Cryptanalysis of Group Key Agreement Protocol Based on Chaotic Hash Function

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SUMMARY In 2010, Guo and Zhang proposed a group key agreement protocol based on the chaotic hash function. This letter points out that Guo-Zhang’s protocol is still vulnerable to off-line password guessing attacks, stolen-verifier attacks and reflection attacks.

key words: cryptanalysis, key agreement, chaotic maps, hash function, Chebyshev map

1. Introduction

Chaos\textsuperscript{1} is a universal, random-like and robust phenomenon in nonlinear systems. Over the past decades, cryptography based on chaos theory has been studied widely to exploit the idea of using chaotic dynamical systems in cryptography because of the random-like, unpredictable dynamics of chaotic systems. For instance, chaotic systems have been widely used to design secure communication protocols\textsuperscript{2}–\textsuperscript{14}, cryptographic hash functions\textsuperscript{15}, \textsuperscript{16}, and secure digital image encryption schemes\textsuperscript{17}.

In 2007, Xiao et al.\textsuperscript{8} proposed a novel key agreement protocol based on chaotic maps. However, Han et al.\textsuperscript{10} pointed out that Xiao et al.’s protocol is insecure against the replay attacks. In 2010, Guo and Zhang\textsuperscript{11} pointed out that none of\textsuperscript{8}, \textsuperscript{10}, \textsuperscript{12} can satisfy the contributory nature of key agreement, that is, the malicious server can predetermine the shared secret key. They also proposed a secure group key agreement protocol based on the chaotic hash function\textsuperscript{7}, \textsuperscript{13}–\textsuperscript{16} to surmount the aforementioned flaws. However, this letter points out that Guo-Zhang’s protocol is still vulnerable to off-line password guessing attacks and stolen-verifier attacks\textsuperscript{18}–\textsuperscript{20}.

Guo-Zhang’s protocol uses user’s password to prove the security. So, the password based key agreement protocols can be vulnerable to off-line password guessing attacks since users usually choose easy-to-remember passwords. Actually, Guo-Zhang’s protocol is vulnerable to offline password guessing attacks in which an adversary can easily obtain the secret password of the legal user from the intercepted values. In addition, Guo-Zhang’s protocol is susceptible to stolen-verifier attacks in which obtaining secret data, which are stored in a server, can allow an illegitimate user to login to a server as a legitimate user.

2. Chaotic Map Based Hash Function

Conventional hash functions such as MD4, MD5 and SHA-1 are realized by a complicated method based on logical operations or multi-round iteration of some available ciphers. However, since the conventional hash functions are successfully attacked by Wang et al.\textsuperscript{21}, the construction of a new and more secure hash function has been studied by lots of researches in recent years. Chaos has been widely utilized to construct cryptographic hash function in the past decade for its interesting characteristics, such as sensitivity to tiny changes in initial conditions and parameters, mixing property, ergodicity, etc. Compared with conventional hash functions, the chaotic hash function based on high-dimensional cat map\textsuperscript{7}, \textsuperscript{13}–\textsuperscript{16} not only is simple and efficient, but also has strong diffusion and confusion capability, good collision resistance, extreme sensitivity to message and secret key (please refer to\textsuperscript{7}, \textsuperscript{13}–\textsuperscript{16} for more detailed information).

3. Review of Guo-Zhang’s Protocol

Figure 1 illustrates Guo-Zhang’s protocol. Before performing the key agreement protocol, assume that user A and server B secretly share the password hash value $h_{pw} = H(ID_A, PW_A)$ of A’s random password $PW_A$ and identification $ID_A$, where $H(\cdot)$ denotes the chaotic hash function\textsuperscript{7}, \textsuperscript{13}–\textsuperscript{16}, and $ID_A$ and $PW_A$ are juxtaposed as the pending message from left to right. The details of Guo-Zhang’s protocol are as follows:

3.1 Authentication Phase

(1) $A \rightarrow B$: $AU_A$

A generates a random number $ra \in [-1, 1]$, and sends the authenticated message $AU_A = \{ID_A, ra, H(h_{pw}, ra)\}$ to B.

(2) $B \rightarrow A$: $AU_B$

After receiving $AU_A$, B takes out his/her own copies of $h_{pw}$, computes $H'(h_{pw}, ra)$ and verifies whether $H(h_{pw}, ra) \approx H'(h_{pw}, ra)$. If not B stops here; otherwise, A is authenticated and B returns a message $AU_B = $
3.2 Key Agreement Phase

\[\{rb, H(h_{pw}, ra, rb)\}\text{ to } A, \text{ where } rb \text{ is a random integer selected by } B.\]

(3) \(A \rightarrow B: ACK\)

After receiving \(AU_A\), A takes out his/her own copies of \(ra\) and \(h_{pw}\), computes \(H'(h_{pw}, ra, rb)\) and checks whether \(H(h_{pw}, ra, rb) = H'(h_{pw}, ra, rb)\). If yes, the mutual authentication is done. A computes \(ACK = H(rb \oplus h_{pw})\) as the acknowledgement message and sends it to B, where \(\oplus\) is the bitwise XOR operator.

(4) \(B\) takes out his/her own copies of \(h_{pw}, rb\) and calculates \(ACK' = H(rb \oplus h_{pw})\). If the verification of \(ACK = ACK'\) is successful, then \(B\) confirms that \(ACK\) is sent by \(A\).

4. Cryptanalysis of Guo-Zhang’s Protocol

This section shows that Guo-Zhang’s protocol is vulnerable to off-line password guessing attacks and stolen-verifier attacks [18]–[20].

4.1 Off-Line Password Guessing Attacks

A guessing attack involves an attacker -- randomly or systematically -- trying long-term private keys (e.g., user passwords or server secret keys) one at a time, in a hope of finding the correct private key. Ensuring that long-term private keys are chosen from a sufficiently large space can reduce exhaustive searches. Most users, however, select passwords from a small subset of the full password space. Unlike typical private keys, a password has low entropy, and is constrained by the memory of the user. Such weak passwords with low entropy are easily guessed by using the so-called dictionary attack. Roughly speaking, the entropy of a user generated password is about 2 bits per character [19]. For example, one alphanumerical character has 6 bits of entropy, and thus the goal of the attacker, which is to obtain a legitimate communication party’s password, can be achieved within a reasonable time. Therefore, the password guessing attacks [20] on Guo-Zhang’s password-based key agreement protocol should be considered a real possibility.

4.1.1 Off-Line Password Guessing Attack 1

Let \(Adv\) be an active adversary who interposes the communication between \(A\) and \(B\). Suppose that \(Adv\) has eavesdropped valid messages \(AU_A = \{DA_A, ra, H(h_{pw}, ra)\}\) from an open network. It is easy to obtain the information since the messages are all exposed over the open network. Then the off-line password guessing attack 1 proceeds as follows:

(1*) To obtain the password \(PW_A\) of user \(A\), the adversary \(Adv\) makes a guess at the secret password \(PW_A\) from dictionary \(D\) and computes \(H'(h_{pw}, ra)\) as follows:

\[H(H(h_{pw}) \oplus H(T_r(ra))) \oplus Y \text{ and validates whether } H(T_r(ra)) = H(T'_r(ra)) \text{ or not. If it holds true, } A \text{ believes that } C_2 \text{ is sent by } B \text{ and } T_r(ra) \text{ is valid, at the same time, } A \text{ computes } C_3 = H(h_{pw} \oplus T_r(ra)) \oplus T_r(ra) \text{ and sends } C_3 \text{ to } B.\]

(2*) \(Adv\) computes \(T'_r(ra) = H(h_{pw} \oplus T_r(ra)) \oplus C_3 \text{ and verifies whether } X = H(T'_r(ra)) \text{ or not. If it holds true, } B \text{ believes } T_r(ra) = T'_r(ra) \text{ and keeps } T_r(ra) \text{ as a secret.}\]

(3) \(A \rightarrow B: C_3\)

While receiving \(C_2\), \(A\) takes out his/her own copies of \(h_{pw}\) and \(T_r(ra)\), computes \(T'_r(ra) = H(h_{pw} \oplus T_r(ra)) \oplus C_3\) and checks if \(H(h_{pw}, ra) = H(h_{pw}, ra)\). If it holds true, \(Adv\) can guess the user \(A\)’s password \(PW_A\). Otherwise, \(Adv\) repeatedly
performs the Steps (1*) and (2*) until $H(h_{pw}, ra) = H(h^*_pw, ra)$.

The following illustrates the algorithm of an off-line password guessing attack 1.

\textbf{Off-linePasswordGuessingAttack1}(IDA, ra, H(h_{pw}, ra), D)
\begin{verbatim}
for i := 0 to |D|
 PW\_\textit{i} \leftarrow D;
 h\_\textit{pw} \leftarrow H(IDA, PW\_\textit{i});
 if H(h_{pw}, ra) = H(h^*_pw, ra) then return PW\_\textit{i}
\end{verbatim}

4.1.2 Off-Line Password Guessing Attack 2

Suppose that $Adv$ has eavesdropped valid messages $AU_A = \{IDA, ra, H(h_{pw}, ra)\}$ and $AU_B = \{rb, H(h_{pw}, ra, rb)\}$ from an open network. Then the off-line password guessing attack 2 proceeds as follows:

(1*) To obtain the password $PW_A$ of user $A$, the adversary $Adv$ makes a guess at the secret password $PW_A$ from dictionary $D$ and computes $h'_{pw} = H(IDA, PW_A)$.

(2*) $Adv$ computes $H(h'_{pw}, ra, rb)$ and checks if $H(h_{pw}, ra, rb) = H(h'_{pw}, ra, rb)$. If it holds true, $Adv$ then can guess the user $A$’s password $PW_A$. Otherwise, $Adv$ repeatedly performs the Steps (1*) and (2*) until $H(h_{pw}, ra, rb) = H(h'_{pw}, ra, rb)$.

The following illustrates the algorithm of an off-line password guessing attack 2.

\textbf{Off-linePasswordGuessingAttack2}(IDA, ra, rb, H(h_{pw}, ra, rb), D)
\begin{verbatim}
for i := 0 to |D|
 PW\_\textit{i} \leftarrow D;
 h\_\textit{pw} \leftarrow H(IDA, PW\_\textit{i});
 if H(h_{pw}, ra, rb) = H(h'_{pw}, ra, rb) then return PW\_\textit{i}
\end{verbatim}

4.1.3 Off-Line Password Guessing Attack 3

Suppose that $Adv$ has eavesdropped valid messages $AU_A = \{IDA, ra, H(h_{pw}, ra)\}$, $AU_B = \{rb, H(h_{pw}, ra, rb)\}$, and $ACK = H(rb \oplus h_{pw})$ from an open network. Then the off-line password guessing attack 3 proceeds as follows:

(1*) To obtain the password $PW_A$ of user $A$, the adversary $Adv$ makes a guess at the secret password $PW_A$ from dictionary $D$ and computes $h'_{pw} = H(IDA, PW_A)$.

(2*) $Adv$ computes $ACK^* = H(rb \oplus h^*_{pw})$ and checks if $ACK = ACK^*$. If it holds true, $Adv$ then can guess the user $A$’s password $PW_A$. Otherwise, $Adv$ repeatedly performs the Steps (1*) and (2*) until $ACK = ACK^*$.

The following illustrates the algorithm of an off-line password guessing attack 3.

\textbf{Off-linePasswordGuessingAttack3}(IDA, rb, ACK, D)
\begin{verbatim}
for i := 0 to |D|
 PW\_\textit{i} \leftarrow D;
 h\_\textit{pw} \leftarrow H(IDA, PW\_\textit{i});
 ACK' = H(rb \oplus h'_{pw});
 if ACK = ACK' then return PW\_\textit{i}
\end{verbatim}

As a result, Guo-Zhang’s protocol is susceptible to the off-line password guessing attacks. In the modern life which the Internet has strong influence to people, passwords are the most common means of user authentication on the Internet. For practical applications, password-based authentication schemes are required when making use of Internet network services like E-learning, on-line polls, on-line ticket-order systems, roll call systems, on-line games, etc. In real applications, users offer the same password as above to access several application servers for their convenience. Thus, the attacker may try to use the password $PW_A^*$ to impersonate the user to login to other systems that the user has registered with outside this authentication server. If the targeted outside server adopts the normal authentication protocol, it is possible that the attacker can successfully impersonate the user to login to it by using the guessed password $PW_A^*$.

4.2 Stolen-Verifier Attacks

In most existing password-based authentication and key agreement protocols, the server stores the user’s verifier (e.g., hashed passwords), rather than the user’s bare password, in order to reduce the security of the breach once the server is compromised. Therefore, servers are always the targets of attacker, because numerous customers’ secrets are stored in their databases. The stolen-verifier attacks [18], [19] mean that an adversary who steals a password-verifier from the server can use it directly to impersonate a legitimate user in a user authentication execution. Note that the main purpose of an authentication and key agreement protocol against the stolen-verifier attacks is to reduce the immediate danger to the authenticate user. In fact, an adversary who has a password-verifier may further mount a guessing attack.

In Guo-Zhang’s protocol, the hash value $h_{pw} = H(IDA, PW_A)$ of the user $A$’s password $PW_A$, which is stored in the server, can be eavesdropped and then used to masquerade as the original user. Guo-Zhang did not explain the stolen-verifier attacks, with regard to obtaining the secret data $h_{pw} = H(IDA, PW_A)$, which is stored in a server. This information can allow an illegitimate user to login to the server as a legitimate user. Suppose an adversary $Adv$ has stolen the hash value $h_{pw} = H(IDA, PW_A)$ from the server $B$ in Guo-Zhang’s protocol. Then, he/she can perform the user $A$ impersonating attack based on the above authentication phase and key agreement phase in the Sects. 3.1 and 3.2. After finishing the phases, $Adv$ and $B$ will compute the same shared secret session key: $sk^* = T_{ps}(ra^*)$, where $r^*$ and $ra^*$ are random numbers chosen by $Adv$. As a result, $Adv$ can continually impersonate the original user $A$ by using $sk^*$ in their subsequent communication.
By using the stolen $h_{pw} = H(ID_A, PW_A)$ and the above stolen-verifier attacks, the adversary $Adv$ can also impersonate the server $B$ in order to cheat the legal user. Therefore, Guo-Zhang’s protocol is not secure against stolen-verifier attacks.

5. Conclusions

This letter pointed out that Guo-Zhang’s group key agreement protocol based on the chaotic hash function is still vulnerable to off-line password guessing attacks and stolen-verifier attacks. As a result, there is no quick tweak that can be applied to make Guo-Zhang’s protocol can withstand both off-line password guessing attacks and stolen-verifier attacks since the user’s password $PW_A$ and the secret data $h_{pw}$ are easily obtained from open transmission channel and target server, respectively.

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