

A n^2+n MQV Key Agreement Protocol

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Abstract: In this paper, a novel scheme to generate (n^2+n) common secret keys in one session is proposed, in which two parties can use them to encrypt and decrypt their communicated messages by using symmetric-key cryptosystem. The proposed scheme is based on the difficulty of calculating discrete logarithms problem. All the session keys can be used against the known key attacks, man-in-the middle attacks, replay attacks or forgery attacks. The security and efficiency of our proposed scheme are presented. Compare with other schemes, the proposed scheme can generate more session keys in one session. Therefore, the propose scheme is more efficient than the others.

Keywords: Authenticated key agreement, cryptography, multiple-key agreement, MQV.

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1. Introduction

What is key agreement? The key agreement protocol allows two parties that have no prior knowledge of each other to jointly establish a shared common secret key over an insecure communications channel. This key can then be used to encrypt/decrypt subsequent communications using a symmetric-key cryptosystem such as [3, 11, 26, 27]. Diffie and Hellman [2] introduced the first well-known key agreement to enable two parties to establish a common secret session key. However, the original Diffie-Hellman scheme does not support the authentication between the two parties as a result of the man-in-the-middle attack [13, 30]. Since then, several authenticated public key protocols [1, 4, 8, 14, 19] have been proposed to solve this problem. Here, we brief the Diffie-Hellman key agreement as follows. Assume that A and B want to establish a common session key to securely communicate with each other. Then, they execute the following steps:

1. A randomly chooses a large number a and computes $K_A = g^a \text{ mod } p$, then sends it to B .
2. B also randomly chooses a large number b and sends $K_B = g^b \text{ mod } p$ to A .
3. After receiving K_A and K_B , they can compute their common session key $SK = K_B^a \text{ mod } p = K_A^b \text{ mod } p = g^{ab} \text{ mod } p$,

where g is a generator and p is a large prime. Adversary cannot compute the session key without knowing a and b because of the Discrete Logarithm Problem (DLP) [12, 18, 25].

1.1. Related Work

Menezes *et al.* [17] proposed the first important key agreement protocol, which is also called the MQV protocol, to sign a signature for the Diffie-Hellman public keys without using a one-way hash function. And the MQV key agreement protocol has become a standard adopted by IEEE P1363 [10].

Harn and Lin [6] presented an authenticated key agreement protocol based on the MQV protocol to efficiently establish n^2 common session keys between two parties. To avoid the known key attack [19], the Harn-Lin protocol adopted no more than (n^2-1) common session keys while two parties send n Diffie-Hellman public keys. Yen and Joye [31] showed a forgery attack in the Harn-Lin protocol and proposed an improved protocol. However, the Yen-Joye protocol still cannot withstand a forgery attack proposed by Wu *et al.* [29]. Therefore, Hwang *et al.* proposed an improved Yen-Joye protocol to overcome its weakness [8]. Harn and Lin [7] modified the signature signing equation in [6] to conquer the forgery attack, but their protocol still limits that only (n^2-1) common session keys to be adopted between two parties.

Tseng [28] firstly proposed a new authenticated multiple-key agreement protocol that can withstand the known-key attack if two parties use all n^2 common session keys. Tseng claimed that his protocol is robust against the forgery attack and the known-key attack if all the secret keys established are adopted. However, Shao showed that Tseng's protocol is insecure against signature forgery attacks and then proposed an improved authenticated multiple-key agreement protocol to resist the attacks [23]. Unfortunately, Shim showed that Shao's protocol is also insecure [24]. Lee *et al.* [16] proposed two new MQV protocols based on

elliptic curves and bilinear pairings. The first protocol based on elliptic curves is more efficient than [7, 9, 15] and it can achieve the same security with smaller key size. And the second protocol based on bilinear pairings keeps the same properties with previous schemes. The available number of shared session keys is more than that in [7, 9, 15]. Ravala *et al.* [21] proposed a novel key generation scheme based on the biometrics. The common secret key is generated from finger prints of sender as well as receiver. However, the scheme only generated one secret key in one session. Key agreement or management is an important issue in any areas for the secure communications in the network. Recently, some key agreement schemes in wireless sensor networks are proposed for the secure communications [5, 20, 22]. However, these schemes only also generated one secret key in one session.

Until to now, all researches focus on how to establish n^2 common secret session keys. In this paper, the authors shall propose a novel protocol to generate (n^2+n) common session keys in one session.

1.2. Organization of This Paper

The organization of this paper is as follows: In section 2, we propose our protocol. Then, we give a security analysis and efficiency analysis in section 3. Finally, our brief conclusion will be in section 4.

2. n^2+n MQV Key Agreement Protocol

In this section, an extension of key agreement protocol is proposed to establish (n^2+n) common session keys between two parties. The proposed protocol can be divided into two phases: the initiation phase and the multiple-key agreement phase which are described below. Now, we suppose that Bob and Alice want to establish 12 common session keys (3^2+3) by $3(n=3)$ short-term keys. The processes are described as follows.

2.1. The Initiation Phase

The system, such as the Diffie-Hellman scheme, chooses a large prime number p . Then, Bob and Alice select their random numbers x_A and x_B . They compute the corresponding long-term public keys $y_A = g^{x_A} \bmod p$ and $y_B = g^{x_B} \bmod p$, individually.

2.2. The Multiple-Key Agreement Phase

1. Alice selects 3 short-term secret keys k_{A1} , k_{A2} , and k_{A3} , randomly and then computes $k_A = k_{A1} + k_{A2} + k_{A3} \bmod q$. Furthermore, the corresponding short-term public keys $r_A = g^{k_A} \bmod p$, $r_{A1} = y_B^{k_{A1}} \bmod p$, $r_{A2} = y_B^{k_{A2}} \bmod p$, $r_{A3} = y_B^{k_{A3}} \bmod p$, are computed. Alice is able to obtain the signature s_A based on the

equation $s_A r_A = x_A r_{A1} k_A \bmod q$. Finally, Alice sends $\{r_{A1}, r_{A2}, r_{A3}, s_A, Cert(y_A)\}$ to Bob, where $Cert(y_A)$ is a certificate for the public key signed by a trustworthy party such as a certificated authority.

- In the same way as Alice does, Bob also gets k_{B1} , k_{B2} , k_{B3} and obtains r_{B1} , r_{B2} , r_{B3} and s_B . Then Bob sends $\{r_{B1}, r_{B2}, r_{B3}, s_B, Cert(y_B)\}$ to Alice.
- Alice verifies the authenticated messages $\{r_{B1}, r_{B2}, r_{B3}, s_B, Cert(y_B)\}$ from Bob, and then makes sure that the equation:

$$y_B = (r_B)^{r_{B1}} g^{s_B r_B} \bmod p \quad (1)$$

is correct, where $r_B = r_{b1} r_{b2} r_{b3} \bmod p$, $r_{b1} = (r_{B1})^{x_A - 1} \bmod p$, $r_{b2} = (r_{B2})^{x_A - 1} \bmod p$, $r_{b3} = (r_{B3})^{x_A - 1} \bmod p$. We show that equation 1 is correct as follows:

$$\begin{aligned} y_B &= g^{x_B} \bmod p \\ &= g^{s_B r_B + r_{B1} k_B} \bmod p \\ &= g^{s_B r_B} (g^{k_B})^{r_{B1}} \bmod p \\ &= g^{s_B r_B} (r_B)^{r_{B1}} \bmod p \end{aligned}$$

If equation 1 holds, Alice could obtain 12 common session keys as follows:

$$\begin{aligned} K_1 &= r_{b1}^{k_{A1}} \bmod p, \\ K_2 &= r_{b1}^{k_{A2}} \bmod p, \\ K_3 &= r_{b1}^{k_{A3}} \bmod p, \\ K_4 &= r_{b2}^{k_{A1}} \bmod p, \\ K_5 &= r_{b2}^{k_{A2}} \bmod p, \\ K_6 &= r_{b2}^{k_{A3}} \bmod p, \\ K_7 &= r_{b3}^{k_{A1}} \bmod p, \\ K_8 &= r_{b3}^{k_{A2}} \bmod p, \\ K_9 &= r_{b3}^{k_{A3}} \bmod p, \\ K_{10} &= r_{b1} \oplus r_{b2}, \\ K_{11} &= r_{b1} \oplus r_{b3}, \end{aligned}$$

and

$$\begin{aligned} K_{12} &= g^{(k_A + k_B)} \bmod p \\ &= g^{k_A} \cdot g^{k_B} \bmod p \\ &= g^{k_A} \cdot r_B \bmod p. \end{aligned}$$

We show that Alice and Bob will share the common session key K_{10} as follows:

$$\begin{aligned} K_{10} &= r_{b1} \oplus r_{b2} \\ &= (r_{B1})^{x_A - 1} \oplus (r_{B2})^{x_A - 1} \bmod p, \\ &= (y_A^{k_{B1}})^{x_A - 1} \oplus (y_A^{k_{B2}})^{x_A - 1} \bmod p \\ &= g^{k_{B1}} \oplus g^{k_{B2}} \bmod p. \end{aligned}$$

Alice can easily get K_{10} from $r_{b1} \oplus r_{b2}$. And Bob can also get the K_{10} from their short-term secret keys k_{B1} and k_{B2} . In the same way, Alice and Bob can obtain

the common session key K_{11} successfully. Even though Alice and Bob use all common secret keys from K_1 to K_{12} , an eavesdropper cannot derive any other shared secret keys. Therefore, the proposed scheme can withstand the known-key attack. We will explain it in next session.

4. Bob also verifies the authenticated messages $\{r_{A1}, r_{A2}, r_{A3}, s_A, Cert(y_A)\}$ from Alice. By using $r_A, r_{A1}, r_{A2},$ and $r_{A3},$ Bob checks the equation $y_A = (r_A)^{r_{A1}} g^{s_{A r_A}} \text{ mod } p.$ Bob can also generate 12 common secret keys when the following equations hold.

$$\begin{aligned} K_1 &= r_{a1}^{k_{B1}} \text{ mod } p, \\ K_2 &= r_{a1}^{k_{B2}} \text{ mod } p, \\ K_3 &= r_{a1}^{k_{B3}} \text{ mod } p, \\ K_4 &= r_{a2}^{k_{B1}} \text{ mod } p, \\ K_5 &= r_{a2}^{k_{B2}} \text{ mod } p, \\ K_6 &= r_{a2}^{k_{B3}} \text{ mod } p, \\ K_7 &= r_{a3}^{k_{B1}} \text{ mod } p, \\ K_8 &= r_{a3}^{k_{B2}} \text{ mod } p, \\ K_9 &= r_{a3}^{k_{B3}} \text{ mod } p, \\ K_{10} &= r_{b1} \oplus r_{b2}, \\ K_{11} &= r_{b1} \oplus r_{b3}, \end{aligned}$$

and

$$\begin{aligned} K_{12} &= g^{(k_A+k_B)} \text{ mod } p \\ &= g^{k_A} \cdot g^{k_B} \text{ mod } p \\ &= g^{k_A} \cdot r_A \text{ mod } p. \end{aligned}$$

Hence, a generalized key agreement protocol without using a one-way hash function is proposed to enable two communicating parties to establish (n^2+n) common session keys in a single round of message exchange. Obviously, the proposed protocol generates more n session keys than other protocols do as shown in Table 1.

Table 1. The comparison of efficiency.

	[7]	[28]	[23]	[16]	Our Scheme
Numbers of Session Key	n^2	n^2	n^2	n^2/n^2	n^2+n
Numbers of Session Key Can Be Used	n^2-1	n^2	n^2	n^2-1/n^2	n^2+n

We take n public keys to combine, exclusive-or operation (XOR) and select all safe keys which will not have any attack as session keys that we called primitive keys. Now, we shall propose a lemma to prove that n public keys will generate $(n-1)$ primitive keys.

- *Theorem 2.1.* The n keys generate $\sum_{s=2}^n C(n,s) = 2^n - n - 1$ combinations from $k_1, \dots, k_n.$ We define $k_i \oplus k_j,$

$i=2, \dots, n$ as the primitive keys from $\sum_{s=2}^n C(n,s).$ All $n-1$ primitive keys can be adopted between two parties as their session keys for safe and sound communication.

- *Proof.* Let I be the number of keys which are selected by two parties, respectively.
- *Case 1.* The property is true for $I=3$: The three keys generate $C(3, 2)+C(3, 3)=4$ combinations from $k_1, k_2, k_3.$ Obviously, the primitive key $k_1 \oplus k_2$ and $k_1 \oplus k_3$ can be adopted as session keys safely. The remainders may lead to the known key attack, which will be described as follows:

1. $k_2 \oplus k_3$ is produced by $(k_2 \oplus k_3) \oplus (k_1 \oplus k_3).$
2. The primitive keys will be inferred if the exclusive-OR (XOR) apply to $k_1 \oplus k_2 \oplus k_3$ and primitive key. Therefore, k_1, k_2, k_3 will be inferred from the $((k_1 \oplus k_2 \oplus k_3) \oplus (k_i \oplus k_j))$ where $i, j=1, 2, 3; i < j.$ For instance, the k_1 infers from $(k_1 \oplus k_2 \oplus k_3) \oplus (k_2 \oplus k_3).$

- *Case 2.* Assume the property is true for $I=n-1$: The $n-1$ keys generate $\sum_{s=2}^{n-1} C(n-1,s) = 2^{n-1} - n - 2$ combinations from $k_1, \dots, k_{n-1}.$ Clearly, the primitive key $k_1 \oplus k_2, \dots, k_1 \oplus k_{n-1}$ can be adopted as a session key safely. The remainders will result in the know key attack.
- *Case 3.* Prove the property is true for $I=n$: The n keys generate $\sum_{s=2}^n C(n,s) = 2^n - n - 1$ combinations from $k_1, \dots, k_n.$ The $2^n - n - 1$ combination keys may be divided into primitive keys and non-primitive keys.

1. Show that the primitive keys is $k_1 \oplus k_i,$ where $i=2, \dots, n.$

- a. $k_1 \oplus k_2, \dots, k_1 \oplus k_{n-1}$ combination keys have been proved in case 2 previously.
- b. $k_1 \oplus k_n$ is still a primitive key which can't be inferred from $k_1 \oplus k_2, \dots, k_1 \oplus k_{n-1}.$

2. Show $2^n - 2n$ non-primitive keys.
 - a. $2^{n-1} - 2n$ non-primitive keys have been proved in Case 2.
 - b. The remainders of 2^{n-1} non-primitive keys are as follows:

1. $k_n \oplus k_i$ where $i=2, \dots, n-1, k_n \oplus k_i$ infer from $(k_n \oplus k_1) \oplus (k_1 \oplus k_i)$ where $i=2, \dots, n-1$ Therefore, $k_n \oplus k_i$ are non-primitive keys.

2. $k_n \oplus k_{i1} \oplus \dots \oplus k_{ij}, k_{ij} \in \{k_1, k_2, \dots, k_{n-1}\}$ where $j=2, \dots, n-1; k_{ij} \neq k_{ip}; j \neq p; jp=2, \dots, n-1.$ In case 2, $(k_{i1} \oplus \dots \oplus k_{ij})$ have been proved. Now, the primitive key k_n will infer from

$(k_n \oplus k_{i1} \oplus \dots \oplus k_{ij}) \oplus (k_{i1} \oplus \dots \oplus k_{ij}) = k_n$, where $ij=2, \dots, n-1$. For instance, k_1 will infer from $(k_n \oplus k_1 \oplus k_2) \oplus (k_1 \oplus k_2) = k_n$ and $k_n \oplus (k_n \oplus k_1) = k_1$. Therefore, k_1, k_2, \dots, k_n will be inferred. (Q.E.D.)

3. Analysis

In this section, we shall show the security and efficiency analysis of our extended protocol as follows:

3.1. Security Analysis

1. *Known-key Attack*: Tseng [28] proved that his protocol could withstand the known-key attack. Similarly, our extended protocol can also withstand the known-key attack [19]. We suppose two parties use the 12 common session keys. Our extended protocol may withstand the known key attack. We derive $g^{x_A x_B}$ as follows:

$$\begin{aligned} g^{x_A x_B} &= g^{(s_A r_A + r_A k_A)(s_B r_B + r_B k_B)} \pmod p \\ &= g^{s_A s_B r_A r_B} \cdot g^{s_A r_A r_B k_B} \cdot g^{s_B r_B r_A k_A} \cdot g^{k_A k_B r_A r_B} \pmod p \\ &= g^{s_A s_B r_A r_B} \cdot g^{s_A r_A r_B k_B} \cdot g^{s_B r_B r_A k_A} \\ &\quad \cdot (g^{(k_{A1} + k_{A2} + k_{A3})(k_{B1} + k_{B2} + k_{B3})})^{r_A r_B} \pmod p \\ &= g^{s_A s_B r_A r_B} \cdot g^{s_A r_A r_B k_B} \cdot g^{s_B r_B r_A k_A} \cdot (\prod_{i=1}^9 K_i)^{r_A r_B} \pmod p \end{aligned}$$

suppose two parties adopt and publish the common session keys $K_1, K_2, \dots, K_{10} = g^{K_{B1}} \oplus g^{K_{B2}}$, and $K_{11} = g^{K_{B1}} \oplus g^{K_{B3}}$, an eavesdropper is still hard to derive the key $K_{12} = g^{K_B} r_A \pmod p$ owing to unknowing secrets r_A and r_B . Furthermore, if an intruder can obtain all the common session keys from K_1 to K_{12} , where the transmitted message involves $(r_{A1}, r_{A2}, r_{A3}, r_{B1}, r_{B2}, r_{B3}, s_A, s_B, g^{K_{B1}} \oplus g^{K_{B2}}, g^{K_{B1}} \oplus g^{K_{B3}}, \text{ and } g^{k_B} r_A \pmod p)$, it is still hard for the intruder to calculate $g^{x_A x_B}$ by intercepting the transmitted message between the two parties. The intruder cannot derive r_A and r_B from any transmitted message. The security is based on the difficulty of calculating discrete logarithms. Consequently, the extended protocol can also withstand the known-key attack.

2. *Replay Attack*: In order to resist the replay attack, our protocol uses short-term keys. The lifetime of the short-term keys k_{Ai} and k_{Bi} ($i \in 1, 2, \dots$) is only one session long, with a view of establishing (n^2+n) keys. The two parties have to randomly choose new short-term keys again in the next session. If the intruder attempts to replay the previously intercepted message to Bob for masquerading as

Alice, Bob will find out and reject this message.

3. *Forgery Attack*: Assume that an intruder wants to impersonate Alice to establish the common session keys with Bob. The intruder forges the previously intercepted message $(r_{A1}, r_{A2}, r_{A3}, s_A, Cert(y_A))$ to $(r'_{A1}, r'_{A2}, r'_{A3}, s'_A, Cert(y'_A))$ and send it to Bob, where $(r'_{A1}, r'_{A2}, r'_{A3}$ and $s'_A)$

$$\begin{aligned} k'_A &= k'_{A1} + k'_{A2} + k'_{A3} \pmod q \\ r_{A1} &= g^{k'_{A1}} \pmod p, \\ r_{A2} &= g^{k'_{A2}} \pmod p, \\ r_{A3} &= g^{k'_{A3}} \pmod p, \\ s'_A r'_A &= x'_A - r'_{A1} k'_{A1} \pmod q. \end{aligned}$$

Because the message cannot pass verification equation 1, bob will reject the transmitted message sent from the intruder.

3.2. Efficiency Analysis

In Table 1, we can see that our scheme is more efficient than Harn-Lin's protocol [7], Tseng's protocol [28], Shao's protocol [23], and Lee et al.'s protocol [16]. Harn-Lin's protocol establishes n^2 common secret session keys in one session within two parties, but only (n^2-1) can be used for withstanding the known-key attack. In Tseng's protocol, the n^2 common secret keys can be used without suffering from the attack. An improvement of Tseng's protocol proposed by Shao establishes n^2 common secret session keys and n^2 keys can be used. The first protocol of Lee et al.'s protocols establishes n^2 keys and only (n^2-1) keys can be used. The second protocol of Lee et al.'s protocols establishes n^2 keys and n^2 keys can be used. In our protocol, two parties can establish (n^2+n) common secret session keys and all the keys can be used. It is seen that our protocol is superior to other protocols. Note that n denotes that two parties send n Diffie-Hellman public keys. In Table 2, we show an example to compare the efficiency of our scheme to the others.

Table 2. An example $n=3$.

	[7]	[28]	[23]	[16]	Our Scheme
Numbers of Session Key	9	9	9	9/9	12
Numbers of Session Key Can Be Used	8	9	9	8/9	12

4. Conclusions

In this paper, we have constructed a more efficient MQV Key agreement protocol. Shown in Table 1. Other protocols establish n^2 common session keys between two parties in one session. Nevertheless, (n^2+n) common session keys can be established in our

extended protocol and what is more, attack is no longer a threat.

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