On the Risk of Opening Distributed Keys

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Abstract. We describe an insider known-key attack on key distribution systems which are based on public keys. This is of a general type and applies to the key distribution system presented by Yacobi at Crypto '90, the Goss system, the Günther system presented at Eurocrypt '89 and the key exchange version of COMSET, based on a system presented by Brandt et al. at Crypto '89. The attack is primarily theoretical, in the sense that it assumes that some session keys are leaked or lost. Well designed systems will prevent this. However it could have practical consequences with certain applications (e.g. negotiation of contracts or poor implementations). We discuss the implications and ways to prevent the attack.

1 Introduction

Matsumoto-Takashima-Imai [21], Yacobi-Shmueli [29] and Yacobi [28] presented a family of variants of the Diffie-Hellman [13] key distribution system which are based on public keys. These are two-party systems which are non-interactive, have a low communication and computation overhead, and offer a good level of security. In particular, the 'non-paradoxical' key distribution system is provably secure against passive attacks and certain types of known-key attacks [28] (provided the Composite Diffie-Hellman problem is hard). In this paper we show that this system is not secure against general known-key attacks. We use an insider attack which is two-pronged, consisting of a passive attack followed by an active known-key attack. In the passive attack the adversary eavesdrops on a conversation. Then the adversary uses a known-key attack to obtain two chosen keys from subsequent sessions. From these, and from the calls exchanged, the adversary computes the key of the eavesdropped session. The attack is general and applies to many other systems including the Goss system [19], the Günther system [20], and the key exchange version of COMSET [9], when the session key is the bitwise exclusive-or of the partial keys.

Known (chosen) key attacks [28] are analogous to chosen-ciphertext attacks for encryptions. With these the cryptanalyst has access to some session keys. As with encryptions, they are the hardest to foil. Various scenarios for known-key attacks are discussed in [12]. These are,

- *Negotiation of contracts*: After a contract is signed, there is no need to keep secrecy and the keys used for privacy may be revealed.

- *Verification of treaties*: To reduce the possibility of hiding a covert message, the key is revealed immediately after the message is authenticated [2, p. 33].
- *Jealous spouse*: Alice wants to get the secret session key K_{bc} which her spouse Bob used to encrypt a file sent to Carol. She expects to receive a large file from Bob, but will not adhere to the rules of the key exchange protocol. As a result she will not know the session key K_{ba} which she will exchange with Bob.¹ So when she gets the encrypted file under the session key K_{ba} from Bob she cannot decrypt it. A few days later she claims to have lost the key K_{ba} . Bob has no reason to refuse to give her *this* key.

The robustness of a protocol against the loss of a session key has been the subject of many recent investigations (e.g. [28, 3, 24]). Yacobi linked it to the “paradox” for signature schemes [28]. Bellare and Rogaway [3] observed that it is necessary for secure authenticated key exchange. They pointed out that even if an adversary gets hold of a session key, this should effect only the session which that key protects. In particular, it should not be any easier for the adversary to compute another session key.

Earlier attacks on key distribution systems such as the mafia attack, or intruder-in-the-middle attack (e.g. [25, 4, 14]), and interleaving attacks [5] (see also [3]), fail to take advantage of the scope of known-key attacks. Typically, they lead to disclosure of secret information which subsequently can be used to obtain session keys, or to impersonate. Our attack is different. The adversary is an insider who succeeds in computing the session key of an earlier conversation, from subsequent sessions with the parties involved in the conversation.

Van Oorschot [27] compared the formal goals of the Goss and Günther systems² by using an extended version of the authentication logic of Burrows, Abadi and Needham [7, 1] (see also [18, 8, 17, 16]) and found that they are essentially the same. One of the main features highlighted was the fact that these systems provide only *implicit* key authentication, i.e. the session key is not authenticated until both parties prove knowledge of it by using it in a subsequent communication. It may seem that that this is not a serious threat [27, p. 241], since even though an adversary can replay old messages and complete fraudulent protocol runs, no real advantage is gained because the resulting key cannot be computed.³ But if some keys are leaked or lost then it is a threat. Indeed with our attack the adversary uses knowledge gained from leaked keys of fraudulent runs to compute the session key of an earlier honest run.

The organization of this paper is as follows. In Section 2 we describe our attack and show how it can be applied to the Yacobi system. In Section 3 we extend it to the Goss [19] system, the Günther [20] system, and to the key exchange version of COMSET [9]. In Section 4 we analyze the attack and discuss ways to foil it. We conclude with remarks.

¹ By doing so she hopes to gain some knowledge about K_{bc} . We shall see that she may succeed in some cases.

² Yacobi’s scheme was not analyzed, but it is similar.

³ Diffie–Oorschot–Wiener warn about a threat to the Station-to-Station protocol when the signatures are not encrypted [14, p. 116]. However in this case an intruder can easily hijack the key and we do not have key authentication.

Remark. It is important to differentiate between theoretical and practical attacks. The attack described in this paper is primarily theoretical since well designed implementations of key distribution systems will prevent session keys being disclosed or lost. Indeed in virtually all real systems the users do not know their encryption keys, and only interact through well defined interfaces. However one should be wary, particularly with poor implementations, or with applications in which the session keys are eventually disclosed (e.g. with negotiations of contracts).

2 Cryptanalysis of the Yacobi System

We first consider the ‘non-paradoxical’ key distribution system presented by Yacobi [28] (see also [21]) and show how our attack applies to it. In the following sections we will show that the attack can be extended to other systems.

2.1 The Yacobi System

This system uses a discrete logarithm setting with composite modulus $m = pq$, p, q large secret primes, and base $\alpha \in Z_m^*$ of large order. Each user U_i has a secret key $s_i \in Z_m$ and a public key $P_i = \alpha^{s_i} \bmod m$. When U_i, U_j want to establish a common session key they select random exponents $e_i, e_j \in Z_m$, respectively, and exchange calls $R_i = \alpha^{e_i} \bmod m$, $R_j = \alpha^{e_j} \bmod m$. The session key is $K_{ij} \equiv R_i^{s_j} \cdot P_i^{e_j} \equiv R_i^{s_j} \cdot R_j^{s_i} \equiv P_j^{s_i} \cdot R_j^{s_i} \pmod{m}$, which both U_i and U_j can compute. Observe that the session key is the modular product of the ‘partial keys’ $R_i^{s_j} \bmod m$ and $R_j^{s_i} \bmod m$, which both parties can compute.

The Yacobi system is secure against ciphertext-only attacks by a passive eavesdropper if the Composite Diffie-Hellman problem is hard [28]. Under the same cryptographic assumption it is also secure against certain types of known-key attacks [28]. However these are rather limited in scope [12].

2.2 Cryptanalysis of the Yacobi System

Let A, B and C be users whose secret and public keys are $(s_a, P_a), (s_b, P_b)$, and (s_c, P_c) respectively. $\tilde{A}$ is a dishonest user who does not follow the prescribed protocol, but knows the secret key s_a of A . B and C execute the prescribed protocol.

In the following attack $\tilde{A}$ eavesdrops on a conversation of B and C . Subsequently, from separate conversations with B and C , and by using a known-key attack, she will compute the session key of B and C .

2.3 The Triangle Attack

Phase 1. $\tilde{A}$ eavesdrops on a conversation of B and C . Let R_b, R_c be the calls exchanged and let $K_{bc} \equiv R_b^{s_c} \cdot R_c^{s_b} \pmod{m}$ be the session key. $\tilde{A}$ wants to compute *this* key. She gets R_b, R_c by eavesdropping.

Phase 2. B exchanges a key with $\tilde{A}$. $\tilde{A}$ uses the call R_c . Let R'_b be the call of B and let $K_{ba} \equiv R'_b^{s_a} \cdot R_c^{s_b} \pmod{m}$ be the session key of B .

Phase 3. C exchanges a key with $\tilde{A}$. $\tilde{A}$ uses the call R_b . Let R'_c be the call of C and let $K_{ca} \equiv R'_c^{s_a} \cdot R_b^{s_c} \pmod{m}$ be the session key of C .

Event 1. *Opening the key K_{ba} .* Suppose that the session key of B , K_{ba} , is revealed to $\tilde{A}$.

Event 2. *Opening the key K_{ca} .* Suppose that the session key of C , K_{ca} , is revealed to $\tilde{A}$.

Computation. $\tilde{A}$ computes the key of B and C . $\tilde{A}$ now computes:

- the ‘partial key’ $R_c^{s_b} \equiv R'_b^{-s_a} \cdot K_{ba} \pmod{m}$,
- the ‘partial key’ $R_b^{s_c} \equiv R'_c^{-s_a} \cdot K_{ca} \pmod{m}$, and finally
- the session key $K_{bc} \equiv R_b^{s_c} \cdot R_c^{s_b} \pmod{m}$.

Observe that in Phase 2 and Phase 3, $\tilde{A}$ cannot compute the keys K_{ba} and K_{ca} by herself, unless the Composite Diffie-Hellman problem is feasible (she does not know the discrete logarithms of R_c and R_b).

Remark. The conventional definition of a known key attack relates to a situation in which an old session key has leaked or is lost. For example, a session key that was used to encrypt a file is stored in a place that was supposed to be safe, but has leaked. Prior to using the session key, the parties use a handshake protocol to authenticate it. In the triangle attack, B and C initiate Phase 2 and Phase 3 respectively because they want to send files to $\tilde{A}$. The session keys they ‘exchange’ are then used to encrypt the files. These keys are leaked to $\tilde{A}$, who then computes the session key of B and C . Observe that the Yacobi ‘handshake’ is non-interactive and provides only implicit authentication ($\tilde{A}$ has sent no file and is not authenticated).

2.4 Hiding the Attack

The attack can be prevented by having the parties keep a cache of received old calls R_i , and requesting fresh calls for each new session. We discuss two methods to hide the triangle attack, based on a variant of Moore’s attack for RSA signatures [10, 11, 22]).

Modification 1

Instead of using the old calls R_c and R_b in Phase 2 and Phase 3, $\tilde{A}$ uses

$$\hat{R}_c \equiv R_c \cdot \alpha^{t_c} \pmod{m} \text{ and } \hat{R}_b \equiv R_b \cdot \alpha^{t_b} \pmod{m}, \quad (1)$$

where t_c, t_b are randomly selected in Z_m by $\tilde{A}$. Then $K_{ba} \equiv R_b'^{s_a} \cdot \hat{R}_c^{s_b} \pmod{m}$ and $K_{ca} \equiv R_c'^{s_a} \cdot \hat{R}_b^{s_c} \pmod{m}$, where R_b' and R_c' are the calls of B and C . In this case $\tilde{A}$ computes $\hat{R}_c^{s_b} \equiv R_b'^{-s_a} \cdot K_{ba} \pmod{m}$ and $\hat{R}_b^{s_c} \equiv R_c'^{-s_a} \cdot K_{ca} \pmod{m}$. From these, and from (1), she gets the partial keys

$$R_b^{s_c} \equiv \hat{R}_b^{s_c} \cdot \alpha^{-t_b s_c} \equiv \hat{R}_b^{s_c} \cdot P_c^{-t_b} \pmod{m}, \quad R_c^{s_b} \equiv \hat{R}_c^{s_b} \cdot \alpha^{-t_c s_b} \equiv \hat{R}_c^{s_b} \cdot P_b^{-t_c} \pmod{m},$$

from which she computes the session key $K_{bc} \equiv R_b^{s_c} \cdot R_c^{s_b} \pmod{m}$ of B and C .

Modification 2

If the modulus is a prime p , then instead of using the calls R_c, R_b in Phase 2 and Phase 3, $\tilde{A}$ may use $\bar{R}_c = R_c^{t_c} \pmod{p}$ and $\bar{R}_b = R_b^{t_b} \pmod{p}$, where t_c, t_b are randomly selected in Z_{p-1} . Then $K_{ba} \equiv R_b'^{s_a} \cdot \bar{R}_c^{s_b} \pmod{p}$ and $K_{ca} \equiv R_c'^{s_a} \cdot \bar{R}_b^{s_c} \pmod{p}$, where R_b' and R_c' are the calls of B and C . So $\tilde{A}$ can compute $\bar{R}_b^{s_c} \equiv R_c'^{-s_a} \cdot K_{ca} \pmod{p}$ and $\bar{R}_c^{s_b} \equiv R_b'^{-s_a} \cdot K_{ba} \pmod{p}$, and hence the partial keys $R_b^{s_c} \equiv R_c'^{-s_a t_b^{-1}} \cdot K_{ca}^{t_b^{-1}} \pmod{p}$ and $R_c^{s_b} \equiv R_b'^{-s_a t_c^{-1}} \cdot K_{ba}^{t_c^{-1}} \pmod{p}$, from which she gets K_{bc} .

3 Cryptanalysis of Other Key Distribution Systems

3.1 The Goss System

This system [19] is similar to the Yacobi system except that the modulus is a prime p , and the session key is the bitwise exclusive-or of the partial keys, instead of their product. That is $K_{ij} = (R_i^{s_j} \pmod{p}) \oplus (R_j^{s_i} \pmod{p})$.

The Attack

This is essentially the same as for the Yacobi system. In this case $\tilde{A}$ computes the session key K_{bc} of B and C from the partial keys $R_b^{s_c} \pmod{p} = K_{ca} \oplus (R_c^{s_a} \pmod{p})$ and $R_c^{s_b} \pmod{p} = K_{ba} \oplus (R_b^{s_a} \pmod{p})$. Both modifications in Section 2.4 apply to this scheme as well.

3.2 The Günther System

This system [20] uses ElGamal signatures [15] for authentication. It is similar to the Yacobi system but with a prime modulus p . A trusted center T with secret key x , $1 \leq x \leq p-1$, and public key $Y = \alpha^x \pmod{p}$, issues each user U_ℓ with a distinguishing identifier D_ℓ and an ElGamal signature (P_ℓ, s_ℓ) of D_ℓ . Thus $P_\ell = \alpha^{k_\ell} \pmod{p}$, where $k_\ell \in Z_{p-1}$ is a random exponent with $\gcd(k_\ell, p-1) = 1$, and s_ℓ is obtained by solving $h(D_\ell) \equiv x P_\ell + k_\ell s_\ell \pmod{p-1}$, where $h(\cdot)$ is a suitable hash function. P_ℓ is the public key of U_ℓ and s_ℓ the secret key. Observe that anyone can compute

$$P_\ell^{s_\ell} \equiv \alpha^{k_\ell s_\ell} \equiv \alpha^{h(D_\ell) - x \cdot P_\ell} \equiv \alpha^{h(D_\ell)} Y^{-P_\ell} \pmod{p}. \quad (2)$$

When U_i wants to establish a session key with U_j it selects a random exponent e_i , computes $R_i = P_j^{e_i} \bmod p$, and sends D_i , P_i and R_i to U_j . Then U_j selects a random e_j , computes $R_j = P_i^{e_j} \bmod p$, and sends D_j , P_j and R_j to U_i . The session key is $K_{ij} \equiv R_i^{s_j} \cdot (P_i^{s_i})^{e_j} \equiv R_i^{s_j} \cdot R_j^{s_i} \equiv (P_j^{s_j})^{e_i} \cdot R_j^{s_i} \pmod{p}$, which both parties can compute by (2).

The Attack

As with the Yacobi system, $\tilde{A}$ eavesdrops on a conversation of B and C with calls R_b , R_c and secret key $K_{bc} \equiv R_b^{s_c} \cdot R_c^{s_b} \pmod{p}$. Subsequently she gets R'_b , R'_c , and computes the partial keys $R_b^{s_c} \bmod p$ and $R_c^{s_b} \bmod p$, and hence the session key K_{bc} . Again both modifications apply. Furthermore, it is easy to see that the attack extends to the 'perfect forward secrecy' variant [20, pp. 34–35].

3.3 COMSET (the Key Exchange Version)

Each user U_ℓ of COMSET [9, 6] selects secretly two appropriate primes $p_\ell \equiv 3 \pmod{8}$ and $q_\ell \equiv 7 \pmod{8}$ and publishes $n_\ell = p_\ell q_\ell$ as its public key. The encryption function of U_ℓ is $z \rightarrow z^2 \bmod n_\ell$, and the decryption function is $z \rightarrow z^{d_\ell} \bmod n_\ell$, where $d_\ell = ((p_\ell - 1)(q_\ell - 1) + 4)/8$. To establish a secret key with U_i , U_j selects a random $x_j \in \mathbb{Z}_{n_i}$ and computes $m_j \equiv x_j^2 \bmod n_i$. Then U_j sends U_i the encryption $r_j \equiv m_j^2 \bmod n_i$ together with a validator v_j of m_j which consists of the $|n_i|/4$ least significant bits of m_j . U_i decrypts r_j to get $m_j' = r_j^{d_i} \bmod n_i$. It checks the validators of m_j' and $n_i - m_j' \pmod{n_i}$, and takes m_j'' to be the one whose validator is v_j . Then it sends U_j the next $|n_i|/4$ significant bits of m_j'' . U_j checks these. If they are the same as the corresponding bits of m_j then the authentication of U_i is successful. The secret (partial) key is $[m_j] = [m_j'']$, where $[z_j]$ is an appropriate substring of z_j . For mutual authentication U_j must also be authenticated. The same protocol is used (the processes can be executed in parallel). The common session key is the bitwise exclusive-or $K_{ij} = [m_i] \oplus [m_j]$ of the partial keys.

The Attack

As with the Yacobi system, $\tilde{A}$ eavesdrops on a conversation of B and C with calls $r_b \equiv m_b^2 \bmod n_c$ and $r_c \equiv m_c^2 \bmod n_b$, and secret key $K_{bc} = [m_b] \oplus [m_c]$ in Phase 1. In Phase 2 she gets the call $r_b^* = m_b^{*2} \bmod n_a$. Since n_a is her own key, she can compute m_b^* and hence send B the appropriate substring for authentication. In Phase 3 she gets the call $r_c^* = m_c^{*2} \bmod n_a$, computes m_c^* , and sends C the appropriate substring for authentication. Then she gets the keys $K_{ca} = [m_c^*] \oplus [m_b]$ and $K_{ba} = [m_b^*] \oplus [m_c]$. Finally she computes the partial key $[m_b]$ and the partial key $[m_c]$ from which she gets the session key K_{bc} of B and C . For this scheme the modifications in Section 2.4 do not apply.

4 Repairing the Systems

When a cryptographic algorithm is used to solve a security problem, it is implemented within the framework of a protocol which ensures that certain levels of

security required by the system are attained. If this goal is not met, this is either because the cryptographic algorithm is defective or because the protocol procedures are inappropriate. Many of the proposed Diffie-Hellman non-interactive variants have succumbed to attacks by passive and/or active adversaries. However their failure can be attributed to a large extent to the protocol procedures, and can be controlled by specifying a different implementation.

The simplest way to foil the triangle attack is to refuse to willingly reveal session keys to anyone. A sensible precaution is to ensure that session keys are destroyed immediately after the session is ended. This is one of the fundamental design principles for secure key management (and has been widely recognized). Alternatively, the users can be prevented from knowing their own session keys. To implement this, the key distribution algorithm can be encapsulated in a tamper-resistant device [4]. To enforce security the encryption algorithm must also be encapsulated.

Another way to foil the triangle attack is to modify the key distribution systems so as to get key confirmation. This can be done by having each user send an additional message which employs the established session key, e.g. via encryption or a MAC [14]. Then $\tilde{A}$ cannot complete Phase 2 and Phase 3 of the attack in Section 2.3, and therefore B and C will destroy the session keys. However this is at the cost of making the key distribution systems interactive: the messages the users send to each other are now dependent (COMSET is already interactive).

Alternatively one can take the session key to be the hash $h(K_{ij})$, where $h(\cdot)$ is a suitable hash function, or, the hash of the concatenation of the partial keys. This will foil the triangle attack. However, it must be pointed out that the fact that this attack is foiled does not guarantee that the system is secure (e.g. from other known key attacks). The problem with these modifications is that the adversary gains some knowledge from fraudulent runs when their session keys are leaked, later on (this is not the case with honest runs when a uniform distribution is used, and the 'view' of the adversary can be simulated [12]). It is sensible to prevent such runs e.g. by requiring key confirmation.

Finally one can strengthen the algorithm. This problem is addressed in [12]. The solution proposed there is to require, additionally, that the users U_i, U_j prove to each other that they *know* the discrete logarithm of their calls R_i, R_j , by using an interactive zero-knowledge proof. This will prevent fraudulent runs (B and C will not compute their session key unless they are convinced that $\tilde{A}$ knows the discrete logarithms of her calls), and furthermore no knowledge about the session keys is leaked to the adversary ($\tilde{A}$ can simulate her view).

5 Conclusion

We have described a general known-key attack for key distribution systems for which the parties compute the session key from partial keys which are established non-interactively, and for which, given the session key and one partial key, the other partial key can be recovered. From our discussion it follows that:

- Revealing keys to legitimate holders may be harmful.
- Ensuring that session keys are deleted at the end of a session is a sensible precaution.
- Implicit key authentication can be dangerous.
- Taking the session key to be the bitwise exclusive-or, or product, of partial keys may be risky.
- It should not be possible to complete a fraudulent session.
- If files are to be stored, then the plaintext should be encrypted with a different key.

The following remains an open problem:

- Do there exist practical non-interactive proven secure⁴ key distribution systems?

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⁴ A system is proven secure if breaking it (e.g. by using a known key attack) is as hard as solving a (believed to be) hard cryptographic 'reference' problem such as, factoring, the discrete logarithm, the Diffie-Hellman problem, etc. For practical systems this seems to be the best achievable level of security.

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