Efficient Password-Authenticated Key Exchange for Three-Party Secure Against Undetectable On-Line Dictionary Attacks^{*}

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Abstract. A password-authenticated key exchange (PAKE) protocol in the three-party setting allows two users communicating over a public network to agree on a common session key by the help of a server. In the setting the users do not share a password between themselves, but only with the server. In this paper, we explore the possibility of designing a round-efficient three-party PAKE protocol with a method to protect against undetectable on-line dictionary attacks without using the random oracle. The protocol matches the most efficient three-party PAKE protocol secure against undetectable on-line dictionary attacks among those found in the literature while providing the same level of security. Finally, we identify the relations between detectable on-line and undetectable on-line dictionary attacks by providing counter-examples to support the observed relations¹.

Keywords: Cryptography, password-authenticated key exchange, dictionary attacks, round complexity, mobile network security.

1 Protocols for PAKE in the Three-Party Setting

We now present our two protocols $3PAKE1$ and $3PAKE2$ for PAKE in the three-party setting. $3PAKE1$ is designated to protect passwords from detectable on-line and off-line dictionary attacks and is explicit authentication. $3PAKE2$ is designated to enhance $3PAKE1$ against undetectable on-line dictionary attacks in addition to detectable on-line and off-line dictionary attacks, yet still requires four rounds and is implicit authentication. In this paper, we assume the parties can transmit messages simultaneously.

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¹ This is a very partial version of the full paper available at <http://cist.korea.ac.kr/pitapat/JeongOkKwonTriS.ps>

3PAKE1

Public information. Two primes p, q such that $p = 2q + 1$, where p is a safe prime such that the decision Diffie-Hellman problem is hard to solve in $\mathbb{G}$. A finite cyclic group $\mathbb{G}$ has order q , and g_1, g_2 are generators of $\mathbb{G}$ both having order q , where g_1 and g_2 must be generated so that their discrete logarithmic relation cannot be known. A hash function H from $\{0, 1\}^*$ to $\{0, 1\}^l$. A message authentication code (MAC), $\text{Mac} = (\text{Mac.gen}, \text{Mac.ver})$. Given a random key k , Mac.gen computes a tag τ for a message M ; we write this as $\tau = \text{Mac.gen}_k(M)$. Mac.ver verifies the message-tag pair using the (shared) key, and returns 1 if the tag is valid or 0 otherwise. F is a pseudo random function family.

Initialization. Each user U_i for $i \in \{1, 2\}$ obtains pw_i at the start of the protocol using a password generation algorithm $\mathcal{PG}(1^k)$ which on input a security parameter 1^k outputs a password pw_i uniformly distributed in a password space **password**. Then U_i sends $v_{i,1} = g_1^{H(U_i \| S \| pw_i)} \bmod p$ and $v_{i,2} = g_2^{H(U_i \| S \| pw_i)} \bmod p$ which are verifiers of the password to the server S over a secure channel. Upon receiving the verifiers, S stores them in a password file with an entry for U_i . The indices are cyclic, i.e., U_{n+1} is U_1 , where $n = 2$.

Round 1. An initiator U_i for $i = 1$ broadcasts (U_i, U_{i+1}, S) .

Round 2. Each user U_i chooses a random number $x_i \in \mathbb{Z}_q^*$, computes $X_{i,S} = g_1^{x_i} \cdot v_{i,2} \bmod p$, and sends $(U_i, X_{i,S})$ to the server.

Round 3. Upon receiving $(U_i, X_{i,S})$, S selects a random number $s \in \mathbb{Z}_q^*$ and computes $X_{S,i} = (X_{i+1,S} / v_{i+1,2})^s \cdot v_{i,2} \bmod p$, and sends $(S, X_{S,i})$ to each user U_i for $i = \{1, 2\}$.

Round 4. Upon receiving $(S, X_{S,i})$, each user U_i computes $k_i = (X_{S,i} / v_{i,2})^{x_i} \bmod p$ and $\tau_i = \text{Mac.gen}_{k_i}(U_i \| U_{i+1} \| S)$ and sends (U_i, τ_i) to U_{i+1} .

Key computation. Upon receiving (U_i, τ_i) , each user U_{i+1} computes $\text{Mac.ver}_{k_{i+1}}(\tau_i)$. Each user U_{i+1} halts if Mac.ver returns 0 or computes the session key $sk_{i+1} = F_{k_{i+1}}(U_1 \| S \| U_2)$ otherwise.

Remark. We have observed that the relations between detectable and undetectable on-line dictionary attacks. This is, the security against detectable on-line dictionary attacks does not necessarily imply the security undetectable on-line dictionary attacks and vice versa. To support the observed relations we consider counter-examples presented in this paper. For the first relation, consider our first protocol 3PAKE1. 3PAKE1 is secure against detectable on-line dictionary attacks but it is insecure against undetectable on-line dictionary attacks. For the second relation, consider our second protocol 3PAKE2. We can modify 3PAKE2 to secure against undetectable on-line dictionary attacks but to insecure against detectable on-line dictionary attacks. If the MAC verification between each user and the server is removed in Round 4 of 3PAKE2, the protocol does not secure against on-line dictionary attacks anymore because the users cannot detect and log the failed guesses. Therefore we must independently consider the both attacks and provide methods to resistant to both attacks when design secure protocol for 3-party PAKE.

3PAKE2

Same as 3PAKE1 except the following points.

Round 2. Each user U_i chooses a random number $x_i \in \mathbb{Z}_q^*$, computes $X_{i,S} = g_1^{x_i} \cdot v_{i,2} \bmod p$, and sends $(U_i, X_{i,S})$ to the server S . For $i = \{1, 2\}$, S chooses random numbers $y_i \in \mathbb{Z}_q^*$, computes $X_{S,i} = g_1^{y_i} \cdot v_{i,2} \bmod p$, and sends $(S, X_{S,i})$.

Round 3. Upon receiving $(S, X_{S,i})$, each user U_i computes $k_{i,S} = (X_{S,i}/v_{i,2})^{x_i} \bmod p$ and $\tau_{i,S} = \text{Mac.gen}_{k_{i,S}}(U_i || S || X_{i,S} || X_{S,i})$ and sends $(U_i, \tau_{i,S})$ to S .

Round 4. Upon receiving $(U_i, \tau_{i,S})$, S computes $\text{Mac.ver}_{k_{S,i}}(\tau_{i,S})$ where $k_{S,i} = (X_{i,S}/v_{i,2})^{y_i} \bmod p$ for $i = \{1, 2\}$. S halts if at least one of $\text{Mac.ver}_{k_{S,i}}$ returns 0 or proceeds to the next process otherwise. S selects a random number $s \in \mathbb{Z}_q^*$, and computes $Y_{S,i} = (g_1^{x_{i+1}})^s$ and $\tau_{S,i} = \text{Mac.gen}_{k_{S,i}}(U_i || U_{i+1} || Y_{S,i})$ and sends $(S, Y_{S,i}, \tau_{S,i})$ to each user U_i .

Key computation. Upon receiving $(S, Y_{S,i}, \tau_{S,i})$, each user U_i computes $\text{Mac.ver}_{k_i}(\tau_{S,i})$. Each user U_i halts if Mac.ver returns 0 or computes the session key $sk_{i+1} = F_{k_{i+1}}(U_1 || S || U_2)$ otherwise, where $k_i = (Y_{S,i})^{x_i} \bmod p$.

SECURITY OF 3PAKE2.

1. 3PAKE2 is secure against *detectable on-line dictionary attacks* since the users are able to detect a failed guess by the MAC verification in Round 4. 3PAKE2 is resistant to *undetectable on-line dictionary attacks* since the server is able to depart honest requests from malicious attempts. If the MAC verification in Round 3 is failed, the server will notice that whose password to being a target of undetectable on-line dictionary attacks and it be at a crisis. After a small amount of failed guesses the server reacts and informs the target user to stop any further use of the password and to change the password into a new one. 3PAKE2 is secure against *off-line dictionary attacks* via the difficulty of the decision DDH problem.
2. **Key secrecy** means that no computationally bounded adversary should learn anything about session keys shared between two honest users. Especially in the 3-party key exchange model existing a server, more desirable security notion is that the participating server should not learn anything about session keys shared between two honest users, additionally. 3PAKE2 provides strong *key secrecy* since passwords are unguessed from dictionary attacks and in order to learn some significant information on session keys, the adversary $\mathcal{A}$ including $\mathcal{S}$ has to solve the DDH problem or break the MAC which is selectively unforgeable against adaptively chosen message attacks.
3. **Forward secrecy** means that even if long-term secret keys of one or more users are compromised, the secrecy of previous session keys established by honest users without any interference by the adversary is not affected. 3PAKE2 provides *forward secrecy* under the DDH assumption. That is, even if the

passwords of users are compromised, any adversary cannot learn any significant information on previously established session keys under the DDH assumption.

4. A protocol is secure against known key attack (or Denning-Sacco attack) if the following conditions hold. First, even with the session key from an eavesdropped session an adversary cannot gain the ability to impersonate the legitimate user directly. Second, an adversary cannot gain the ability to performing off-line dictionary attacks on the users' passwords from using the compromised session keys which are successfully established between honest entities. Third, a legitimate user $\mathcal{U}_i$ knowing pw_i does not learn any information about the partner U_{i+1} 's password pw_{i+1} from the session key established with U_{i+1} . In $3\mathcal{PAKE}2$, the session keys are computationally independent from each other. Thus, a compromised old session key is not helpful for $\mathcal{A}$ in attempting known key attack. To break the second condition $\mathcal{A}$ has to solve the DDH problem. The security on the third condition is also provided under the DDH assumption. That is, to successfully mount an off-line dictionary attack from the session key established with U_{i+1} , $\mathcal{U}_i$ knowing pw_i has to solve the DDH problem, in which one's password pw_i is not helpful in attempting the off-line dictionary attack against pw_{i+1} .

2 Concluding Remarks

In this paper, we have proposed a three-party PAKE protocol secure against detectable/undetectable on-line and off-line dictionary attacks without making use of the random oracle model. However, we only provided informal security analysis. Proving the security of our protocol in the standard model is the subject of ongoing work.