-1 algorithm. This method enhances security by providing an additional security layer beyond passwords and is convenient, as OTPs can be generated on various devices. However, OTPs require accurate time synchronization and are valid only for a short period. TOTP generation function is represented as follows: $TOTP(K,T) = Truncate(HMAC-SHA-1(K,T))$, where K is the pre-shared secret, $T = (T_c - T_0)/X$, X is the time step, T_c and T_0 are the current time and initial time, respectively. The output of $HMAC-SHA-1$ [18] is truncated into a user-friendly value (e.g., a 6-digit number).

B. Related Works of OTP

In 1981, Lamport first proposes the prototype [4] of constructing one-time passwords based on one-way hash functions. The terminal pre-stores the result of 1000 iterations of hash computations for authentication. Later, Lamport's scheme is standardized as the S/KEY OTP system [5] and used as an Internet standard [19]. The shortcomings of S/KEY include the limited number of OTPs and the security reliance on the pre-selected key. In addition, the S/KEY scheme has some inherent

flaws. Unused OTPs remain valid for a long time and can be stolen. The S/KEY scheme is also vulnerable to a "small n" attack [20], where an attacker can impersonate a server to trick the client into leaking unused OTPs. Furthermore, the hash function in the S/KEY hash chain is fixed, making it susceptible to pre-computation attacks.

Eldefrawy et al. [21] propose a scheme that constructs two nested hash chains, one for seed updates and the other for OTP generation. The use of multiple hash chains addresses the limited lifespan of hash chains in Lamport's scheme [4], eliminating the need to reset. In Eldefrawy et al.'s scheme, OTP generation and verification involve four rounds of challenge-response interactions. Gong et al. [22] constructed an OTP verification scheme based on sub-passwords. During the registration phase, the device stores the lists of random permutation function and sub-passwords generated by the server, and the verification involves 4 interaction rounds. Park [23] proposes an OTP scheme using multiple short hash chains to address the limitations of hash chain length and OTP generation in Lamport's scheme [4]. However, the seeds for multiple chains still require a pre-shared secret and a counter for generation. Each OTP consists of three different digits and hash values, making the scheme less user-friendly compared to short OTPs. This scheme still requires online interaction for verification.

In 2005, HMAC-based One-Time Password (HOTP) algorithm is published as RFC 4226 [6] and is adopted worldwide. The HOTP algorithm provides an authentication method where the client and server share a secret and a counter to symmetrically generate human-readable OTPs. The counter increments after each OTP generation, introducing a potential risk of losing synchronization. Time-based One-Time Password (TOTP) algorithm [7] is an improvement on HOTP. TOTP replaces the counter in HOTP with the current timestamp, and the client and server must keep their clocks synchronized. By using the timestamp, TOTP avoids counter desynchronization in HOTP.

There is an asymmetric TOTP method named T/Key [8]. The idea is based on the hash chain structure of Lamport's scheme [4], but each chain node consists of a timestamp and a salt. The salt is used to construct different hash functions for nodes on the chain. The device generates a time seed and then builds a hash chain, and the tail node of the chain is stored by the server. For verification, the device sends the chain node corresponding to the current timestamp to the server, and then the server calculates the hash from the received node to the tail node to verify. Adversaries who try to crack the asymmetric TOTP public key cannot infer any unused passwords. The chain's lifespan is limited, and excessively long chains can lead to uncontrollable verification times. Additionally, the device must regenerate a new chain and interact with the server regularly to initialize the chain.

Yang et al. propose a scheme called Group TOTP (GTOTP) [24], which allows users to prove their group membership without revealing their real identities. GTOTP can transform an asymmetric TOTP scheme into a GTOTP scheme based on permutation schemes and Merkle tree structures. The root of the Merkle tree serves as the group's public key, while the leaf nodes bind the verification points of group members, the points are used only briefly during verification. Anonymity is achieved through the randomization of the leaf nodes. However, GTOTP structure faces limitations, especially in dynamic group management. Additionally, each member in the group incurs significant storage overhead, posing challenges to scalability and efficiency in large-scale deployments.

Cao et al. [25] further improve the dynamic group management in GTOTP, reducing the storage and computational overhead for group members. As an alternative, the proposed Dynamic GTOTP (DGTOTP) introduces a third-party Registration Authority (RA) to handle part of the storage and computation. RA uses virtual verification points as leaves to create a Merkle tree, and then dynamically issues independent secret seeds to joining group members. Each group member's secret seed serves as the secret key for the chameleon hash function, allowing the real verification points of the TOTP instances to be dynamically bound to the Merkle tree leaves during authentication. However, both GTOTP and DGTOTP are vulnerable to replay attacks.

Erdem et al. propose an OTP service called OTPaaS [17], which introduces an additional OTP provider between the user and the server. The user first registers with the OTP provider, which stores the pairing table of the user, service provider, and OTP provider. OTPaaS transforms the authentication process into a three-party interaction, requiring five rounds of communication. However, the password verification is independent, and OTP as the second factor cannot mitigate the threat to the password if the server is compromised. Additionally, the service provider must trust the OTP provider, and the uncertainty and trust costs associated with the third party are also challenges that hinder implementation.

Sun et al. propose an OTP strengthening scheme called TrustOTP [26] based on additional hardware ARM TrustZone. All code and data in TrustOTP are securely isolated from the mobile operating system running in the normal domain. This secure isolation ensures that actions in the operating system do not compromise the confidentiality and integrity of the generated OTP or seeds. The OTP or seeds can only be accessed in the secure domain.

Peeters et al. propose a SMS OTP Security (SOS) protocol [27], aiming to improve the security of SMS-based OTP against message rerouting attacks via Signaling System 7 (SS7) and SIM Swap attacks. During the registration phase, the server and the user's device agree a session key based on the DH key agreement protocol and store the derived keys. During authentication, the server sends a random, 256-bit string to the device via SMS. The device generates an OTP based on the string and the pre-shared key, and returns the OTP to the server for verification through the client. Even if an adversary intercepts the SMS, they cannot generate the correct OTP.

A representative hardware-based OTP service provider is Yubico [28], whose OTP server is also used by other companies, including Okta [29], Ping Identity [30], and Secret Double Octopus [31]. Yubico OTP is a 44-character long secret encrypted by a hardware device and verified by a central server, YubiCloud. The verification server pre-stores the user ID and the AES keys, and maintains a counter of OTPs. The server verifies OTPs by decrypting them. YubiKey also supports OATH-HOTP/TOTP [32], providing feedback for the

HOTP token when touched. However, since YubiKey does not have a built-in clock and power, an application (Yubico Authenticator) needs to be installed for TOTP authentication. It may not be practical for users to carry an additional hardware device. In addition, if the device lacks strong security measures, the hardware may be vulnerable to attacks if acquired.

In HOTP [6], the user device and the server pre-share a counter for generating OTPs, which is incremented accordingly after each generation. However, if the counters of the user device and the server lose synchronization (exceeding the look-ahead window, usually 5), the OTPs will not match unless the counters are reset. In terms of specific implementation, HOTP [6] is suitable for scenarios involving specific hardware devices and low-frequency authentication requirements. TOTP [7] is widely adopted in mobile applications and online services due to its simplicity and high security. Google Authenticator [9], [33] and Microsoft Authenticator [10] are popular software-based authenticators. These applications use both HOTP [6] and TOTP [7] algorithms to generate correct OTPs, even when the mobile device is offline. During registration, the server generates a key for the user's device. The user saves the key by scanning a QR code displayed on the screen.

Additionally, there are implementations that enhance HOTP and TOTP. Authy [34] employs the same OTP generation method as Google Authenticator and offers device synchronization and backup features, enabling users to utilize the same OTP across multiple devices. LastPass Authenticator [35] and 1Password [36] integrate TOTP with password managers, enhancing password management services. Moreover, alongside TOTP, Duo Mobile [37] introduces push notification-based verification. Duo Push streamlines the verification process by sending push notifications to the user's device, where users simply need to accept or reject the login request.

Above implementations use the OTP-generating/receiving device as a second factor for authentication. However, the second factor and other factors are independent and loosely coupled. An adversary who compromises the server can potentially access both the user's password and the OTP seed. Device loss, secret leakage, and server compromise are all devastating to OTP security. Additionally, untrusted login terminals pose a threat to usernames and passwords, and the leakage of users' long-term keys is extremely dangerous.

C. Related Works of Honeywords

Juels and Rivest first proposed a method named honeywords at CCS'13 to detect password leaks [16]. Honeywords, as decoy passwords, are stored on the server together with the users' real passwords. The index of the real password is stored on an additional server (called honeychecker). The server cannot distinguish the real password and can only interact with the honeychecker to verify the password. An adversary who compromises the server must distinguish the real password from the other $k-1$ honeywords (e.g., the recommended k = 20 [16]). Attempting to log in with honeywords indicates a server compromise, triggering an alert from the honeychecker.

Juels and Rivest [16] divide honeyword generation methods into two categories: methods based on the legacy User Interface (UI) and methods based on the modified UI. The former does not require modifying the client or user behavior, while the latter requires the user to input a password that meets specific requirements. However, the cost of changing behavior is usually high. Chakraborty and Mondal [38] point out that the generation of honeywords by Juels-Rivest is based on random substitution and essentially cannot resist semantic-aware adversaries. Erguler [39] presents a heuristic method named "Honeyindex", which utilizes the real passwords of other users as honeywords.

Wang et al. [40] use heuristic experiments to reveal that four honeyword generation methods of Juels-Rivest [16] fail to reach the claimed security. Wang et al. suggest combining different generation models together to overcome the shortcomings of each model. Additionally, Akshima et al. [41] use heuristic arguments to point out that the honeyword generation methods of Juels-Rivest [16] and Chakraborty-Mondal [38] cannot achieve the purported security level. Akshima et al. propose three methods for legacy UI and modified UI.

Wang et al. [3] point out that there are security and deployment issues in "Honeyindex" [39] and the two legacy UI methods of Akshima et al. [41]. Wang et al. [3] propose a series of theoretical models based on various capabilities available to the adversary. These models use real-world data sets to design effective experiments to evaluate the flatness of the generation methods, thereby addressing the unresolved issues left by Juels and Rivest [16]. In addition, Wang et al. [3] propose four honeywords generation methods based on the existing probabilistic password cracking models, and provide a method to re-adjust the cracking model to construct flat honeywords to adapt to future model fusions and deployments.

Research on honeywords provides guidance for generation and application. Li and Wang [42] apply honeywords to Password-Authenticated Key Exchange (PAKE), based on the representative work OPAQUE [43] of asymmetric PAKE (aPAKE) and propose the concept of Honey PAKE (HPAKE). For external adversaries, HPAKE realizes protection based on honeywords. For internal adversaries, the principle of HPAKE is similar to that of aPAKE, and the server stores the one-way value of the password instead of plaintext.

III. Security Model

A. Evaluation Criteria

Wang and Wang [44] propose an evaluation set for 2FA schemes in general environments. Erdem and Sandıkkaya [17] then extend these criteria to OTP schemes in cloud environments. However, we find that the updated evaluation criteria are still not suitable for more general OTP schemes. Therefore, we propose evaluation criteria suitable for the widely used and popular OTP schemes.

$S1$. **Resistance to device loss:** The device serves as an authentication factor and is used to generate or receive OTPs. Loss or capture of the device means that this factor may be compromised. We aim to ensure that an adversary's acquisition of the device does not allow them to impersonate the user's possession of the device. In other words, an adversary who compromises the device

is hard to forge the user's login or compromise the user's other authentication factors.

$S2$. **Resistance to server compromise:** Generally, the server stores parameters for verifying authentication factors. Server compromise means that the adversary may be able to break the authentication factors offline. Additionally, a server compromise may go undetected, so we aim to ensure that even if the server is compromised, the adversary cannot break all of the authentication factors. Furthermore, it should be difficult for an adversary who compromises the server to impersonate the user for login.

$S3$. **Resistance to channel hijacking:** In SMS-based OTP authentication, adversaries can capture OTPs by various means [45]. Therefore, we aim to ensure that even if an adversary hijacks the channel and intercepts the communication, she/he should not be able to obtain or compute the OTP or other authentication factors.

$S4$. **OTP unlinkability:** The correlation between OTPs is unknown to the adversary. That is, even if the adversary masters a large number of used OTPs, she/he cannot recover the previous or subsequent OTPs.

$S5$. **Resistance to replay attacks:** An adversary who intercepts legitimate communication messages or OTPs and resends them later cannot impersonate a legitimate user to gain unauthorized access.

$S6$. **Two (multi)-factor security:** Authentication involves two or more factors, and the user cannot successfully log in unless they possess all the required factors.

$S7$. **Secret leak alert:** Generally, server data compromise can go unnoticed. However, when an adversary attempts to log in using a leaked secret, the service provider can detect the breach and respond by issuing alerts.

$S8$. **Guessing attack alert:** When the second factor (e.g., the user device) is compromised, an adversary may attempt to guess the user's password to log in. In such case, the server can detect these attempts and respond with alerts.

In addition to security evaluation criteria, we also develop usability evaluation criteria. These criteria allow for a comprehensive evaluation of the OTP system's user experience, ensuring it provides convenient and reliable identity authentication services while maintaining security.

$C1$. **No verifier table:** Devices and servers do not store pre-generated OTP lists, as OTPs are generated in real-time for each authentication. This method eliminates the need for a verifier table, reducing both storage space requirements and the risk of leakage.

$C2$. **No online interaction:** During the verification phase, OTP generation and verification are offline and do not require interaction between device and server. This criterion reduces the demands on equipment and network.

$C3$. **Easy to back up and restore:** The device's secret is easy to back up and restore on a new device, but it cannot be directly exploited by adversaries. This ensures that users can still log in even if the original device is lost.

$C4$. **Password/OTP friendly:** The length and characters of OTPs should balance usability and security, making them user-friendly and convenient for manual input.

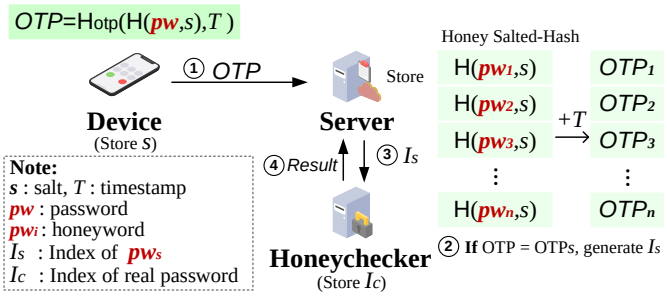


Fig. 1: Overview of OTP verification. The user device first calculates OTP, where $OTP = H_{otp}(H(pw, s)T)$, with $H_{otp}()$ and $H()$ are hash functions. After receiving the OTP, the server generates OTPs using the stored salted honeyword hash value and compares them with the received OTP. The index I_s obtained from the comparison is sent to the honeychecker. The honeychecker compares I_s with the real password index I_c and returns the verification result to the server.

$C5$. **Resistance to keyboard/screen recording attacks:** OTP schemes should be designed to withstand potential threats at the login terminal, including shoulder surfing, screen logging, and keylogging. This resistance ensures that long-term secrets, such as passwords and OTP seeds, remain secure and are not leaked.

$C6$. **No additional expenses:** Beyond registration and verification, there is no additional overhead required for devices and servers to maintain the OTP scheme.

$C7$. **No periodic synchronisation:** The lifespan of the device after registration is unlimited, and it does not need to interact with the server periodically online to synchronize parameters to ensure the stored parameters remain valid.

$C8$. **No additional third party:** Besides the user (with the device) and the service provider, the OTP authentication does not require the participation of additional third parties, that is, the two parties do not need to bear additional trust costs.

Table II shows the comparison between OTP implementations and popular schemes under the above criteria. The proposed HTOTP has advantages in resisting device loss (S1), server compromise (S2), and subsequent attacks (S7, S8).

B. System Model

In the setup phase, the service provider initializes and publishes public parameters. The user registers the password on a device (e.g., a smartphone), which generates honeywords and calculates corresponding decoy seeds. The device stores the salt and sends the decoy seeds along with the encrypted index of real password to the service provider. In the verification phase, the device generates a One-Time Password (OTP) based on the entered password. The service provider verifies the OTP and can determine whether the server has been compromised or subjected to online guessing attacks based on the decoy seeds. The process of the verification phase is shown in Figure 1. The entities of our scheme include the user device, server, and honeychecker. The algorithms are as follows:

- $\{\mathbb{G}, g, k_{HC}, PK_{HC}, H(), H_{OTP}()\} \leftarrow$ Setup(): The service provider executes Setup() to initialize. Setup() generates a private key k_{HC} for the honeychecker, and returns the public parameters $\{\mathbb{G}, g, PK_{HC}, H(),$

TABLE II: Comparison of Security Attributes and Application Requirements of OTP Schemes.

Scheme	Year	Ref.	Round*	S1	S2	S3	S4	S5	S6	S7	S8	C1	C2	C3	C4	C5	C6	C7	C8
DGTOTP (Cao et al.)	2024	[25]	2	×	×	✓	✓	⊗[1]	×	×	×	✓	×	✓	×	✓	×	×	×
GTOTP (Yang et al.)	2021	[24]	2	×	×	✓	✓	⊗[1]	×	×	×	✓	×	✓	×	✓	×	×	✓
SOS (Peeters et al.)	2022	[27]	2	×	×	✓	✓	✓	✓	×	×	✓	×	✓	✓	✓	✓	✓	✓
OTPaaS (Erdem et al.)	2019	[17]	5	✓	×[5]	×	△[6]	△[6]	✓	×	×	×	×	△[6]	△[6]	×	✓	✓	×
T/Key (Kogan et al.)	2017	[8]	1	×	✓	✓	✓	⊗[1]	×	×	×	✓	✓	✓	✓	✓	×	×	✓
YubiKey (OATH-HOTP)	2011-	[32]	2	✓	×	✓	✓	✓	⊗[3]	×	×	✓	✓	×	✓	✓	✓	✓	✓
YubiKey (OATH-TOTP)	2011-	[32]	2	✓	×	✓	✓	⊗[1]	⊗[3]	×	×	✓	✓	×	✓	✓	✓	✓	✓
Yubico OTP	2010-	[28]	2	✓	×	×	✓	✓	✓	×	×	✓	×	×	×	×	✓	✓	×
Google Authenticator (HOTP)	2010-	[6]	1	✓	×	✓	✓	✓	✓	×	×	✓	⊗[2]	✓	△[4]	×	✓	✓	✓
Google Authenticator (TOTP)	2010-	[7]	1	✓	×	✓	✓	⊗[1]	✓	×	×	✓	⊗[2]	✓	△[4]	×	✓	✓	✓
Proposed HTOTP	Current	\	1	✓	✓	✓	✓	⊗[1]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

✓ : Achieving (Resisting) the corresponding goal (attack). × : Not achieving (Resisting) the corresponding goal (attack). \ : Not considered.
⊗ : Achieving (Resisting) with additional conditions. △: Depending on other implementation conditions.
*: Interaction rounds during the OTP verification. [1]: Replay is valid within the time window.
[2]: Original HOTP [6] and TOTP [7] achieve, Google adds addition online password authentication.
[3]: Yubico Authenticator adds password authentication. [4]: Depends on the password verification strategy of Google Authenticator.
[5]: Service provider is compromised, user passwords leak, and no need for OTP verification.
[6]: Depends on the OTP verification strategy adopted by third-party OTP service providers.

S1: Resistance to device loss. **S2**: Resistance to server compromise. **S3**: Resistance to channel hijacking.
S4: OTP unlinkability. **S5**: Resistance to replay attacks. **S6**: Two (multi)-factor security.
S7: Secret leak alert. **S8**: Guessing attack alert.
C1: No verifier table. **C2**: No online interaction. **C3**: Easy to back up and restore.
C4: Password/OTP friendly. **C5**: Resistance to keyboard/screen recording attacks. **C6**: No additional expenses.
C7: No periodic synchronisation. **C8**: No additional third party.

$H_{OTP}()\}$, where $\mathbb{G}$ is a cyclic group, g is a generator of $\mathbb{G}$, PK_{HC} is the corresponding public key of k_{HC}, $H()$ and $H_{OTP}()$ are the hash function and OTP generation function, respectively.

- $\{r_c, T_1, EI_c, \mathbb{Q}\} \leftarrow \mathsf{Registration}(pw)$: The user (with the device) interacts with the server and the honeychecker to execute $\mathsf{Registration}(pw)$. The device processes the password offline to generate salted hashes containing the real password and honeywords. The device then sends the salted hashes list $\mathbb{Q}$ and the index EI_c encrypted with PK_{HC} to the server. Finally, the device stores the salt r_c and the registration timestamp T_1. The server stores the salted hash list $\mathbb{Q}$ and T_1, and the honeychecker stores the index EI_c of the real password hash within $\mathbb{Q}$.
- $\{0, 1, NULL\} \leftarrow \mathsf{verification}(pw')$: The user enters the candidate password pw' on the device and then inputs the generated OTP into the login terminal. The server interacts with the honeychecker to determine whether the OTP is correct, incorrect, or a generation result of guessed passwords or leaked OTP seeds. The server ultimately receives one of three results $\{0, 1, NULL\}$ and responds accordingly with an alert, login, or re-login action.
- $EI_c \leftarrow \mathsf{Enc}_{PK_{HC}}(I_c), I_c \leftarrow \mathsf{Dec}_{k_{HC}}(EI_c)$: The user side encrypts the index I_c using the honeychecker's public key PK_{HC}, and the honeychecker decrypts the ciphertext EI_c using the private key k_{HC}. The encryption and decryption algorithms are variants of ElGamal.
- $\{0,1\}^l \leftarrow \mathsf{H}(\{0,1\}^*), OTP \leftarrow \mathsf{H}_{OTP}(\{0,1\}^*, T)$: $\mathsf{H}(.)$ is a one-way hash function that hashes an input of arbitrary length into a fixed-length output. $\mathsf{H}_{OTP}(.)$ is an OTP generation function that takes an OTP seed and a timestamp as inputs and outputs a six-digit OTP. $\mathsf{H}_{OTP}(.)$ consists of two functional components responsible for hashing and truncating, respectively.

C. Threat Model and Security Definition

In our OTP scheme, the adversary's goals are to obtain the user's password and forge the user's long-term login respectively. The adversary may compromise any one of the user device, the server, or the honeychecker, but it is difficult to compromise multiple components simultaneously [44]. According to the Dolev-Yao threat model [46], the adversary may intercept and store the OTP during transmission. The adversary may be inside [47] the service provider and obtain the data stored by the server and the honeychecker.

We formally define the adversary games to measure the advantage of attacking HTOTP under different capabilities. The adversary's objectives are divided into guessing password and forging login. Please note that the advantage discussed here is distinct from the probability of the adversary guessing the password or OTP in a single attempt. When the advantage is negligible, the guessing approximates randomness.

Password/login security under device compromising: In this scenario, we assume that the adversary compromises the user's device, with the goal of guessing password and impersonating the user for login. For the sake of discussion, we refer to the service provider composed of the server and the honeychecker collectively as the server. Here, we define two threat models for password guessing and login impersonation, which are used in Section V to demonstrate the adversary's advantage in launching above attacks after compromising device.

First, we define a game to measure the adversary's advantage in guessing password. In HTOTP, the user's device stores only the salt r_c and the timestamp T_1 after registration, without storing the hashed password. Therefore, the adversary cannot guess password offline after compromising the device. This game is denoted as PS-DC and involves two phases. In the first phase, an honest device D and an honest server S interact for registration, with D and S referred to as challenger $\mathcal{R}_D$ and $\mathcal{R}_S$, respectively. In the second phase, the server continues

from the first phase, but the device becomes malicious, denoted as adversary $\mathcal{A}$. The game proceeds as follows:

- Setup: $\mathcal{R}_S$ initializes the system by executing Π.Setup, $\mathcal{R}_S$ can access the oracle $\mathbb{O} \leftarrow \{$ Π.Setup, $\Pi. < \mathcal{R}_D, \mathcal{R}_S >_X$, $X \in \{reg, verf\}\}$. $\mathcal{A}$ generates two different passwords, pw_0 and pw_1, and sends them to $\mathcal{R}_D$. $\mathcal{R}_D$ randomly selects one of the passwords, the corresponding password is recorded as pw_b, $b \in \{0,1\}$. $\mathcal{R}_D$ executes $\Pi. < \mathcal{R}_D(pw_b), \mathcal{R}_S >_{reg}$.
- Challenge: The adversary $\mathcal{A}$ inherits the challenger $\mathcal{R}_D$'s parameters, and possesses the passwords pw_0, pw_1, the salt r_c, and the timestamp T_1. $\mathcal{A}$ is allowed only one verification interaction to determine the guess, that is, $\mathcal{A}$'s goal is to guess the bit b selected by $\mathcal{R}_S$.
- Output: $\mathcal{A}$ selects the password $pw_{b'}$ and executes $\Pi. < \mathcal{R}_D(pw_{b'}), \mathcal{R}_S >_{verf}$. $b' = b$ represents $\mathcal{A}$ wins the game. The advantage is defined as

$$Adv^{\mathcal{A}}_{PS-DC}(\lambda) = |\Pr[b' = b] - \frac{1}{2}|. \tag{1}$$

***Definition** 1 (Password security under device compromising):* If for an OTP scheme, an adversary cannot achieve advantage $Adv^{\mathcal{A}}_{PS-DC}(\lambda)$ greater than a negligible function $negl(\lambda)$ in Probabilistic Polynomial Time (PPT), the scheme satisfies password security under device compromising.

Second, we define a game to measure the adversary's advantage in impersonating login. There are two scenarios in which the adversary can successfully log in: one is by guessing the password after compromising the device and thereby generating the correct OTP, and the other is colliding the dynamic OTPs. The adversary's advantage in achieving the former is $Adv^{\mathcal{A}}_{PS-DC}(\lambda)$. Next, we define a two-phase game C-OTP to assess the advantage of colliding OTPs. In the first phase, an honest device D and an honest server S interact for registration, with D and S referred to as challenger $\mathcal{R}_D$ and $\mathcal{R}_S$, respectively. In the second phase, the server continues from the first phase, but the device becomes malicious, denoted as adversary $\mathcal{A}$. The game proceeds as follows:

- Setup: $\mathcal{R}_S$ initializes the system by executing Π.Setup, $\mathcal{R}_S$ can access the oracle $\mathbb{O} \leftarrow \{$ Π.Setup, $\Pi. < \mathcal{R}_D, \mathcal{R}_S >_X$, $X \in \{reg, verf\}\}$. $\mathcal{R}_D$ generates a password pw, and then executes $\Pi. < \mathcal{R}_D(pw), \mathcal{R}_S >_{reg}$. $\mathcal{R}_D$ deletes pw, stores the salt r_c and the timestamp T_1.
- Challenge: The adversary $\mathcal{A}$ inherits the challenger $\mathcal{R}_D$'s parameters, including the salt r_c and the timestamp T_1. $\mathcal{R}_S$ generates a correct OTP OTP_b ($b \in \{0,1\}$) based on the registration record and simultaneously generates another different random OTP OTP_{1-b}. $\mathcal{R}_S$ sends both OTPs to $\mathcal{A}$. $\mathcal{A}$ is allowed only one verification interaction to determine the guess. $\mathcal{A}$'s goal is to guess which OTP is correct.
- Output: $\mathcal{A}$ selects the OTP $OTP_{b'}$ and executes $\Pi. < \mathcal{R}_S(OTP_{b'}, OTP_b) >_{verf}$. $b' = b$ represents $\mathcal{A}$ wins the game. The advantage is defined as

$$Adv^{\mathcal{A}}_{C-OTP}(\lambda) = |\Pr[b' = b] - \frac{1}{2}|. \tag{2}$$

***Definition** 2 (Login security under device compromising):* If for an OTP scheme, an adversary cannot achieve attack advantages $Adv^{\mathcal{A}}_{PS-DC}(\lambda)$ and $Adv^{\mathcal{A}}_{C-OTP}(\lambda)$ greater than negligible function $negl(\lambda)$ within PPT, then we say the scheme satisfies login security under device compromising.

Password security under server compromising: Server compromising implies that the adversary gains access equivalent to that of the server, rendering login security unachievable. Therefore, we focus on password security instead of login security. For the sake of analysis, we assume an enhanced adversary capability where the adversary compromises both the server and the honeychecker maintained by the service provider. This assumption allows us to evaluate the adversary's advantage in guessing the user's password after obtaining the real secret stored on the server. This game is defined as PS-SC and comprises two phases. In the first phase, an honest device D and an honest server S interact for registration, with D and S referred to as challenger $\mathcal{R}_D$ and $\mathcal{R}_S$, respectively. In the second phase, the device continues from the first phase, but the server becomes malicious, denoted as adversary $\mathcal{A}$. The game proceeds as follows:

- Setup: $\mathcal{R}_S$ initializes the system by executing Π.Setup, $\mathcal{R}_S$ can access the oracle $\mathbb{O} \leftarrow \{$ Π.Setup, $\Pi. < \mathcal{R}_D, \mathcal{R}_S >_X$, $X \in \{reg, verf\}\}$. $\mathcal{A}$ generates two different passwords, pw_0 and pw_1, and sends them to $\mathcal{R}_D$. $\mathcal{R}_D$ randomly selects pw_b ($b \in \{0,1\}$) and executes $\Pi. < \mathcal{R}_D(pw_b), \mathcal{R}_S >_{reg}$.
- Challenge: The adversary $\mathcal{A}$ inherits the challenger $\mathcal{R}_S$'s parameters, including the salted hash $q_c \leftarrow H(pw_b \parallel r_c)$ and the timestamp T_1, where r_c is the salt stored by $\mathcal{R}_D$. $\mathcal{A}$'s goal is to guess the bit b selected by $\mathcal{R}_D$. $\mathcal{A}$ can access the oracle $\mathbb{O} \leftarrow \{\Pi$.Setup, $\Pi. < \mathcal{R}_D, \mathcal{R}_S >_{verf}\}$.
- Output: $\mathcal{A}$ determines the password $pw_{b'}$. $b' = b$ represents $\mathcal{A}$ wins the game. The advantage is defined as

$$Adv^{\mathcal{A}}_{PS-SC}(\lambda) = |\Pr[b' = b] - \frac{1}{2}|. \tag{3}$$

***Definition** 3 (Password security under server compromising):* If for an OTP scheme, an adversary cannot achieve an attack advantage $Adv^{\mathcal{A}}_{PS-SC}(\lambda)$ greater than a negligible function $negl(\lambda)$ within PPT, then we say the scheme satisfies password security under server compromising.

IV. The Proposed HTOTP

A. Construction Overview

In addition to password authentication, OTP serves as the second factor, representing the device in the authentication process. Device loss or OTP secret leakage poses significant threats to the security of authentication factors. Therefore, it is crucial to strengthen the security of these factors. Additionally, in the event of a leak, it is essential to resist offline guessing attacks and potential threats to password security.

The design goals and construction ideas are as follows:

Unforgeability of the second factor: Devices are utilized as the second factor, typically generating [7], [18] or receiving OTPs [12] in the 2FA architecture. However, we observe that in the specific implementation of google 2FA (device and password) [9], OTPs don't necessarily equate to device possession, adversaries can steal OTPs through various means

(such as SMS interception, screen capture to obtain OTP generation seeds, server/device compromise), thereby bypassing the device. Our objective is to establish a robust correlation between OTPs and the user's possession of the device. The correlation ensures that even if adversaries acquire the device, they cannot impersonate the user to generate OTPs.

Tightly coupled two factors: The loosely coupled 2FA, such as Google 2FA, has independent password and device authentication. The main challenge is that adversaries compromising the server can simultaneously breach both the password and OTP seed. More generally, adversaries can compromise one factor while the other factor fails to provide the necessary obstruction. Our goal is to tightly couple two factors of password and device, making it difficult for adversaries to bypass one factor to attack the other. An additional objective is to make it difficult for adversaries to compromise the other factor even if they have already obtained one factor.

Resisting offline password guessing attacks/Key Compromise Impersonation (KCI) attacks: In the existing 2FA with password and OTP, adversaries can steal OTP seeds and launch offline password guessing attacks after compromising server data, thereby initiating KCI attacks. Our goal is to prevent adversaries from guessing user passwords or explicitly obtaining OTP seeds after compromising the server.

Secret leakage/password guessing alert: Server data leakage and user device loss are typically difficult for servers to detect but pose significant threats to user authentication. Our goal is for the server to identify and alert when there is a server data breach or offline guessing based on devices.

To achieve Goals 1 and 2, it is essential to ensure the security of the OTP seed shared between the device and the server, thereby preventing adversaries from obtaining. We convert the secret sharing method from server distribution to device distribution. The OTP seed consists of a user password and the salt value generated by the device. After registration, the device stores the salt value, ensuring that only the user with the device can generate correct OTPs. Moreover, adversaries cannot verify another factor offline after obtaining one factor. Furthermore, to prevent offline password guessing as outlined in Goal 3, the server and the user device store the password salted hash and the salt separately. Additionally, the server stores multiple honey password salted hashes for each account simultaneously. Consequently, even if the adversary compromises the server, they cannot distinguish the genuine OTP seed, and cannot verify the correctness of the guessed passwords without knowing the salt.

To achieve Goal 4, Honeywords incorporates popular passwords and decoy passwords derived from user personal information. When an adversary generates an OTP based on decoy OTP seeds after compromising the server or generates OTPs based on guessed passwords after compromising the device, the honeychecker can compare the received OTPs to detect data leakage or password guessing, thereby triggering an alert.

Next, we introduce the specific scheme steps.

B. Scheme Description

1) Setup phase: The service provider selects a cyclic group $\mathbb{G}$ of order q with a generator g. $H : \{0,1\}^* \rightarrow \{0,1\}^l$ represents a one-way hash function. $H_{OTP}(\{0,1\}^l, \{0,1\}^{32}) = Truncate(HMAC-SHA-1(\{0,1\}^l, \{0,1\}^{32}))$ represents the OTP generation function [7], where $HMAC-SHA-1 : (\{0,1\}^l, \{0,1\}^{32}) \rightarrow \{0,1\}^{160}$ is a one-way hash function [18], and $Truncate$ is a truncation function that reduces the hash value to a 6-digit number. Honeychecker generates a public-private key pair, denoted as (PK_{HC}, k_{HC}). The authentication server and honeychecker server communicate over a secure channel. The public parameters $\mathsf{pp} = \{\mathbb{G}, g, H(), H_{OTP}(), PK_{HC}\}$ are embedded in the authentication application downloaded by users.

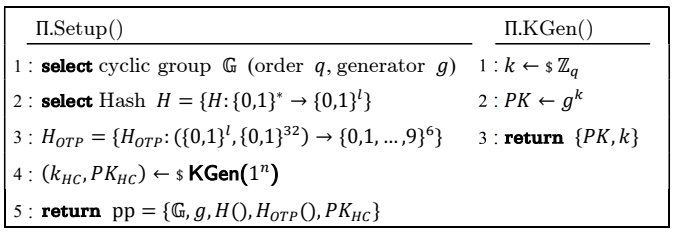


Fig. 2: The main operations of setup phase.

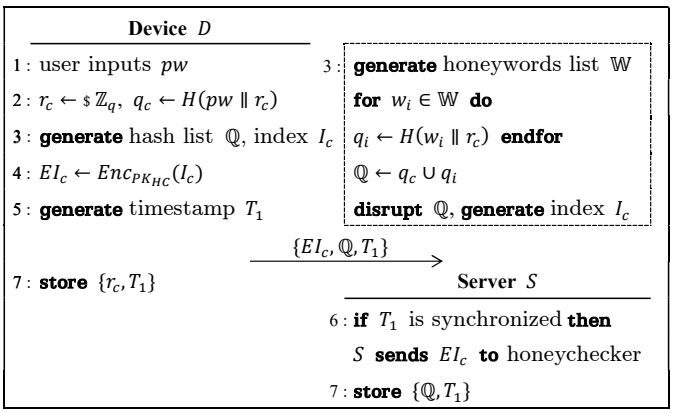


Fig. 3: The main operations of registration phase.

The verification phase is illustrated in Figure 2.

2) Registration phase: The verification phase is illustrated in Figure 3, with the corresponding description as follows:

R1: The user U inputs a password pw on the device D. Afterwards, D randomly selects a salt value r_c from $\mathbb{Z}_q$ and computes the salted hash $q_c \leftarrow H(pw \parallel r_c)$ of the password. D generates a honeywords list $\mathbb{W}$, for each honeyword w_i in the list, D computes the corresponding salted hash $q_i \leftarrow H(w_i \parallel r_c)$. The list composed of the salted hash q_c of the real password and the salted hashes q_i of honeywords is referred to as sweet-hashes list $\mathbb{Q} \leftarrow q_c \cup q_i$. D disrupts $\mathbb{Q}$ and generates an index I_c to indicate q_c. Then, D encrypts I_c to $EI_c \leftarrow Enc_{PK_{HC}}(I_c)$ using honeychecker's public key PK_{HC}, the encryption is based on a variant of ElGamal. During encryption, D selects $e \leftarrow \$\, \mathbb{Z}_q$, and calculates $E \leftarrow g^e$ and $M \leftarrow PK_{HC}^e \oplus I_c$, $EI_c = \{E, M\}$, where $\oplus$ is XOR operation. Finally, D generates the current Unix timestamp T_1 and sends $\{EI_c, \mathbb{Q}, T_1\}$ to the server S through a secure channel. Please note that it is convenient for the device to initiate the establishment of a secure channel based on the server's public key. D stores $\{r_c, T_1\}$.

R2: On receiving $\{EI_c, \mathbb{Q}, T_1\}$, the server S first verifies the freshness of T_1. Specifically, S generates the current

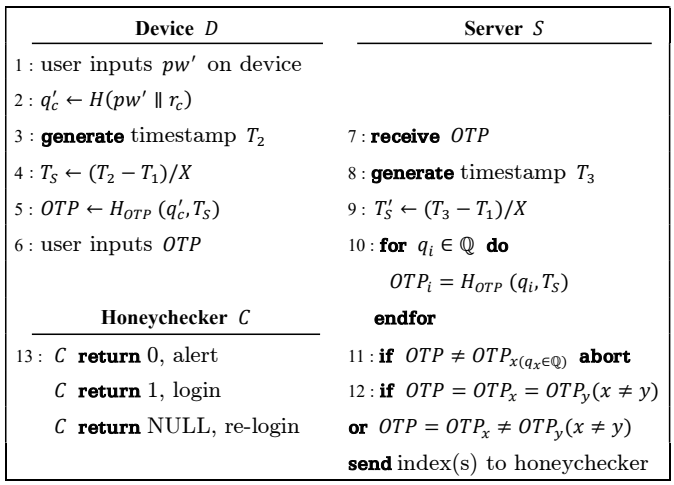


Fig. 4: The main operations of verification phase.

timestamp T_1' and verifies if $\mid T_1' - T_1 \mid < \triangle T$, where $\triangle T$ is the maximum delay. If the clocks of S and D are synchronized, S sends EI_c to the honeychecker C and stores $\{\mathbb{Q}, T_1\}$.

R3: On receiving EI_c, the honeychecker C decrypts EI_c by calculating $I_c = Dec_{k_{HC}}(EI_c) = E^{k_{HC}} \oplus M$.

The server and the honeychecker are independent entities that interact through a secure channel. They store the honey list and the index of the real secrets, respectively. Compromising both the server and the honeychecker is difficult for adversaries. Furthermore, even if an adversary compromises the real salted hash $q_c = H(pw \parallel r_c)$, they cannot guess the password offline without knowing the salt r_c.

The registration process of HTOTP differs from Google Authenticator in that the shared keys are distributed from the device to the server rather than the server distributing keys. In the case of Google Authenticator, the server generates a shared key and converts it into a QR code, which users scan to obtain the key. On the one hand, upon decoding, we discover that the QR code contains the username and secret in plaintext. Since the QR code remains static, any adversary can capture the user's identity and long-term secret through methods like screen capture or shoulder surfing attacks. On the other hand, strengthening the method of secret sharing doesn't appear to be the optimal solution. If the server initiates to establish a secure channel, it would require the device to maintain and share a public key, incurring additional storage and computational overhead for both the device and the server. More importantly, secret generation and distribution by the server always remain vulnerable to attacks caused by server breaches.

3) Verification phase: The verification phase is illustrated in Figure 4, with the corresponding description as follows:

V1: The user U first enters a candidate password pw' into the device D, then D computes the corresponding salted hash $q_c' \leftarrow H(pw' \parallel r_c)$. Note that D does not store password verification information, so even if an adversary obtains D, she cannot use it for offline password guessing. Afterward, D generates the current Unix timestamp T_2 and calculates the time difference $T_S \leftarrow (T_2 - T_1)/X$ with the registration timestamp T_1, where X represents the time step, typically set to 30 seconds, meaning that within a 30-second window, both parties generate the same OTP based on the same secret. D calculates $OTP \leftarrow H_{OTP}(q_c', T_S)$ using the time difference T_S and the salted hash q_c', where $H_{OTP}(q_c', T_S) = Truncate(HMAC - SHA-1(q_c', T_S))$, *Truncate* represents the truncation function [7], truncating the hash value $HMAC - SHA-1(q_c', T_S)$ to a 6-digit number. U inputs the OTP on terminal.

V2: On receiving OTP, the server S generates the current Unix timestamp T_3 and calculates the time difference $T_S' \leftarrow (T_3 - T_1)/X$. Then, S calculates the corresponding OTPs for hashes in the sweethashes list $\mathbb{Q}$. If the received OTP does not match any of the calculated candidate OTPs, the user's login attempt fails, and the server terminates the process. If the received OTP matches one or more candidate OTPs, the server sends the index(s) of the matching OTP(s) to the honeychecker C via a secure channel.

V3: On receiving index(s), the honeychecker C first verifies whether the received index(s) match(es) the correct index I_c. If there is no match, honeychecker returns 0, indicating a warning that the server may have leaked data or that an adversary is guessing the password on the device. If the single index matches the correct index, honeychecker returns 1, indicating successful login. If there is a match among multiple indexes, indicating an OTP collision, honeychecker returns a blank message, prompting the server to re-authenticate the user.

Please note that the server first generates the current timestamp T_3 upon receiving the message and then proceeds with OTP calculation and comparison. The time difference between T_3 and T_2 is primarily due to transmission delay. The server's computation and comparison overhead do not cause delays that would affect the accuracy of OTP verification.

During the verification phase of HTOTP, the user inputs the OTP generated offline into the login terminal. The usage of OTP aligns with the user's accustomed usage of Google Authenticator. We modify the underlying logic of Google's 2FA, transitioning from loosely coupled to tightly coupled factors. Ttwo factors refer to the password and the device. The server authenticates the device by verifying the OTP derived from the secret stored on the device. Loosely coupled 2FA means that password authentication and OTP authentication are independent, with Google Authenticator separately (step-by-step) authenticating the password and OTP. Therefore, it is easier for adversaries to compromise individual factors separately than to compromise both factors simultaneously.

In HTOTP, the device combines stored salt and passwords to derive OTPs, transforming the OTP from solely representing the device to simultaneously representing both the password and the device. Compromising the tightly coupled password-device is difficult for adversaries. Moreover, the introduction of honeywords prevents adversaries compromising the server from discerning the real secret and guessing the password without knowing the salt. Adversaries attempting to generate OTP directly after compromising the server or guessing the password to generate OTP after obtaining the device (salt) may trigger alerts from the honeychecker, leading to an account freeze. In terms of practicality, users can back up the salt on other clock-synchronized devices to enhance availability.

4) Password change phase: In the event of device loss or a honeychecker alert, account security can be restored by rotating the passwords. The steps are as follows:

PC1: The user U inputs the previous password pw and the new password pw^n on the device D. D selects a random salt r_c^n from $\mathbb{Z}_q$ and computes the salted hash $q_c^n \leftarrow H(pw^n \parallel r_c^n)$. D generates a new honeywords list $\mathbb{W}^n$, for $w_i^n \in \mathbb{W}^n$, D computes $q_i^n \leftarrow H(w_i^n \parallel r_c^n)$, $\mathbb{Q}^n \leftarrow q_c^n \cup q_i^n$. D disrupts $\mathbb{Q}^n$ and generates an index I_c^n to indicate q_c^n. Then, D encrypts I_c^n to $EI_c^n \leftarrow Enc_{PK_{HC}}(I_c^n)$ using honeychecker's public key PK_{HC}. D computes $q_c \leftarrow H(pw \parallel r_c)$. Finally, D generates the current Unix timestamp T_n and sends $\{q_c, EI_c^n, \mathbb{Q}^n, T_n\}$ to the server S through a secure channel.

PC2: S sends $q_c, EI_c^n, \mathbb{Q}$ to the honeychecker. If the verification of q_c is successful, S replaces $\mathbb{Q}$ with $\mathbb{Q}^n$, and the honeychecker replaces EI_c with EI_c^n. D replaces r_c with r_c^n.

V. Security Analysis

In this section, we formally prove the adversary's advantage in launching attacks when compromising the user device or the server, and informally discuss the probability of the adversary's successful attacks.

A. Formal Security Proof

The hash functions in this work are assumed to possess the properties of pre-image resistance, second-pre-image resistance, and collision resistance. Pre-image resistance means that given a hash value $h = H(x)$, it is computationally infeasible to find an input x such that $H(x) = h$. Second-pre-image resistance implies that given an input x_1, it is computationally infeasible to find a different input $x_2 \neq x_1$ such that $H(x_1) = H(x_2)$. Collision resistance ensures that it is computationally infeasible to find two different inputs $x_1 \neq x_2$ such that $H(x_1) = H(x_2)$.

1) Password Security under Device Compromising:

***Theorem** 1: Let $Adv_{TLS}^{\mathcal{A}}$ represents the adversary's advantage in breaking TLS to obtain the content, and $Adv_{CS}^{\mathcal{A}}$ represents the adversary's advantage in compromising the server to obtain the stored content. then the adversary's advantage in determining the password after compromising the device can be represented as:*

$$Adv_{PS-DC}^{\mathcal{A}}(\lambda) \leq max(Adv_{TLS}^{\mathcal{A}}, Adv_{CS}^{\mathcal{A}}) \tag{4}$$

***Proof** 1:* The validity of this theorem is established through the formalization of the game, where the advantage lies in identifying the bit $b \in 0, 1$, representing the adversary's determination of which of the two passwords is the registered one. When the adversary's advantage is negligible, she/he have no significant advantage in determining the password.

To break down the proof, we analyze the adversary's actions through a series of games. Each game incrementally reveals more information to the adversary, allowing us to measure their advantage in different scenarios.

- $\mathbf{Game_0}$: This game is identical to the game PS-DC described in Section III-C. The adversary's advantage is quantified as the absolute difference between the probability that the adversary correctly identifies the bit b. The adversary's goal is to determine which of the two passwords (pw_0 or pw_1) is the registered one. Formally, we have:

$$Adv_{PS-DC}^{\mathcal{A}}(\lambda) = |\Pr[b' = b] - \frac{1}{2}|.$$

- $\mathbf{Game_1}$: In this game, the adversary $\mathcal{A}$ has access to the passwords pw_0, pw_1 and the salt r_c, but not the salted hash $q_c \leftarrow H(pw_b \parallel r_c)$ stored on the server. Since the adversary lacks the salted hash, they cannot directly verify which password is correct. The adversary's probability of correctly determining b is $\frac{1}{2}$, implying that:

$$Adv_{PS-DC}^{\mathcal{A}}(\lambda) = |\Pr[b' = b] - \frac{1}{2}| \leq negl(\lambda).$$

- $\mathbf{Game_2}$: Here, we consider the adversary having access to the compromised device's state, including nonces or intermediate values used during the OTP generation process. However, without the salted hash q_c, the adversary still cannot effectively distinguish between the two passwords. Unless the adversary intercepts the message during registration and has the ability to break the TLS to obtain the message. Otherwise, the security properties of the hash function H ensure that any attempt to guess the password is no better than random guessing. Consequently, the probability is:

$$Adv_{PS-DC}^{\mathcal{A}}(\lambda) \leq Adv_{TLS}^{\mathcal{A}}.$$

- $\mathbf{Game_3}$: In this final game, we account for any additional auxiliary information that the adversary might obtain from the compromised server, such as partial state leakage, the advantage is $Adv_{CS}^{\mathcal{A}}$. Thus, the adversary's advantage can be expressed as:

$$Adv_{PS-DC}^{\mathcal{A}}(\lambda) \leq max(Adv_{TLS}^{\mathcal{A}}, Adv_{CS}^{\mathcal{A}}).$$

By analyzing the adversary's advantage through these games, we demonstrate that even with access to significant amounts of information from the compromised device, the adversary cannot gain a significant advantage in determining the user's password. This proof establishes that the adversary's advantage in determining the user's password after compromising the device is bounded by a negligible function, ensuring robust security.

2) Login Security under Device Compromising:

***Theorem** 2: The adversary's advantage in distinguishing OTPs can be represented as:*

$$Adv_{C-OTP}^{\mathcal{A}}(\lambda) = Adv_{PS-DC}^{\mathcal{A}}(\lambda) \tag{5}$$

***Proof** 2:* The adversary's advantage in distinguishing OTPs when compromising the device is the same as the advantage in distinguishing passwords. The proof is as in *Proof* 1.

3) Password Security under Server Compromising:

***Theorem** 3: Let $Adv_{Hash}^{\mathcal{A}}(\lambda)$ represent the adversary's advantage in reversing the hash to obtain the original value, $negl(\lambda)$ represent a negligible function. Then, the probability of the adversary obtaining the password after compromising the server can be represented as:*

$$Adv_{PS-SC}^{\mathcal{A}}(\lambda) \leq Adv_{Hash}^{\mathcal{A}} \tag{6}$$

***Proof** 3:* The theorem's validity is shown through the formalization of the game, where the advantage lies in identifying the bit $b \in \{0, 1\}$, representing the adversary's determination

of which password is correct after compromising the server. When the adversary's advantage is negligible, she/he has no significant advantage in guessing passwords.

To prove thoroughly, we consider a series of hypothetical games, each building on the previous to establish the password's security under server compromise.

- $\mathbf{Game_0}$: This game is identical to the game PS-SC as described in Section III-C. In this scenario, the adversary's advantage is measured by their ability to correctly identify the bit b, which indicates whether a given password guess is correct. The adversary's advantage is defined as:
$$Adv^{\mathcal{A}}_{PS-SC}(\lambda) = |\Pr[b' = b] - \frac{1}{2}|.$$
- $\mathbf{Game_1}$: In this game, the adversary $\mathcal{A}$ makes a direct guess at the bit $b \in 0, 1$. Without any additional information, the best strategy for the adversary is to guess randomly. Therefore, the probability of the adversary correctly determining b is $\frac{1}{2}$, resulting in:
$$|\Pr[b' = b] - \frac{1}{2}| \leq negl(\lambda).$$
- $\mathbf{Game_2}$: In this game, the adversary $\mathcal{A}$ has access to both candidate passwords pw_0 and pw_1, the salted hash $q_c \leftarrow H(pw_b \parallel r_c)$, and the timestamp T_1. However, they do not have the salt r_c. Without the salt, the adversary cannot generate the correct salted hash to compare against q_c. Unless the adversary can recover the password pw_b from the hash q_c, their advantage in this game remains the same as in $\mathbf{Game_1}$. The adversary's ability to reverse the hash to obtain the password is denoted as $Adv^{\mathcal{A}}_{Hash}$.
Combining the results of these games, we can conclude:
$$Adv^{\mathcal{A}}_{PS-SC}(\lambda) \leq Adv^{\mathcal{A}}_{Hash}.$$

This means that the adversary's advantage in guessing the password after compromising the server is at most as large as their advantage in reversing the hash function. Since modern cryptographic hash functions are designed to be resistant to inversion, the adversary's practical ability to recover the password from the hash is negligible, thereby ensuring the security of the password under server compromise.

In conclusion, by formalizing the adversary's advantage through these games, we demonstrate that the probability of an adversary successfully guessing the password after a server compromise is effectively bounded by their ability to reverse the hash function. This provides a strong assurance of password security, as long as the underlying hash function remains secure against inversion attacks.

B. Further Security Discussion

In this subsection, we heuristically analyze the satisfaction of HTOTP for the security criteria involved in Section III-A, and discuss the probability of achieving the goal with a single attack under different adversary capabilities.

1) Resistance to device loss: The device stores the salt of the password hash. An adversary compromising the device cannot directly obtain the other authentication factor (password) or generate the correct OTPs for login unless online guessing is performed. According to the research of Wang et al. [2], the password set conforms to the Zipf distribution. The probability of correctly guessing the password after obtaining the device is no more than $C' \cdot q_{guess}^{s'}$, where q_{guess} is the time of guess, C' and s' are the linear regression parameters of the password set $\mathbb{D}$ that conform to zipf's law. The probability of the adversary guessing the OTP correctly is $q_{guess}/2^{l_{OTP}}$, where l_{OTP} is the bit length of OTP. To summarize, the probability that the adversary forges the user's login with q_{guess} times online guesses after obtaining the device is $max(q_{guess}/2^{l_{OTP}}, C' \cdot q_{guess}^{s'})$, and the probability of breaking the user's password is at most $C' \cdot q_{guess}^{s'}$.

2) Resistance to server compromise (insider attack): The server stores the salted hashes of the passwords, while the corresponding salt is retained on the device. Even if an adversary manages to compromise the server's data (which can also be regarded as an insider attacker on the server side), they are unable to conduct offline password guessing verification without knowing the salt. In addition to the salted hash of the real password, the server also stores the salted hashes of $k-1$ honeywords. Unless the original content of the hashes is recovered, the adversary cannot distinguish the salted hashes according to the semantics. The probability that the adversary distinguishes the real OTP seed is $1/k$. Meanwhile, the adversary's login attempt has a probability of $(k-1)/k$ of being recognized and alerted by the honeychecker.

Assume that the adversary is an insider attacker within Honeychecker. They can obtain the index of the correct password among the honeywords, but they are unable to learn the user's password or the salted hash corresponding to the index. Therefore, the insider attacker within Honeychecker cannot launch subsequent attacks.

Assume that the adversary is an insider attacker within the service provider and can compromise both the server and Honeychecker. In this scenario, it is simplistic and pointless for the adversary to forge user logins. At this point, the adversary has already obtained the salted hash of the user's actual password, and their objective is to crack the user's password. However, since the salt is stored on the user's device, the adversary is unable to verify their password guesses. In summary, the above analysis clearly demonstrates that our proposed scheme is effective in withstanding insider attacks.

3) Resistance to channel hijacking: Generally speaking, the registration stage is initiated by the device based on the public key of the service provider, and the established TLS channel is generally secure. Without the salt of the salted hash, even if the adversary hijacks the registration channel, she cannot break the user's password. In addition, at the verification stage, both the generation of OTP by the device and the input of OTP by the user are offline, and the channel hijacking is ineffective.

4) OTP unlinkability and resistance to replay attacks: A one-way hash function has an avalanche effect, and a slight difference in input will lead to completely different results. Unless the adversary can restore the input of the hash function from the truncated hash value, it is impossible to judge whether there is a correlation between OTPs. In addition, time-based OTP is only valid within a time window. The basis for replaying an expired OTP to be valid is that the replayed OTP

is the same as the current OTP, with a probability of $1/2^{l_{OTP}}$, where l_{OTP} is the bit length of OTP.

5) Two (multi)-factor security: The authentication factors consist of the password and the device. The adversary cannot forge the user login if obtaining only one of the factors. When the adversary holds the user's device, it is necessary to guess the user password online to attempt to log in, and it may trigger the guess alert. When the adversary holds the user password, it does not have the device (the salt stored in the corresponding device), and cannot generate the correct OTPs. Therefore, the proposed HTOTP has two-factor security.

6) Secret leak and guessing attack alert: The server stores the honey hashes list composed of decoy passwords, and honeywords includes popular passwords. When the adversary uses the leaked secret or the guessed popular passwords to attempt to log in, the honeychecker can match the decoy in the list and issue an alert.

VI. Evaluation

In this Section, we evaluate the efficiency of the proposed HTOTP through experiments, and make comparisons among related schemes in terms of overhead and usability, etc.

Deployment of the experimental environment. The server environment is built based on Ubuntu (Version: 22.04.3 LTS), and the hardware specification is Intel Xeon Gold 6320R @ 2.10GHz, 256GB of RAM, NVIDIA RTX 3090 GPU. In the server program, we use the Mac class under the javax.crypto package to implement the HMAC-SHA-1 algorithm, and the construction of the Truncation function refers to RFC4226 [6]. The login interface is a web page written in Python that returns the input content to the server. The deployment of honeychecker is the same as that of the server.

The device program is written based on JAVA and is deployed on Android devices with the specification (Version: Android 13, Hardware: MediaTek Dimensity 8100 @ 4 × 2.85 GHz, 8GB of RAM, Mali-G610 MC6 GPU). The algorithms such as key generation, hash, and encryption involved in the initialization and registration stages are provided by the JCA (Java Cryptography Architecture) library. The secure channels between the device-server in the registration stage, the login terminal-server, and the server-honeychecker in the verification stage are based on the TLS protocol of the SSL class under the javax.net package.

In Table III, we additionally measure the overhead of basic operations on devices with varying performance levels as a reference. While the overheads measured on different platforms and hardware vary, we believe that the comparisons between schemes under the same conditions still offer valuable insights, and the variation in overhead does not significantly affect the comparative analysis between the schemes' performance.

In the verification protocol, the server immediately obtains the current timestamp after receiving the OTP, so the delay in generating the OTP between the device and the server does not include the operations involved in verifying the OTP. We set the time step X to 30 seconds, which is the same as the step of common OTP authentications such as Google Authenticator and Microsoft Authenticator. The time step is in line with user habits and does not affect the implementation of the scheme. In the given hardware environment, we measure the communication latency between the terminal and the server to be approximately $1ms$ in a Local Area Network (LAN) and $90ms$ in a Wide Area Network (WAN). OTP schemes' communication latency mainly lies in the aforementioned interaction, specifically the transmission of OTP. Since the process of generating the OTP on the user device is offline and there is only one round of communication contributing to the overhead latency, the evaluation primarily focuses on the computational overhead of the scheme. In practical applications, the time step X can be appropriately adjusted according to the communication latency and the length of the OTP to provide redundancy.

TABLE III: Overhead of Basic Operations

Operation	Server Overhead[1] (μs)	Phone Overhead[2] (μs)
Hash(SHA-256)	0.9961-2.173	25.14-1694
Hash(HMAC-SHA-1)	2.812-7.454	63.85-4823
Enc/Dec(AES-128)	203.7-524.9	974.46-25913
ECC point mul(P-256)	34.61-105.48	1672-48135

1: Server performance measurements were conducted on the following devices:
Ubuntu (22.04.3 LTS), Intel Xeon Gold 6320R@2.10GHz, 256GB of RAM, NVIDIA RTX 3090 GPU.
Ubuntu (22.04.3 LTS), Intel Core i7-12700H@2.30GHz, 16GB of RAM, NVIDIA RTX 3060 GPU.
Ubuntu (20.04.3 LTS), Intel Core i5-1135G7@2.40GHz, 16GB of RAM, Intel Iris Xe Graphics.
Ubuntu (16.04 LTS), Intel Core i3-2310M@2.10GHz, 4GB of RAM, AMD Radeon HD 6370M.
2: Phone performance measurements were conducted on the following devices:
Android 14, MediaTek Dimensity9300+@4×3.0GHz, 12GB of RAM, Immortalis-G720 MP10 GPU.
Android 14, Kirin9100@4×3.0GHz+4×2.5GHz, 16GB of RAM, Mali-G78 MP20 GPU.
Android 13, MediaTek Dimensity8100@4×2.85GHz, 8GB of RAM, Mali-G610 MC6 GPU.
Android 13, Qualcomm Snapdragon 4Gen2@2×2.2GHz+6×1.8GHz, 8GB of RAM, Adreno 705 GPU.

A. Performance of HTOTP

Setup phase. The expense in the setup phase mainly lies in the generation and distribution of key pairs. We select public parameters based on the common elliptic curve P-256. The lengths of the public and private key of honeychecker are both 256 bits. The hash function is selected as SHA-256, and the output is 256 bits. We truncate HMAC-SHA-1 to a 6-character OTP, with the entropy approximately 19.93 bits. At this point, the entropy is approximately equal to that of the password selected by the human (according to the study by Wang et al. [2] [48], the entropy of the human chosen passwords is 20-22 bits). If the OTP specification is set to an 8-digit number, then the entropy value is 26.58 bits, which is higher than the human chosen passwords. For users, there is no need to worry that the OTP is more likely to be guessed by the adversary.

Registration phase. The registration phase involves the interaction between the user's device and the server. The device establishes a TLS channel based on the server's public key and is considered secure. Generally, the details about establishing the TLS channel are ignored. Here, the server's public-private key pair is only used for establishing the channel, so we omit it. The device generates corresponding honeywords according to the user's password. The number of honeywords is in accordance with the recommended $k = 40$ [3].

Taking the 32M Rockyou password data set as an example, the training is based on the hybrid model of $\frac{1}{3}$TarList + $\frac{1}{3}$TarMarkov + $\frac{1}{3}$TarPCFG, and a common computer only needs $1.17ms$ to generate 20 honeywords. We combine popular passwords and generated passwords, and control the total number to 20. The device needs to calculate 20 hashes and an asymmetric encryption of the index. The time cost of single hash (SHA-256) and an asymmetric encryption based on ECC (P-256) is approximately $0.9961\mu s$ (microseconds, $1\mu s$

$= 10^{-3}ms = 10^{-6}s$) and $71.87\mu s$ respectively. The computational cost of the device is approximately $1.121ms$. The device constructs a secure TLS channel using the server's public key to send messages, and the total cost of the registration stage is approximately $1.310ms$.

Verification phase. In the verification stage, the device generates OTP offline based on the password without interacting with the server. The device computes hash and HMAC-SHA-1 and truncates them into OTP. The time cost of a single HMAC-SHA-1 is approximately $2.999\mu s$. After the user inputs the password, the total time cost for the device to generate the OTP is approximately $4.1524\mu s$. On the server side, the server performs OTP generation for 40 candidate OTP seeds and interacts with the honeychecker for verification. The relationship between the number of candidate OTPs and server overhead is shown in Figure 5. The time cost from receiving OTP to verifying OTP on the server is approximately $0.2376ms$.

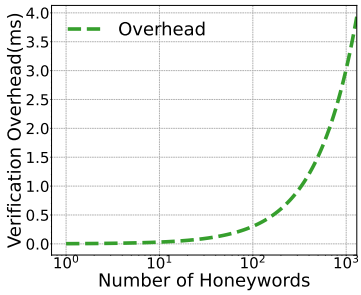


Fig. 5: The relationship between server overhead and the number of honeywords (X-axis shows exponential growth). When the number of honeywords is no greater than 100, the overhead is less than $0.3ms$.

B. Comparison

In this subsection, we compare HTOTP with the OTP implementations and the popular schemes in terms of performance and cost, and the comparison is shown in Table IV.

In the implementations of HOTP [6] and TOTP [7], taking the default registration steps of Google Authenticator and Microsoft Authenticator as examples. The device scans the QR code generated by the server to pre-share the OTP seed, and both the device and the server generate an OTP once for the successful verification of synchronization. In the verification stage, the device generates an OTP based on the stored OTP seed combined with the counter (or timestamp in TOTP), and the cost is the same as that of registration. In addition, the OTP seeds and the counters (or timestamps in TOTP) are symmetrically stored by the device and the server.

In scheme T/Key [8], the device generates a hash chain of k nodes (k is set as 2×10^6 in [8]), and each node consists of a timestamp and a salt, and the server stores the tail node of the chain. In the verification stage, the device calculates t_1 hashes according to the difference between the current time and the initialization time, and the server calculates t_2 hashes according to the difference between the tail node and the current time. Both the device and the server store the user identity, the initial (tail) node hash, and the timestamp. During the initial verification, $t_1 + t_2 = k$. Subsequently, $t_1 + t_2$ is k minus the time point indicated by the previous verification.

The scheme OTPaaS [17] introduces an additional OTP provider beyond the user's device and the server, thus requiring additional interaction rounds during registration and verification. Except for the interaction framework, OTPaaS does not provide a specific implementation algorithm, so it is unfair to discuss the computational overhead in table IV. In terms of storage overhead, the device stores the user name and the information of the OTP provider. The OTP provider maintains a verification table including three-party information such as the user name, the OTP seed, and the service provider. The service provider stores information like the user name, the password, and the OTP provider. Here we combine and count the storage of the service provider and the OTP provider.

In the scheme GTOTP [24], at the registration stage, the server generates a Merkle tree according to the device nodes and encrypts the user information as the verification token, the relationship between the generation cost of the Merkle tree and the number of devices d is approximately $(2d-1)H_Z$. We measure that the time for the AES-128 algorithm to symmetrically encrypt a block (both the plaintext and the ciphertext are 128bits) is $215.4\mu s$. In addition, for fairness, here we equivalently replace the modular exponentiation multiplication of all schemes with ECC point multiplication based on P-256, a single ECC point multiplication is approximately $35.94\mu s$. At the verification stage, the server decrypts the token submitted by the user to generate the OTP.

DGTOTP [25] is improved from GTOTP [24]. DGTOTP additionally introduces a Registration Authority (RA) to dynamically manage device nodes, and here we merge the overhead of RA and the server. A series of Pseudo-random Functions (PRF) are defined in DGTOTP for generating keys, and in the simulation we use sha-256 instead. RA pre-generates keys and the corresponding Merkle tree for the virtual device nodes. After that, RA records the mapping relationship between the joined devices and the virtual nodes. The device generates verification credentials (passwords). In the verification stage, the verification server obtains the records from RA, and then verifies the Merkle tree and the OTP.

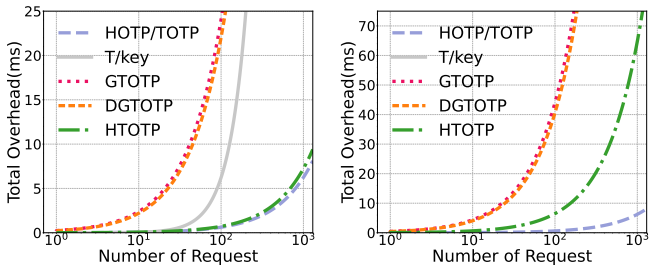
In the proposed HTOTP, a variant of ElGamal encryption and decryption is involved in the registration stage, with an overhead of 2 ECC point multiplications. Additionally, in table IV, we use w to represent the size of honeywords, which generally takes the values of 20 [16] or 40 [3]. From the simulation results, even if the value of w is relatively large, the overheads of registration and verification still remain at a low level. According to the parameter specifications in this section, the overheads are not higher than $0.5ms$. Therefore, the deployment of honeywords can obtain higher security guarantee while not introducing high overhead.

We summarize the overheads of devices and servers during the verification phase and compare the overheads of the schemes. In Figure 6(a), we present the basic overheads. In our HTOTP, the size w of the honeyword is set to 1. In GTOTP [24] and DGTOTP [25], the number d of user devices is set to 1. In T/key [8], $t_1 + t_2$ is set to the number of requests required for each test. The abscissa grows exponentially. From the overhead curves, it can be seen that the overhead of our scheme for a single operation is comparable to that of the basic HOTP/TOTP [6], [7]. In T/key [8], $t_1 + t_2$ represents the total number of blocks set, which is related to the verification overhead. Therefore, the slope of its overhead curve is higher than that of other curves as the abscissa increases.

TABLE IV: Comparison of Overheads.

Scheme	Registration			Verification			Storage	
	Round	Device	Server	Round	Device	Server	Device	Server
HOTP [6]	1	H_{OTP}(67.14μs)	H_{OTP}(3.027μs)	1	H_{OTP}(67.14μs)	H_{OTP}(3.027μs)	$L_{seed}+L_{C/T}$	$L_{seed}+L_{C/T}$
TOTP [7]	1	H_{OTP}(67.14μs)	H_{OTP}(3.027μs)	1	H_{OTP}(67.14μs)	H_{OTP}(3.027μs)	$L_{seed}+L_{C/T}$	$L_{seed}+L_{C/T}$
T/Key [8]	1	kH_Z(0.9961$k\mu s$)	\	1	t_1H_Z(0.9961$t_1\mu s$)	t_2H_Z(0.6283$t_2\mu s$)	$L_{ID}+L_{HZ}+L_{C/T}$	$L_{ID}+L_{HZ}+L_{C/T}$
OTPaaS [17]	7	\	\	5	\	\	$2L_{ID}$	$6L_{ID}$
GTOTP [24]	2	$2H_Z+2E_M$(78.31μs)	$Mt+d(Enc+2H_Z+2E_M)$ (299.64d-3.027μs)	2	\	$Mt+H_Z+Dec$ (6.054d+215.4μs)	$L_{En}+2H_Z$	L_{Mt}
DGTOTP [25]	2	$8H_Z+Enc$(223.4μs)	$Mt+7dH_Z$(8.965d-0.9961μs)	2	\	$Mt+4H_Z+Dec$ (5.977d+214.4μs)	L_{En}	$L_{Mt}+2dL_{HZ}$
HTOTP	1	wH_Z+2EM (691.88+0.9961$w\mu s$)	$2E_M$(71.88μs)	1	H_Z+H_{OTP}(114.1μs)	wH_{OTP}(3.027$w\mu s$)	$L_H+L_{C/T}$	$wL_H+L_{C/T}$

H_{OTP}: Hash from $\{0,1\}^*$ to OTP.
E_M: ECC point multiplication in P-256.
Enc: Symmetric encryption.
L_{En}: Length of encryption block.
$L_{C/T}$: Length of counter/timestamp (64bits).
w: The size of honeywords.
L_{seed}: Length of OTP seed (256bits).
L_{ID}: Length of identity (32bits).
Dec: Symmetric decryption.
k: The number of nodes in the hash chain.
\: Not considered.
t_1+t_2: Total nodes minus previous verification nodes.
H_Z: Hash from $\{0,1\}^*$ to $\{0,1\}^l$.
L_{HZ}: Length of the hash H_Z.
Mt: Merkle tree generation.
d: The number of user devices.
L_{Mt}: Length of Merkle tree.



(a) Overhead of Schemes in Single User/Device/Password (b) Overhead of Schemes in Recommended Deployments

Fig. 6: Comparison of verification overhead between OTP schemes (HOTP [6], TOTP [7], T/Key [8], GTOTP [24], DGTOTP [25], our HTOTP). Figure 6(a) shows the overhead of the solution when handling multiple requests under a single verification condition. Figure 6(b) shows the overhead of the solution when handling multiple requests under their respective recommended deployments. The abscissa represents exponential growth.

Figure 6(b) shows the comparison of the scheme costs under deployments based on recommended settings. In HTOTP, the size w of the honeyword is set to 20. In GTOTP [24] and DGTOTP [25], the number d of user devices is set to 32 (the average value obtained during the evaluation). In T/key [8], t_1+t_2 is set to $k=2\times10^6$. The overhead in the initial verification is approximately 2 seconds, which exceeds the range of the coordinate. Subsequently, the overhead will decrease as the chain length reduces. The overhead of our solution increases as the honeyword grows, and the overhead curve is in line with Figure 5.

VII. Conclusion

In this work, we first revisit academic OTP schemes and industrial solutions, demonstrating that the current schemes and solutions are unsatisfactory due to several vulnerabilities, including security threats arising from loosely coupled OTP architectures, device compromises, and OTP forgery. Subsequently, we construct a tightly coupled password-OTP two-factor architecture to address device compromises and OTP forgery. Additionally, we incorporate honeywords into this tightly coupled architecture to counter server compromises and online password guessing attacks. *For the first time*, our scheme extends the security of OTP schemes to meet resistance against server/device compromises and OTP factor forgery. Specifically, we present a comprehensive set of security attributes and application metrics to analyze OTP schemes. We provide proofs and probabilistic analyses of the scheme's security. This work is expected to contribute to the development of more secure OTP authentication in 2FA/MFA.

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