

## Cryptanalysis of Two Password-Authenticated Key Exchange Protocols between Clients with Different Passwords

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### Abstract

In large-scale client-client communication environments, Password-Authenticated Key Exchange (PAKE) based on trusted server is very convenient in key management. For enhancing the efficiency and preventing various attacks, Wang and Mo proposed a three-PAKE protocol, Yoon and Yoo proposed a C2C-PAKE protocol. However, in this paper, we show that the Wang-Mo protocol and the Yoon-Yoo protocol exist impersonation attack.

**Keywords:** Information security; password; authentication; cryptanalysis

### 1. Introduction

Password-Authenticated Key Exchange (PAKE) enables two communication entities to authenticate each other and establish a session key via easily memorable passwords. The first PAKE protocol was introduced by Bellare and Merritt in 1992 [1] known as Encrypted Key Exchange (EKE).

Two-party password-based authenticated key exchange (two-PAKE) protocol is quite useful for client-server architectures. However, in large-scale client-client communication environments where a user wants to communicate with many other users, Two-PAKE protocol is very inconvenient in key management that the number of passwords that the user would need to remember. Gong, Lomas, Needham, and Saltzer [3] proposed a three-party password-based key transfer protocol using server's public key. Later, Steiner, Tsudik and Waider [7] proposed a three-party PAKE (three-PAKE) protocol between two clients without server's

public key. Recently, Lee et al. [5] proposed an efficient three-PAKE protocol. Wang and Mo [8] show that Lee et al.'s protocol is vulnerable to the impersonation attack. Wang and Mo also proposed an improved method to withstand this attack.

To provide a cross-realm authentication, where clients from one environment (realm) wish to communicate with clients from other realms, Byun et al.[2] presented a Client-to-Client Password-Authenticated Key Exchange (C2C-PAKE) protocol. Kim et al. [4] showed that the C2C-PAKE scheme is vulnerable to a Denning-Sacco-style attack where the attacker is an insider with knowledge of the password of a client in a different realm. Kim et al. also proposed an improved C2C-PAKE protocol. Recently, Yoon and Yoo [9] demonstrated that Kim et al.'s C2C-PAKE protocol is vulnerable to one-way man-in-the-middle attack and password-compromise impersonation attack. Yoon and Yoo also presented an enhancement to resolve these problems.

In this paper, we show that the Wang-Mo protocol and the Yoon-Yoo protocol exist impersonation attack.

## 2. Cryptanalysis of Wang and Mo's Three -PAKE Protocol

### 2.1 Review of the Wang-Mo Protocol

Wang and Mo show that once Alice's verifier has stolen by the attacker Eve, the attacker Eve can impersonate Bob to communicate with Alice in Lee et al.'s protocol. To withstand this attack, Wang and Mo proposed an improved protocol.

Let  $p$  and  $q$  be two large prime integers such that  $q|p-1$  and  $g$  be a generator with order  $q$  in  $Z_p^*$ .  $pwa$ ,  $pwb$  are Alice and Bob's passwords.  $H$  is a secure one-way hash function. Before the running of the protocol, Alice and Bob send their verifiers  $v_A$  and  $v_B$  to authentication server AS through a secure channel where  $v_A = g^{H(A, S, pwa)}$  and  $v_B = g^{H(B, S, pwb)}$ . AS stores  $v_A$  and  $v_B$  in a password table. We omit 'mod  $p$ ' from expressions for simplicity.

(1) Alice chooses  $a \in_R Z_p^*$ , and computes  $X_A = g^a$ . Then, she sends the identity  $A$  and  $g^a$  to Bob.

(2) Bob chooses  $b \in_R Z_p^*$ , and computes  $X_B = g^b$ . Then, he sends  $X_B$  and  $(A, X_A, B, X_B)$  to Alice and AS, respectively.

(3) After receiving the messages, AS retrieves  $v_A$  and  $v_B$  from password table. Then AS computes  $X_{SA} = (v_A)^c \oplus v_A$  and  $X_{SB} = (v_B)^d \oplus v_B$ , where  $c$  and  $d \in_R Z_p^*$ . AS sends  $X_{SA}$  and  $X_{SB}$  to Alice and Bob respectively. Finally, AS computes  $K_{SA} = (X_A)^c = g^{ac}$  and  $K_{SB} = (X_B)^d = g^{bd}$ .

(4) Alice computes  $K_{AS} = (X_{SA} \oplus v_A)^{t_A^{-1}a} = g^{ac}$  and  $v_{AS} = H(A, B, S, X_A, X_B, g^c, K_{AS})$ . Alice sends  $v_{AS}$  to AS. Similarly, Bob computes  $K_{BS} = (X_{SB} \oplus v_B)^{t_B^{-1}b} = g^{ad}$  and  $v_{BS} = H(B, A, S, X_B, X_A, g^d, K_{BS})$ . Bob sends  $v_{BS}$  to AS. Note that  $t_A = H(A, S, pwa)$  and  $t_B = H(B, S, pwb)$ .

(5) AS verifies whether  $v_{AS}$  and  $v_{BS}$  are true or not. If they are true, AS sends  $v_{SA}$  and  $v_{SB}$  to Alice and Bob respectively, where  $v_{SA} = H(S, A, B, X_A, X_B, K_{SA})$  and  $v_{SB} = H(S, B, A, X_B, X_A, K_{SB})$ .

(6) Alice and Bob verify whether  $v_{SA}$  and  $v_{SB}$  are true or not respectively. If they are true, Alice computes  $K_{AB} = (X_B)^a = g^{ba}$  and Bob computes  $K_{BA} = (X_A)^b = g^{ab}$ . Finally, Alice and Bob negotiate a common session key  $K = H(A, B, S, K_{AB}) = H(A, B, S, K_{BA})$ . We use figure 1 to introduce Wang and Mo's protocol.

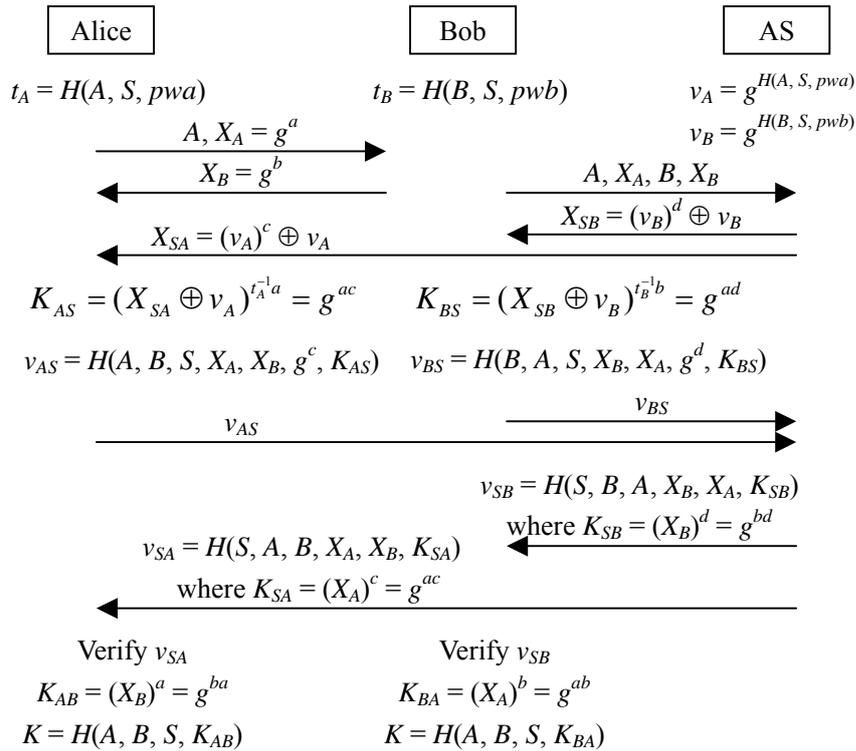


Fig.1 The Wang-Mo Protocol

## 2.2 Cryptanalysis

We show that the Wang-Mo Protocol exists the impersonation attack (see Figure 2). Once Alice's verifier  $v_A$  has stolen by the attacker. The attacker can impersonate Bob to communicate with Alice by performing the following steps.

(1)\* When Alice wants to communicate with Bob. Alice sends the identity  $A$  and  $X_A = g^a$  to Bob. Eve intercepts it.

(2)\* Eve chooses a random number  $b \in_R Z_p^*$  and sends  $X_B = g^b$  to Alice.

(3)\* Eve chooses a random number  $c \in_R Z_p^*$  and sends  $X_{SA} = (v_A)^c \oplus v_A$  to Alice.

(4)\* Alice computes  $K_{AS} = (X_{SA} \oplus v_A)^{t_A^{-1}a} = g^{ac}$  and  $v_{AS} = H(A, B, S, X_A, X_B, g^c, K_{AS})$ . Alice sends  $v_{AS}$  to AS. Eve intercepts it.

(5)\* Eve sends  $v_{SA} = H(S, A, B, X_A, X_B, K_{SA})$  to Alice, where  $K_{SA} = (X_A)^c = g^{ac}$ .

(6)\* Alice verifies  $v_{SA}$ . Alice computes  $K_{AB} = (X_B)^a = g^{ba}$  and Eve computes  $K_{BA} = (X_A)^b = g^{ab}$ . In the end, Eve would successfully authenticate itself to Alice as Bob, and also share a secret session key  $K = H(A, B, S, K_{AB}) = H(A, B, S, K_{BA})$  with Alice.

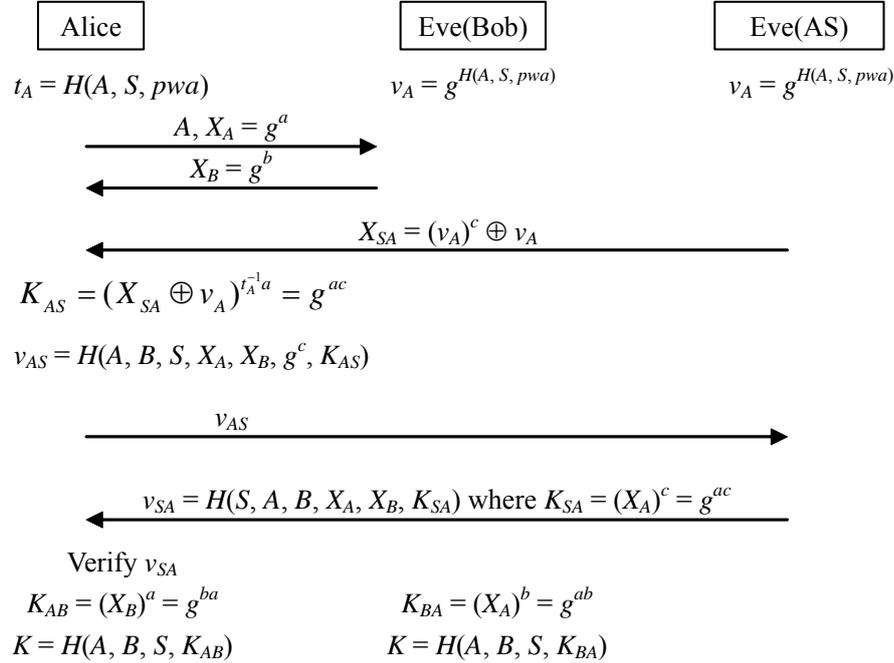


Fig.2 Impersonation attack in the Wang-Mo protocol

### 3. Cryptanalysis of Yoon and Yoo's C2C-PAKE Protocol

#### 3.1 Review of the Yoon-Yoo Protocol

Yoon and Yoo [9] demonstrated that Kim et al.'s C2C-PAKE protocol [4] is vulnerable to one-way man-in-the-middle attack and password-compromise impersonation attack. They proposed an improved protocol (see Figure 3).

Let  $KDC_A, KDC_B$  are two key distribution centers which store  $A, pwa, B, pwb$ .  $E_X$  is a symmetric encryption with secret value  $X$ .  $K$  is the symmetric secret key shared between  $KDC_A$  and  $KDC_B$ .  $Ticket_B$  is Kerberos ticket issued to Alice for service from Bob.  $L$  is a lifetime of  $Ticket_B$ .

The Yoon-Yoo's C2C-PAKE protocol involves the following steps.

(1) Alice chooses  $x \in_R Z_p^*$ , and computes  $g^x$  and  $M_1 = E_{pwa}(g^x)$ . Then, she sends  $M_1, A$  and  $B$  to  $KDC_A$ .

(2)  $KDC_A$  obtains  $g^x$  by decrypting  $E_{pwa}(g^x)$ .  $KDC_A$  chooses  $r \in_R Z_p^*$ , computes  $g^{xr}$  and  $M_2 = E_{pwa}(g^r)$ , and makes Kerberos ticket  $Ticket_B = E_K(g^{xr}, g^r, A, B, L)$ . Finally,  $KDC_A$  sends  $M_2, Ticket_B$  and  $L$  to Alice.

(3) Upon receiving the message from  $KDC_A$ , Alice obtains  $g^r$  by decrypting  $M_2$  and computes  $g^{xr}$ . Then, Alice stores  $g^{xr}$  and  $L$ , and forwards  $A$  and  $Ticket_B$  to Bob.

(4) Bob chooses  $y \in_R Z_p^*$  and computes  $M_2 = E_{pwb}(g^y)$ . Then, he sends  $A, B, M_2$ , and  $Ticket_B$  to  $KDC_B$ .

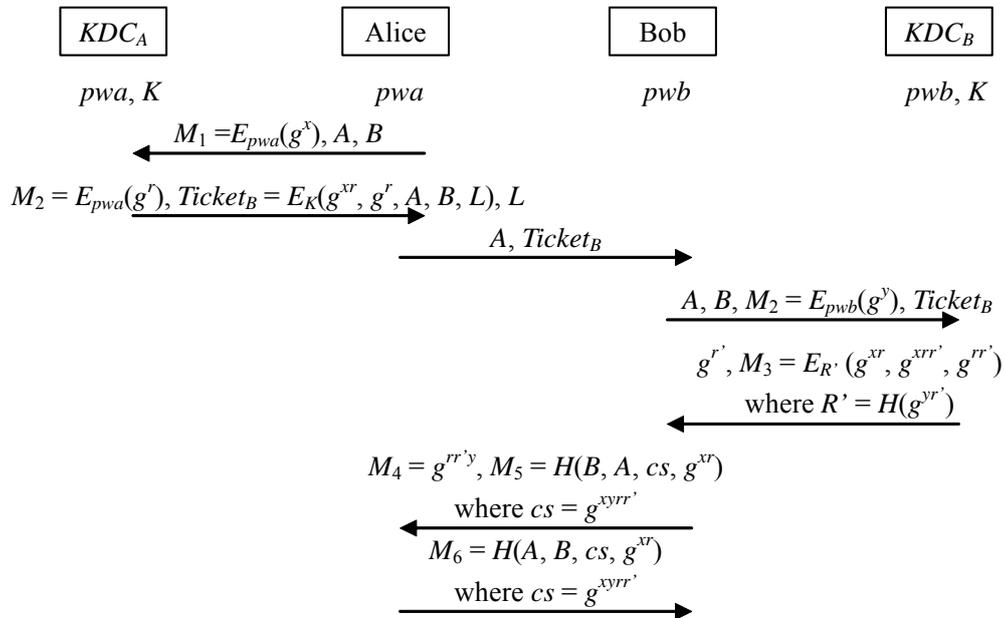


Fig.3 The Yoon-Yoo Protocol

(5)  $KDC_B$  obtains  $g^y$ ,  $g^{xr}$  and  $g^r$  by decrypting  $M_2$  and  $Ticket_B$ , respectively. Then,  $KDC_B$  chooses  $r' \in_R Z_p^*$ , computes  $g^{r'}$ ,  $g^{yr'}$ ,  $g^{xrr'}$  and  $g^{rr'}$ , and makes  $M_3 = E_{R'}(g^{xr}, g^{xrr'}, g^{rr'})$ , where  $R' = H(g^{yr'})$ . Finally,  $KDC_B$  sends  $g^{r'}$  and  $M_3$  to Bob.

(6) Upon receiving the message from  $KDC_B$ , Bob computes  $R' = H(g^{r'y})$ , and obtains  $g^{xr}$ ,  $g^{xrr'}$  and  $g^{rr'}$  by decrypting  $M_3$ . If it contains  $B$ , then Bob computes  $cs = g^{xyrr'}$ ,  $M_4 = g^{rr'y}$ , and  $M_5 = H(B, A, cs, g^{xr})$ . Finally, Bob sends  $M_4$  and  $M_5$  to Alice for session key confirmation.

(7) After receiving  $M_4$  and  $M_5$ , Alice computes  $cs = g^{xyrr'}$ . Then, Alice computes  $H(B, A, cs, g^{xr})$  and verifies it with  $M_5$ . If it holds, Alice authenticates Bob. Finally, Alice computes  $M_6 = H(A, B, cs, g^{xr})$ , and sends it to Bob for session key confirmation.

(8) After receiving  $M_6$ , Bob computes  $H(A, B, cs, g^{xr})$  and verifies it with  $M_6$ . If it holds, Bob authenticates Alice. After the Step 8,  $SK = H(g^{xyrr'})$  is used as Alice and Bob's common secret session key.

### 3.2 Cryptanalysis

Suppose Alice's password is disclosed. Obviously, an adversary who knows this secret password can impersonate Alice to other entities. However, it is desired that this disclosure does not allow the adversary to impersonate other entities to Alice. We show the Yoon-Yoo protocol is also vulnerable to this impersonation attack (see Figure 4). The attack works as follows.

(1)\* When Eve comprises  $pwa$ , she is able to get  $g^x$  from intercepted  $M_1$ .

(2)\* Eve chooses  $r$  and  $Ticket_B$ , computes  $M_2 = E_{pwa}(g^r)$ . Eve sends  $M_2$ ,  $Ticket_B$  and  $L$  to Alice.

(3)\* Alice obtains  $g^r$  by decrypting  $M_2$  and computes  $g^{xr}$ . Then, Alice stores  $g^{xr}$  and  $L$ , and forwards  $A$  and  $Ticket_B$  to Bob. Eve intercepts this message.

(4)\* Eve chooses  $y$ ,  $r' \in_R Z_p^*$ , and computes  $cs = g^{xyrr'}$ ,  $M_4 = g^{rr'y}$ , and  $M_5 = H(B, A, cs, g^{xr})$ . Eve sends  $M_4$  and  $M_5$  to Alice for session key confirmation.

(5)\* After receiving  $M_4$  and  $M_5$ , Alice computes  $cs = g^{xyrr'}$ . Alice computes  $H(B, A, cs, g^{xr})$  and verifies it with  $M_5$ . Alice computes  $M_6 = H(A, B, cs, g^{xr})$ , and sends it to Bob for session key confirmation. Eve intercepts this message.

(6)\* After receiving  $M_6$ , Eve computes  $SK = H(g^{xyrr'})$  and masquerade as Bob to complete the protocol. In the end, Eve would successfully authenticate itself to Alice as Bob, and also share a secret session key with Alice, but all the while Alice thinking it is sharing a key with Bob.

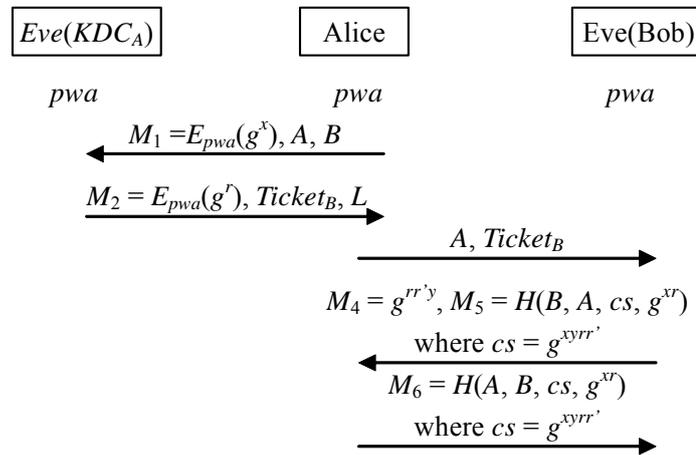


Fig.4 Impersonation attack in the Yoon-Yoo protocol

#### 4. Conclusion

In this paper, we presented a cryptanalysis of two password-authenticated key exchange protocols newly published. Our results show that once Alice’s verifier (or password) has stolen by the attacker, the attacker can impersonate another client to communicate with Alice.

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