Journal of The Korea Society of Computer and Information
Vol. 17 No. 9, September 2012
www.ksci.re.kr
http://dx.doi.org/10.9708/jksci/2012.17.9.091

Zhao와 Gu가 제안한 키 교환 프로토콜의 안전성 분석

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A Security Analysis of Zhao and Gu's Key Exchange Protocol

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요 약

키 교환 프로토콜은 공개 네트워크상에서 안전한 통신 채널을 구축하는데 필수적인 요소이다. 특히, 패스워드 기반 키 교환 프로토콜에서는 패스워드를 이용하여 사용자 인증이 이루어지며 이를 바탕으로 안전하게 키 교환이 이루어지도록 설계되어야 한다. 그러나 패스워드는 인간이 쉽게 기억할 수 있는 반면에 엔트로피가 낮고 따라서 사전공격에 쉽게 노출될 수 있다. 최근, Zhao와 Gu가 서버의 도움을 필요로 하는 새로운 패스워드 기반 키 교환 프로토콜을 제안하였다. Zhao와 Gu가 제안한 프로토콜은 일회성 비밀키의 노출 상황을 고려하는 공격자 모델에서도 안전성이 증명가능하다고 주장하였다. 본 논문에서는 Zhao와 Gu의 프로토콜에 대한 재전송 공격을 통하여 이 프로토콜이 저자들의 주장과 달리 일회성 비밀키의 노출 시에 안전하지 않다는 것을 보일 것이다. 본 연구 결과는 Zhao와 Gu가 제시한 안전성 증명이 성립하지 않음을 의미한다.

▸ Keywords : 안전성, 키 교환 프로토콜, 패스워드, 공격

Abstract

Key exchange protocols are essential for building a secure communication channel over an insecure open network. In particular, password-based key exchange protocols are designed to work when user authentication is done via the use of passwords. But, passwords are easy for human beings to remember, but are low entropy and thus are subject to dictionary attacks. Recently, Zhao

• 제1저자 : 남정현 • 교신저자 : 원동호
• 투고일 : 2012. 07. 05, 심사일 : 2012. 08. 02, 게재확정일 : 2012. 09. 03.
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※ This paper was written as part of Konkuk University's research support program for its faculty on sabbatical leave in 2012.

and Gu proposed a new server-aided protocol for password-based key exchange. Zhao and Gu's protocol was claimed to be provably secure in a formal adversarial model which captures the notion of leakage of ephemeral secret keys. In this paper, we mount a replay attack on Zhao and Gu's protocol and thereby show that unlike the claim of provable security, the protocol is not secure against leakage of ephemeral secret keys. Our result implies that Zhao and Gu's proof of security for the protocol is invalid.

▸ Keywords : Security, Key exchange protocol, Password, Attack

I. Introduction

Key exchange protocols are designed to allow two or more parties to establish a common secret key over a public network. This secret key, commonly called a session key, is then typically used to build confidential or integrity-protected communication channel between the parties. The highest priority in designing a key exchange protocol is placed on ensuring the security of session keys to be established by the protocol. Roughly speaking, establishing a session key securely means that the key is being known only to the intended parties at the end of the protocol run. But unfortunately, the experience has shown that the design of secure key exchange protocols is notoriously difficult. Thus, key exchange protocols must be subjected to a thorough and systematic scrutiny before they are deployed into a public network, which might be controlled by an adversary.

Secure session-key generation requires an authentication mechanism to be integrated into key exchange protocols. In turn, achieving any form of authentication inevitably requires some secret information to be established between users in advance of the authentication stage. Cryptographic keys, either secret keys for symmetric cryptography or private/public keys for asymmetric cryptography, may be one form of the underlying secret information pre-established between users. However, these high-entropy cryptographic keys are random in appearance and thus are difficult for humans to remember, entailing a significant amount of administrative work and costs. Eventually, it is this drawback that password-based authentication has come to be widely used in reality. Passwords are drawn from a relatively small space like a dictionary, and are easier for humans to remember than cryptographic keys with high entropy.

Bellovin and Merritt [1] was the first to consider how two parties, who only share a weak, low-entropy password, and who are communicating over a public network, authenticate each other and agree on a high-entropy cryptographic key to be used for protecting their subsequent communication. Their protocol, known as encrypted key exchange, or EKE, was a great success in showing how one can exchange password authenticated information while protecting poorly-chosen passwords from the notorious password guessing attacks. Due in large part to the practical significance of password-based authentication, this initial work has been followed by a number of two-party protocols (e.g., [2][3][4][5][6][7]) offering various levels of security and complexity.

While two-party protocols for password-authenticated key exchange (PAKE) are well suited for client-server architectures, they are inconvenient and costly for use in large scale peer-to-peer systems. Since two-party PAKE protocols require each pair of potential communication parties to share a password, a large number of parties result in an even larger number of passwords to be shared. It is due to this problem that three-party models have been often used in

A, B : The clients
S : The authentication server
$ID_2 \stackrel{\text{def}}{=} ID_A, ID_B$
$ID_3 \stackrel{\text{def}}{=} ID_A, ID_B, ID_S$

A		S		B
$a_1, a_2 \in \mathbb{Z}_q^*$				$b_1, b_2 \in \mathbb{Z}_q^*$
$A_1 = g^{a_1}, A_2 = g^{a_2}$				$B_1 = g^{b_1}, B_2 = g^{b_2}$
$x = H_1(PW_A, a_1, a_2), X = g^x$				$y = H_1(PW_B, b_1, b_2), Y = g^y$
$k_A = H_2(R^{a_1}, R^{a_2}, X, PW_A, ID_2)$				$k_B = H_2(R^{b_1}, R^{b_2}, Y, PW_B, ID_2)$
$c_A = \mathsf{Enc}_{k_A}(PW_A, \omega_A)$				$c_B = \mathsf{Enc}_{k_B}(PW_B, \omega_B)$
$M_A = \langle X, A_1, A_2, c_A, \omega_A, ID_2 \rangle$				$M_B = \langle Y, B_1, B_2, c_B, \omega_B, ID_2 \rangle$
	$M_A \longrightarrow$		$\longleftarrow M_B$	
$k'_A = H_2(A_1^r, A_2^r, X, PW_A, ID_2)$				$k'_B = H_2(B_1^r, B_2^r, Y, PW_B, ID_2)$
$(PW'_A, \omega'_A) = \mathsf{Dec}_{k'_A}(c_A)$				$(PW'_B, \omega'_B) = \mathsf{Dec}_{k'_B}(c_B)$
$PW'_A \stackrel{?}{=} PW_A, PW'_B \stackrel{?}{=} PW_B$				
$V_A = H_2(k'_B, \omega_{SA}, X, A_1, A_2, ID_3)$				
$V_B = H_2(k'_A, \omega_{SB}, Y, B_1, B_2, ID_3)$				
$M_{SA} = \langle Y, B_1, B_2, V_B, \omega_{SB}, ID_S \rangle$				
$M_{SB} = \langle X, A_1, A_2, V_A, \omega_{SA}, ID_S \rangle$				
	$\longleftarrow M_{SA}$		$M_{SB} \longrightarrow$	
$V_B \stackrel{?}{=} H_2(k_A, \omega_{SB}, Y, B_1, B_2, ID_3)$				$V_A \stackrel{?}{=} H_2(k_B, \omega_{SA}, X, A_1, A_2, ID_3)$
$sid = (X, Y, A_1, A_2, B_1, B_2, ID_3)$				$sid = (X, Y, A_1, A_2, B_1, B_2, ID_3)$
$Z_1 = (YB_1)^x, Z_2 = (YB_2)^x$				$Z_1 = (X)^{y+b_1}, Z_2 = (X)^{y+b_2}$
$Z_3 = Y^{x+a_1}, Z_4 = Y^{x+a_2}$				$Z_3 = (XA_1)^y, Z_4 = (XA_2)^y$
$SK = H(Z_1, Z_2, Z_3, Z_4, sid)$				$SK = H(Z_1, Z_2, Z_3, Z_4, sid)$

Fig. 1. Zhao and Gu's Three-Party PAKE Protocol

designing PAKE protocols (e.g., [8][9][10][11][12]). In a typical three-party setting, each party (often called client) does not need to remember and manage multiple passwords, but shares only a single password with a trusted server who then assists clients in establishing a session key by providing authentication services to them. However, this convenience comes at the price of clients' trust in the server. Despite this drawback, the three-party model offers an effective, realistic solution to the problem of session key exchange in large peer-to-peer systems, and in fact is assumed by the popular Kerberos authentication system [13].

Recently, Zhao and Gu [14] proposed a three-party PAKE protocol making use of the trapdoor test technique introduced by Cash, Kiltz, and Shoup [15]. Zhao and Gu's protocol was claimed to be provably secure under the assumption that the hash functions used in the protocol are random oracles. The adversarial model, where security of the protocol is proven, captures the notion of strong corruption by allowing the adversary to ask EphemeralKeyReveal queries. An EphemeralKeyReveal query against a user instance outputs all the ephemeral secrets used by the instance during the protocol execution. Allowing an adversary to ask EphemeralKeyReveal queries models the adversary's capability to embed a Trojan horse or other form of malicious code into a user's machine and then obtain all the session-specific information of the victim. Since Zhao and Gu's protocol is proven secure in a model that allows EphemeralKeyReveal queries, it should be secure against strong corruption. But what we found is the opposite: Zhao and Gu's protocol does not exhibit resistance against strong corruption. Indeed, Zhao and Gu's protocol is vulnerable to a replay attack where the adversary asks an EphemeralKeyReveal query in its attack. We here reveal this security vulnerability of Zhao and Gu's protocol. Our result invalidates the claimed proof of security for the protocol.

II. Review of Zhao and Gu's Protocol

This section describes the three-party PAKE protocol proposed by Zhao and Gu [14]. The protocol participants consist of a single server S and two clients A and B. The clients A and B wish to establish a session key between them while the server S exists to provide the clients with authentication services. We denote by ID_A, ID_B and ID_S the identities of A, B and S, respectively. Let PW_A and PW_B be the passwords of A and B, respectively. Each client's password is assumed to be shared with the authentication server S via a secure channel. The followings are the public system parameters used in the protocol.

Two large primes p and q with $q|(p-1)$, and a generator g of group G of order q.

A pair of symmetric encryption/decryption algorithms (Enc, Dec) modeled as an ideal cipher [2].

Three hash functions H_1, H_2 and H modeled as random oracles [16]. H_1 and H_2 map $\{0,1\}^*$ to Z_q^* while H maps $\{0,1\}^*$ to $\{0,1\}^\lambda$, where λ is a security parameter representing the length of session keys.

Once p, q and g are fixed, the server S generates its long-term private/public keys (r,R) such that $r \in Z_q^*$ and $R = g^r \bmod p$. A high-level depiction of the protocol is given in Fig. 1, and a more detailed description follows:

Client A chooses random $a_1, a_2 \in Z_q^*$ and computes $A_1 = g^{a_1}$ and $A_2 = g^{a_2}$. Then A verifies if R lies in G. If not, A aborts. Otherwise, A computes $x = H_1(PW_A, a_1, a_2)$, $X = g^x$, $k_A = H_2(R^{a_1}, R^{a_2}, X, PW_A, ID_A, ID_B)$, and $c_A = Enc_{k_A}(PW_A, \omega_A)$, where ω_A is a random value. Finally, A deletes the ephemeral secret x and sends $M_A = \langle X, A_1, A_2,$

$c_A, \omega_A, ID_A, ID_B\rangle$ to S.

Similarly, B chooses random $b_1, b_2 \in Z_q^*$ and computes $B_1 = g^{b_1}$ and $B_2 = g^{b_2}$. Then B verifies if R lies in G. If not, B aborts. Otherwise, B computes $y = H_1(PW_B, b_1, b_2)$, $Y = g^y$, $k_B = H_2(R^{b_1}, R^{b_2}, Y, PW_B, ID_A, ID_B)$ and $c_B = Enc_{k_B}(PW_B, \omega_B)$, where ω_B is a random value. Finally, B deletes y and sends $M_B = \langle Y, B_1, B_2, c_B, \omega_B, ID_A, ID_B\rangle$ to S.

Upon receiving M_A and M_B, the server S verifies if all of X, A_1, A_2, Y, B_1 and B_2 lie in G. If not, S aborts. Otherwise, S computes $k'_A = H_2(A_1^r, A_2^r, XPW_A, ID_A, ID_B)$ and $k'_B = H_2(B_1^r, B_2^r, Y, PW_B, ID_A, ID_B)$ by using its private key r. Then S performs the decryptions $(PW'_A, \omega'_A) = Dec_{k'_A}(c_A)$ and $(PW'_B, \omega'_B) = Dec_{k'_B}(c_B)$ and verifies that $PW'_A = ?PW_A$ and $PW'_B = ?PW_B$. If $PW'_A \neq PW_A$ or $PW'_B \neq PW_B$, then S aborts. Otherwise, S computes $V_A = H_2(k'_B, \omega_{SA}, X, A_1, A_2, ID_A, ID_B, ID_S)$ and sends $M_{SB} = \langle X, A_1, A_2, V_A, \omega_{SA}, ID_S\rangle$ to B, where ω_{SA} is a random value chosen by S. Similarly, S computes $V_B = H_2(k'_A, \omega_{SB}, Y, B_1, B_2, ID_A, ID_B, ID_S)$ and sends $M_{SA} = \langle Y, B_1, B_2, V_B, \omega_{SB}, ID_S\rangle$ to A, where ω_{SB} is a random value chosen by S. At last, S deletes the session-specific information: k'_A, k'_B, PW'_A, PW'_B.

After receiving M_{SA}, A checks if (1) Y, B_1 and B_2 lie in G and (2) $V_B = ?H_2(k_A, \omega_{SB}, Y, B_1, B_2, ID_A, ID_B, ID_S)$. If any of these are untrue, A aborts. Otherwise, A computes $x = H_1(PW_A, a_1, a_2)$, $Z_1 = (YB_1)^x$, $Z_2 = (YB_2)^x$, $Z_3 = Y^{x+a_1}$ and $Z_4 = Y^{x+a_2}$. Finally, A defines the session ID $sid = (X, Y, A_1, A_2, B_1, B_2, ID_A, ID_B, ID_S)$ and computes the session key $SK = H(Z_1, Z_2, Z_3, Z_4, sid)$.

Similarly, on receiving M_{SB}, B checks if (1) X, A_1 and A_2 lie in G and (2) $V_A = H_2(k_B, \omega_{SA}, X, A_1, A_2, ID_A, ID_B, ID_S)$. If any of these are untrue, B aborts. Otherwise, B computes $y = H_1(PW_B, b_1, b_2)$, $Z_1 = X^{y+b_1}$, $Z_2 = X^{y+b_2}$, $Z_3 = (XA_1)^y$ and $Z_4 = (XA_2)^y$. Finally, B defines the session ID $sid = (X, Y, A_1, A_2, B_1, B_2, ID_A, ID_B, ID_S)$ and computes the session key $SK = H(Z_1, Z_2, Z_3, Z_4, sid)$.

III. Adversarial Model

Zhao and Gu's protocol comes along with a claimed proof of its security in a formal model of adversarial capabilities. The adversarial model that they used is the one of Yoneyama [12] and captures security against strong corruption [2][17][18]. Here we provide an overview of the adversarial model as a preliminary step towards mounting an ephemeral-key reveal attack against the protocol.

1. Participants

Each participant U in a three-party key exchange is either a client C or the trusted server S. Each U may run the protocol multiple times either serially or concurrently, with possibly different participants. Thus, at a given time, there could be many instances of a single client and the server. Π_U^i denotes instance i of a participant U. An instance Π_U^i is said to accept when it computes a valid session key SK_U^i. During the initialization phase of the protocol, the server S generates its long-term private/public key pair (r, $R = g^r$) and each client C chooses a password PW_C as their long-term secret key and shares it with S.

Passwords are drawn from a dictionary D.

2. Adversary

The adversary is in complete control of every aspect of all communications between participants, and may ask, at any time, them to open up access to their long-term secret keys. These capabilities and others of the adversary are modeled via various oracles to which the adversary is allowed to make queries.

Execute(Π_C^i, $\Pi_{C'}^j$, Π_S^k): This query prompts an honest execution of the protocol among the client instances Π_C^i and $\Pi_{C'}^j$ and the server instance Π_S^k. The transcript of the honest execution is returned to the adversary as the output of the query. This oracle call represents passive eavesdropping of a protocol execution.

SendClient(Π_C^i, msg): This query sends message msg to the client instance Π_C^i. The instance Π_C^i proceeds as it would in the protocol upon receiving msg. The response message generated by Π_C^i, if any, is the output of this query and is returned to the adversary. A query of the form SendClient(Π_C^i, start:C') prompts Π_C^i to initiate the protocol with a client C' ($\neq C$).

SendServer(Π_S^i, msg): This query sends message msg to the server instance Π_S^i. The instance Π_S^i proceeds as it would in the protocol upon receiving msg. The response message generated by Π_S^i, if any, is the output of this query and is returned to the adversary.

Long-termKeyReveal(U): This query outputs the long-term secret key of U. This oracle call captures the idea that damage due to loss of U's long-term key should be restricted to those sessions where U will participate in the future.

EphemeralKeyReveal(Π_U^i): This query returns all short-term secrets used by instance Π_U^i. This models the adversary's capability to embed a Trojan horse or other form of malicious code into a user's machine and then obtain all the session-specific information of the victim.

SessionKeyReveal(Π_C^i): This query returns the session key SK_C^i held by instance Π_C^i, modeling leakage of session keys. This oracle call captures the idea that exposure of some session keys should not affect the security of other session keys.

EstablishParty(C, S, PW_C): This query models the adversary to register a password PW_C on behalf of a client C. In this way the adversary totally controls that client. Clients against whom the adversary did not issue this query are called honest.

Test(Π_C^i): This query provides a means of defining security of session keys. The output of this query depends on the hidden bit b chosen uniformly at random from $\{0,1\}$. The Test oracle returns the real session key held by Π_C^i if $b=1$, or returns a random key drawn from the session-key space if $b=0$. The adversary is allowed to access the Test oracle only once.

TestPassword(C, PW'_C): This query provides a means of defining security of passwords. If the password guess PW'_C is the same as the client C's real password PW_C, then return 1. Otherwise, return 0. The adversary can make TestPassword query only once.

3. Partnership

Loosely stated, two instances are partners of each other if they participate together in a protocol execution and share a session key as a result of the execution. The notion of partners is used in the definition of security to disallow the adversary to

ask the Test query against an instance whose partner instance has already been asked for the session key (with a SessionKeyReveal query), ephemeral keys (with an EphemeralKeyReveal query), or long-term keys (with a Long-termKeyReveal query). It is thus important to define partnership correctly. An error in the partnership definition may render a protocol insecure (in the proof model used) when there is no known attack on the protocol (for a concrete example, see the work by Choo et al. [19]).

Let the session identifier (sid) of an instance be a function of the messages sent and received by the instance during its execution. Zhao and Gu follow the recent practice of relying on the notion of sids to define partnership between instances. According to their definition of partnership, two instances Π_C^i and $\Pi_{C'}^j$ (with $C \neq C'$) are said to be partnered if the following conditions hold: (1) both Π_C^i and $\Pi_{C'}^j$ have accepted, (2) Π_C^i and $\Pi_{C'}^j$ have computed the same sid, (3) the partner identifier for Π_C^i is $\Pi_{C'}^j$ and vice versa, and (4) no instance besides Π_C^i and $\Pi_{C'}^j$ has accepted with a partner identifier equal to Π_C^i and $\Pi_{C'}^j$. When an instance Π_C^i accepts, it holds a session key, a session identifier, and a partner identifier.

4. Security Definition

Definition of security is based on the notion of freshness. Intuitively, a fresh instance is an instance which holds a session key about which the adversary should not know. More precisely:

Definition 1 (freshness). Let Π_C^i be an instance who has accepted and let $\Pi_{C'}^j$ be Π_C^i's partner instance (if it exists). An instance Π_C^i is considered fresh if none of the following conditions hold:

The adversary reveals the session key of the instance Π_C^i or its partner instance $\Pi_{C'}^j$.

The adversary asks neither SendClient(Π_C^i, msg) nor SendClient($\Pi_{C'}^j$, msg') query. Then the adversary either makes queries:

EphemeralKeyReveal(Π_C^i) or

EphemeralKeyReveal($\Pi_{C'}^j$)

The adversary asks SendClient($\Pi_{C'}^j$, msg') query. Then the adversary either makes queries:

Long-termKeyReveal(C),

Long-termKeyReveal(S),

EphemeralKeyReveal(Π_C^l) for any session l or

EphemeralKeyReveal($\Pi_{C'}^j$).

The adversary asks SendClient(Π_C^i, msg) query. Then the adversary either makes queries:

Long-termKeyReveal(C'),

Long-termKeyReveal(S),

EphemeralKeyReveal(Π_C^i) or

EphemeralKeyReveal($\Pi_{C'}^l$) for any session l.

In this definition of freshness, all the queries for $\Pi_{C'}^j$ are defined if $\Pi_{C'}^j$ exists.

The security of a protocol π against an adversary C is defined in terms of the probability that C succeeds in distinguishing a real session key established in an execution of π from a random session key. That is, the adversary C is considered successful in attacking π if it breaks the semantic security of session keys generated by π. More precisely, the security is defined in the following context. The adversary C executes the protocol exploiting as much parallelism as possible and asking any queries allowed in the adversarial model. During executions of the protocol, the adversary C, at any time, asks a Test query to a fresh instance, gets back a key as the response to this query, and at some later point in time, outputs a bit b' as a guess for the value of the hidden bit b used by the Test oracle. Then the advantage of C in attacking protocol

π is denoted by $Adv_{\pi}(C)$, and is defined as $Adv_{\pi}(C) = |2\Pr[b = b'] - 1|$.

Let $Adv_{\pi}(t, Q)$ denote the maximum value of $Adv_{\pi}(C)$ over all C with time complexity at most t and asking at most Q queries. Then, protocol π is said to be AKE-secure if $Adv_{\pi}(t, Q)$ is only negligibly larger than $nq_{send}/|D|$, where n is a constant and q_{send} is the number of SendClient/ SendServer queries. This notion of security is commonly termed as "AKE security".

IV. Breaking AKE Security

In this section, we break the AKE security of Zhao and Gu's key exchange protocol. The security model described in the previous section allows the adversary to ask EphemeralKeyReveal queries. The EphemeralKeyReveal oracle is allowed to check that the protocol is secure against strong corruption. In other words, the EphemeralKeyReveal oracle call captures the idea that exposure of ephemeral secrets of a session should not affect the security of other sessions. Hence, a key exchange protocol proven secure in a model that allows EphemeralKeyReveal queries ought to be secure against an adversary who tries to break the security of a session by exploiting ephemeral secrets obtained from some other sessions. Zhao and Gu's protocol carries a claimed proof of its AKE security, but as we will see below, it does not provide security against strong corruption. This implies that their security proof is flawed.

The vulnerability of Zhao and Gu's protocol against strong corruption is attributed to the fact that clients' messages $M_A = \langle X, A_1, A_2, c_A, \omega_A, ID_A, ID_B \rangle$ and $M_B = \langle Y, B_1, B_2, c_B, \omega_B, ID_A, ID_B \rangle$ can replayed without being detected by the server. Our attack starts from this observation. Let SES be an honest protocol session where A and B established a session key as per protocol specification. Suppose now that a malicious adversary C eavesdropped the message M_B sent by B to S in the protocol session SES. Suppose also that the adversary C obtained the ephemeral secrets – y, b_1 and b_2 – which B used in the session SES. As also stated in the definition of EphemeralKeyReveal oracle, this leakage of the ephemeral secrets can be justified under the assumption that C has the capability to embed a Trojan horse or other form of malicious code into B's machine and then log

Table 1. The Sequence of Oracle Queries

	Query	Response
1	Execute(Π_A^1, Π_B^1, Π_S^1)	Transcript: M_A, M_B, M_{SA}, M_{SB}
2	EphemeralKeyReveal(Π_B^1)	$\langle b_1, b_2, y, k_B \rangle$
3	SendClient(Π_A^2, start:B)	$M'_A = \langle X', A'_1, A'_2, c'_A, \omega'_A, ID_A, ID_B \rangle$
4	SendServer(Π_S^2, M'_A)	
5	SendServer(Π_S^2, M_B)	$M_{SA} = \langle Y, B_1, B_2, V'_B, \omega'_{SB}, ID_S \rangle$
		$M_{SB} = \langle X', A'_1, A'_2, V'_A, \omega'_{SA}, ID_S \rangle$
6	SendClient(Π_A^2, M_{SA})	(accept)
7	Test(Π_A^2)	SK_A^2 or a random key

all the session-specific information of B. With y, b_1 and b_2 in hand, C can easily impersonate B to A as follows:

C initiates a new session with A as if the initiation message is from B.

Next, C sends the message $M_B = \langle Y, B_1, B_2, c_B, \omega_B, ID_A, ID_B \rangle$ (eavesdropped in the previous session SES) to S alleging that the message is from B.

C then intercepts the message sent by S to B for this new session.

Finally, using y, b_1 and b_2, the adversary C computes the same session key as that of A.

This allows C to impersonate B to A.

The above attack on Zhao and Gu's protocol is well captured in the adversarial model. Let again A and B denote two registered clients and M also be any registered client other than A and B. Table 1 shows the sequence of oracle queries corresponding to the attack scenario described above. The goal of the adversary C is to break the AKE security of Zhao and Gu's protocol. C begins by letting A and B execute the protocol together by asking Execute (Π_A^1, Π_B^1, Π_S^1). As a result, C obtains the message $M_B = \langle Y, B_1, B_2, c_B, \omega_B, ID_A, ID_B \rangle$ from B to S. Then C asks EphemeralKeyReveal(Π_B^1) to obtain all the ephemeral secrets $\langle b_1, b_2, y, k_B \rangle$ used by instance Π_B^1. Now C asks SendClient (Π_A^2, start:B) which prompts instance Π_A^2 to initiate the protocol with client B. In response to this query, Π_A^2 will output the message $M'_A = \langle X', A'_1, A'_2, c'_A, \omega'_A, ID_A, ID_B \rangle$. The next queries C makes correspond to an honest execution of the protocol among Π_A^2, Π_B^2 (impersonated by C) and Π_S^2. Hence, the rest of the queries are straightforward: C asks SendServer(Π_S^2, $\langle X', A'_1, A'_2, c'_A, \omega'_A, ID_A, ID_B \rangle$) and SendServer($\Pi_S^2$, $\langle Y, B_1, B_2, c_B, \omega_B, ID_A, ID_B \rangle$), and then, as Π_S^2 responds to the queries, asks SendClient(Π_A^2, $M_{SA} = \langle Y, B_1, B_2, V'_B, \omega'_{SB}, ID_S \rangle$). Notice that C replays the message M_B obtained from Π_B^1. When Π_A^2 is sent the query SendClient (Π_A^2, $\langle Y, B_1, B_2, V'_B, \omega'_{SB}, ID_S \rangle$), it accepts with the session key SK_A^2 being computed as $SK_A^2 = H(Z_1, Z_2, Z_3, Z_4, sid)$, where $Z_1 = (YB_1)^{x'}$, $Z_2 = (YB_2)^{x'}$, $Z_3 = Y^{x' + a'_1}$ and $Z_4 = Y^{x' + a'_2}$. It can be easily verified that the instance Π_A^2 is fresh under Definition 1; (1) no one in $\{A, B, S\}$ has been sent a Corrupt query, (2) no Reveal query has been made against any instance, and (3) the query EphemeralKeyReveal(Π_B^1) has been asked before the SendClient queries to Π_A^2 have been asked. Thus, C may test (i.e., ask the Test query against) the instance Π_A^2. C is able to compute SK_A^2 on its own since it knows the values of the exponents b_1, b_2, y used to compute B_1, B_2 and Y. This means that $\Pr[b = b'] = 1$ and hence $Adv_\pi(C) = 1$. Therefore, C achieves its goal of breaking the AKE security of Zhao and Gu's protocol.

Generally speaking, it is desirable that ephemeral secrets exposed in a session should not jeopardize the session-key secrecy of any other sessions. For this reason, key exchange protocols proven AKE-secure in a model that allows strong corruption ought to be resistant against any attacks similar to ours. Our attack shows that the proof of security for Zhao and Gu's protocol is invalid. The problem with the proof is that the result of EphemeralKeyReveal queries was not adequately considered in the simulation.

V. Conclusion

This work has considered the security of Zhao and Gu's three-party protocol [14] for password authenticated key exchange. Although Zhao and Gu's protocol comes along with a claimed proof of its security, we have shown that the protocol is not secure against strong corruption in the context of the proof model. This vulnerability, however, is not just a failure of Zhao and Gu's protocol but it is an inherent limitation of all three-party protocols that do not require the server to verify the freshness of incoming messages. Thus, there is no quick tweak we can apply to make Zhao and Gu's protocol resistant to strong corruption. Moreover, it is not clear how to make the protocol achieve any form of provable security.

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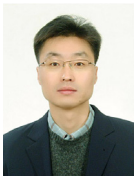

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