

# Revisit of McCullagh–Barreto Two-Party ID-Based Authenticated Key Agreement Protocols\*

Kim-Kwang Raymond Choo

Information Security Institute, Queensland University of Technology  
GPO Box 2434, Brisbane, QLD 4001, Australia (Email: k.choo@qut.edu.au)

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## Abstract

We revisit the two-party identity-based authenticated key agreement protocol (2P-IDAKA) and its variant resistant to key-compromise impersonation due to McCullagh & Barreto (2005). Protocol 2P-IDAKA carries a proof of security in the Bellare & Rogaway (1993) model. In this paper, we demonstrated why both the protocol and its variant are not secure if the adversary is allowed to send a *Reveal* query to reveal non-partner players who had accepted the same session key (i.e., termed *key-replicating attack* in recent work of Krawczyk (2005)). We also demonstrate that both protocols do not achieve the *key integrity* property, first discussed by Janson & Tsudik (1995).

*Keywords:* Cryptographic protocols, identity-based cryptography, authenticated key agreement, provable security

## 1 Introduction

Despite cryptographic protocols being the *sine qua non* of many diverse secure electronic commerce applications, the design of secure cryptographic protocols is still notoriously hard. The difficulties associated in obtaining a high level of assurance in the security of almost any new or even existing protocols are well illustrated with examples of errors found in many such protocols years after they were published [2, 3, 4, 5, 18, 19, 21, 22, 23, 26, 31, 33, 34, 35, 36, 37, 40]. The many flaws discovered in published protocols for key establishment and authentication over many years, have promoted the use of formal models and rigorous security proofs.

The treatment of computational complexity analysis adopts a deductive reasoning process whereby the emphasis is placed on a proven reduction from the problem of breaking the protocol to another problem believed to be

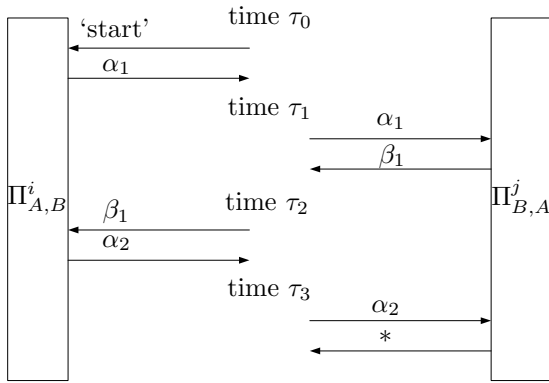
hard. Such an approach for key establishment protocols was made popular by Bellare & Rogaway [9] who provided the first formal definition for a model of adversary capabilities with an associated definition of security (which we refer to as the BR93 model in this paper). Since then, the BR93 model is one of the widely used proof models in the computational complexity approach for protocol analysis [17]. An extension of the BR93 model was used to analyse a three-party server-based key distribution (3PKD) protocol by Bellare & Rogaway [10]. A more recent revision to the model was proposed in 2000 by Bellare, Pointcheval and Rogaway [8]. In independent yet related work, Bellare, Canetti, & Krawczyk [7] build on the BR93 model and introduce a modular proof model. However, some drawbacks with this formulation were discovered and this modular proof model was subsequently modified by Canetti & Krawczyk [14].

## Case Study

McCullagh & Barreto propose a new two-party identity-based authenticated key agreement (2P-IDAKA) protocol in CT-RSA 2005 [30], which carries a proof of security in the BR93 model. In the BR93 model, there exists a powerful probabilistic polynomial-time (PPT) adversary,  $\mathcal{A}$ , which controls all the communications that take place between parties via a pre-defined set of oracle queries, namely:

- *Send*( $U, s, m$ ) query which  $\mathcal{A}$  allows to send message  $m$  to oracle  $\Pi_U^s$ ,
- *Reveal*( $U, s$ ) query which  $\mathcal{A}$  allows to reveal session key (if any) accepted by  $\Pi_U^s$ ,
- *Corrupt*( $U, K$ ) query which  $\mathcal{A}$  allows to reveal state of  $U$  and/or set the long-term key of  $U$  to  $K$ , and
- *Test*( $U, s$ ) query returns to  $\mathcal{A}$  a test key, in which  $\mathcal{A}$  will determine whether the test session is random or the actual session key (i.e., indistinguishability).

\*A preliminary version of this work appears in [16].



Note that the construction of conversation shown in Definition 1 depends on the number of parties and the number of message flows. Informally, both  $\Pi_{A,B}^i$  and  $\Pi_{B,A}^j$  are said to be BR93 partners if each one responded to a message that was sent unchanged by its partner with the exception of perhaps the first and last message.

Figure 1: Matching conversation [9]

Xie pointed out a flaw in the 2P-IDAKA protocol, where a malicious adversary is able to successfully launch a key compromise attack on the protocol [38]. To address this attack pointed out by Xie, McCullagh & Barreto propose a fix resistant to key-compromise impersonation in their paper [30].

In this paper, we demonstrate why the 2P-IDAKA protocol and the fix (variant) are not secure if the adversary is allowed to reveal non-partner players who had accepted the same session key. However, such a **Reveal** query is important as it captures the notion of known key security, whereby a protocol should still achieve its goal in the face of a malicious adversary who has learned some other session keys [12, 24].

## Organization of Paper

The remainder of this paper is structured as follows: Section 2 briefly explains the BR93 model. Section 3 describes both the 2P-IDAKA protocol and the fix (variant), and the attack sequences on both protocols. Section 4 presents the conclusions.

## 2 Overview of the BR93 Model

In this section, an informal overview of the BR93 model is provided primarily for the benefit of the reader who is unfamiliar with the model. For a more comprehensive description, the reader is referred to the original paper [9].

The BR93 model defines provable security for entity the authentication and key distribution goals. The adversary  $\mathcal{A}$  in the model, is a probabilistic machine that controls all the communications that take place between parties by interacting with a set of  $\Pi_{U_1,U_2}^i$  oracles ( $\Pi_{U_1,U_2}^i$  is defined to be the  $i^{\text{th}}$  instantiation of a principal  $U_1$  in a specific protocol run and  $U_2$  is the principal with whom  $U_1$  wishes to establish a secret key). The predefined oracle queries are described informally as follows.

- The **Send**( $U_1, U_2, i, m$ ) query allows  $\mathcal{A}$  to send some message  $m$  of her choice to either the client  $\Pi_{U_1,U_2}^i$  at will.  $\Pi_{U_1,U_2}^i$ , upon receiving the query, will compute

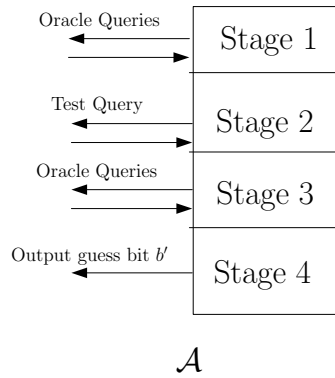
what the protocol specification demands and return to  $\mathcal{A}$  the response message and/or decision. If  $\Pi_{U_1,U_2}^i$  has either accepted with some session key or terminated, this will be made known to  $\mathcal{A}$ .

- The **Reveal**( $U_1, U_2, i$ ) query allows  $\mathcal{A}$  to expose an old session key that has been previously accepted.  $\Pi_{U_1,U_2}^i$ , upon receiving this query and if it has accepted and holds some session key, will send this session key back to  $\mathcal{A}$ .
- The **Corrupt**( $U_1, K_E$ ) query allows  $\mathcal{A}$  to corrupt the principal  $U_1$  at will, and thereby learn the complete internal state of the corrupted principal. The corrupt query also gives  $\mathcal{A}$  the ability to overwrite the long-lived key of the corrupted principal with any value of her choice (i.e.  $K_E$ ). This query can be used to model the real world scenarios of an insider cooperating with the adversary or an insider who has been completely compromised by the adversary.
- The **Test**( $U_1, U_2, i$ ) query is the only oracle query that does not correspond to any of  $\mathcal{A}$ 's abilities. If  $\Pi_{U_1,U_2}^i$  has accepted with some session key and is being asked a **Test**( $U_1, U_2, i$ ) query, then depending on a randomly chosen bit  $b$ ,  $\mathcal{A}$  is given either the actual session key or a session key drawn randomly from the session key distribution.

Note that in the original BR93 model, the **Corrupt** query is not allowed. However, such a query is important as it captures the notion of unknown key share attack [25] and insider attack. Hence, later proofs of security in the BR93 model [1, 11, 12, 15, 20, 29, 30, 37] allow such a query.

### 2.1 Definition of Partnership

Partnership is defined using the notion of matching conversations, where a conversation is defined to be the sequence of messages sent and received by an oracle. The sequence of messages exchanged (i.e., only the **Send** oracle queries) are recorded in the transcript,  $T$ . At the end of a protocol run,  $T$  will contain the record of the **Send** queries and the responses as shown in Figure 1. Definition 1 gives


 Figure 2: Game simulation  $\mathcal{G}$ 

**Stage 1:**  $\mathcal{A}$  is able to send any **Send**, **Reveal**, and **Corrupt** oracle queries at will.

**Stage 2:** At some point during  $\mathcal{G}$ ,  $\mathcal{A}$  will choose a fresh session on which to be tested and send a **Test** query to the fresh oracle associated with the test session. Note that the test session chosen must be fresh. Depending on a randomly chosen bit  $b$ ,  $\mathcal{A}$  is given either the actual session key or a session key drawn randomly from the session key distribution.

**Stage 3:**  $\mathcal{A}$  continues interacting with the protocol by making any **Send**, **Reveal**, and **Corrupt** oracle queries of its choice.

**Stage 4:** Eventually,  $\mathcal{A}$  terminates the game simulation and outputs a bit  $b'$ , which is its guess of the value of  $b$ .

a simplified definition of matching conversations for the case of the protocol shown in Figure 1.

**Definition 1 (BR93 Definition of Matching Conversations [9]).** Let  $n$  be the maximum number of sessions between any two parties in the protocol run. Run the protocol shown in Figure 1 in the presence of a malicious adversary  $\mathcal{A}$  and consider an initiator oracle  $\Pi_{A,B}^i$  and a responder oracle  $\Pi_{B,A}^j$  who engage in conversations  $C_A$  and  $C_B$  respectively.  $\Pi_{A,B}^i$  and  $\Pi_{B,A}^j$  are said to be partners if they both have matching conversations, where

$$\begin{aligned} C_A &= (\tau_0, 'start', \alpha_1), (\tau_2, \beta_1, \alpha_2) \\ C_B &= (\tau_1, \alpha_1, \beta_1), (\tau_3, \alpha_2, *), \text{ for } \tau_0 < \tau_1 < \dots \end{aligned}$$

The matching conversations play a significant role as they bind together incoming and outgoing messages, and uniquely identify a particular session.

## 2.2 Definition of Freshness

The notion of freshness is used to identify the session keys about which  $\mathcal{A}$  ought not to know anything because  $\mathcal{A}$  has not revealed any oracles that have accepted the key and has not corrupted any principals knowing the key. Definition 2 describes freshness in the BR93 model, which depends on the notion of partnership in Definition 1.

**Definition 2 (Definition of Freshness).** Oracle  $\Pi_{A,B}^i$  is fresh (or it holds a fresh session key) at the end of execution, if, and only if, oracle  $\Pi_{A,B}^i$  has accepted with or without a partner oracle  $\Pi_{B,A}^j$ , both oracle  $\Pi_{A,B}^i$  and its partner oracle  $\Pi_{B,A}^j$  (if such a partner oracle exists) have not been sent a **Reveal** query, and the principals  $A$  and  $B$  of oracles  $\Pi_{A,B}^i$  and  $\Pi_{B,A}^j$  (if such a partner exists) have not been sent a **Corrupt** query.

## 2.3 Definition of Security

Security is defined using the game  $\mathcal{G}$ , played between a malicious adversary  $\mathcal{A}$  and a collection of  $\Pi_{U_x, U_y}^i$  oracles for players  $U_x, U_y \in \{U_1, \dots, U_{N_p}\}$  and instances  $i \in \{1, \dots, N_s\}$ . The adversary  $\mathcal{A}$  runs the game simulation  $\mathcal{G}$ , whose setting is described in Figure 2.

Success of  $\mathcal{A}$  in  $\mathcal{G}$  is quantified in terms of  $\mathcal{A}$ 's advantage in distinguishing whether  $\mathcal{A}$  receives the real key or a random value.  $\mathcal{A}$  wins if, after asking a **Test**( $U_1, U_2, i$ ) query, where  $\Pi_{U_1, U_2}^i$  is fresh and has accepted,  $\mathcal{A}$ 's guess bit  $b'$  equals the bit  $b$  selected during the **Test**( $U_1, U_2, i$ ) query. Let the advantage function of  $\mathcal{A}$  be denoted by  $\text{Adv}^{\mathcal{A}}(k)$ , where

$$\text{Adv}^{\mathcal{A}}(k) = 2 \times \Pr[b = b'] - 1.$$

We require the definition of a negligible function, as described in Definition 3.

**Definition 3 ([6]).** A function  $\epsilon(k) : \mathbb{N} \rightarrow \mathbb{R}$  in the security parameter  $k$ , is called negligible if it approaches zero faster than the reciprocal of any polynomial. That is, for every  $c \in \mathbb{N}$  there is an integer  $k_c$  such that  $\epsilon(k) \leq k^{-c}$  for all  $k \geq k_c$ .

Definition 4 describes the BR93 security definition.

**Definition 4 (BR93 Definition of Security [9]).** A protocol is secure in the BR93 model if for all PPT adversaries  $\mathcal{A}$ ,

- 1) if uncorrupted oracles  $\Pi_{A,B}^i$  and  $\Pi_{B,A}^j$  complete with matching conversations, then the probability that there exist  $i, j$  such that  $\Pi_{A,B}^i$  accepted and there is no  $\Pi_{B,A}^j$  that had engaged in a matching session is negligible.
- 2)  $\text{Adv}^{\mathcal{A}}(k)$  is negligible.

If both requirements of Definition 4 are satisfied, then  $\Pi_{A,B}^i$  and  $\Pi_{B,A}^j$  will also have the same session key.

### 2.4 Protocol Security

Security of a protocol is proved by finding a reduction to some well known computational problem whose intractability is assumed, and in this paper, the Bilinear Inverse Diffie-Hellman (BIDH) problem. Let  $\mathbb{G}_1, \mathbb{G}_2$  be two groups of prime order  $q$ ,  $\hat{e} : \mathbb{G}_1 \times \mathbb{G}_1 \rightarrow \mathbb{G}_2$ ,  $P$  be a generator of  $\mathbb{G}_1$ , and  $a, b \in_R \mathbb{Z}_q^*$ .

#### Bilinear Inverse Diffie-Hellman (BIDH) Problem.

Instance :  $(P, aP, bP)$   
 Output :  $\hat{e}(P, P)^{a^{-1}b} \in \mathbb{G}_2$ .

The BIDH problem has been shown to be polynomial time equivalent to the better known Bilinear Diffie-Hellman (BDH) problem [13] in recent work of Zhang, Safavi-Naini, & Susilo [39]. In order to help the descriptions later we here introduce another property which is often ignored.

**Definition 5 (Key Integrity [27]).** *Key integrity is the property that the key has not been modified by the adversary, or equivalently only has inputs from legitimate principals.*

- For a key transport protocol, key integrity means that if the key is accepted by any principal it must be the same key as chosen by the key originator.
- For a key agreement protocol, key integrity means that if a key is accepted by any principal it must be a known function of only the inputs of the protocol principals.

## 3 McCullagh–Barreto Protocols

In this section, we revisit the 2P-IDAKA protocol and its variant due to McCullagh & Barreto [30]. Example executions of the protocols in the presense of a malicious adversary are used to demonstrate why the protocols are not secure if the adversary is allowed access to **Reveal** query. We omit the standard (mathematical preliminaries) details, which are not necessary to understand the key replicating attack in this section. Interested reader can refer to the original paper of McCullagh & Barreto.

Notation used in the protocols is as follows:  $(s + a)P$  denotes the public key of A,  $A_{pri} = ((s + a))^{-1}P$  denotes the private key of A,  $(s + b)P$  denotes the public key of B, and  $B_{pri} = ((s + b))^{-1}P$  denotes the private key of B,  $x_a$  and  $x_b$  denote random nonces where  $x_a, x_b \in_R \mathbb{Z}_r^*$ .

### 3.1 2P-IDAKA Protocol

The 2P-IDAKA protocol is shown in Figure 3. There are two entities in the protocol, namely an initiator player A and a responder player B. The 2P-IDAKA protocol shown in Figure 3 carries a proof of security in the BR93 model.

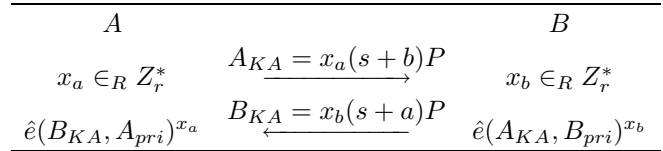


Figure 3: McCullagh–Barreto 2P-IDAKA protocol

At the end of the 2P-IDAKA protocol execution, both A and B accept session keys

$$\begin{aligned}
 SK_{AB} &= \hat{e}(B_{KA}, A_{pri})^{x_a} = \hat{e}(P, P)^{x_a x_b} \\
 SK_{BA} &= \hat{e}(A_{KA}, B_{pri})^{x_b} = \hat{e}(P, P)^{x_a x_b} \\
 &= SK_{AB}.
 \end{aligned}$$

### 3.2 A Variant of 2P-IDAKA Protocol

Figure 4 describe a variant of the 2P-IDAKA protocol proposed to address Xie’s attack [38].

At the end of the fixed protocol execution, both A and B accept session keys

$$\begin{aligned}
 SK_{AB} &= e(P, P)^{x_a} e(B_{KA}, A_{pri}) = e(P, P)^{x_a + x_b} \\
 SK_{BA} &= e(P, P)^{x_b} e(A_{KA}, B_{pri}) = e(P, P)^{x_a + x_b} \\
 &= SK_{AB}.
 \end{aligned}$$

### 3.3 Key Replicating Attacks on the Protocols

We now describe the key replicating attack first discussed by Krawczyk [28] as presented in Definition 6.

**Definition 6 (Key Replicating Attack [28]).** *A key replicating attack is defined to be an attack whereby the adversary,  $\mathcal{A}$ , succeeds in forcing the establishment of a session,  $S$ , (other than the **Test** session or its matching session) that has the same key as the **Test** session. In this case,  $\mathcal{A}$  can distinguish whether the **Test**-session key is real or random by asking a **Reveal** query to the oracle associated with  $S$ .*

Figures 5 and 6 illustrate example execution of the protocols in the presense of a malicious adversary,  $\mathcal{A}$ .

In the attack sequences shown in Figures 5 and 6, both A and B have accepted the same session key. However, both A and B are non-partners since they do not have matching conversations as described in Definition 1. Hence,  $\mathcal{A}$  succeeds in forcing the establishment of a session,  $\Pi_B$ , (other than the **Test** session or its matching session) that has the same key as the **Test** session (i.e.,

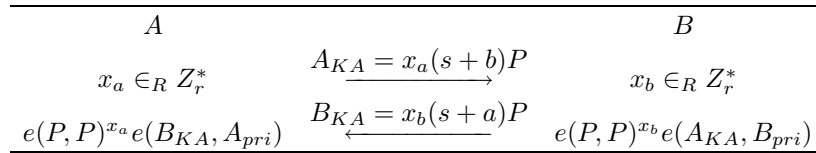


Figure 4: Proposed fix to Xie (2004)'s attack – variant protocol

key-replicating attack as described in Definition 6). Consequently,  $\mathcal{A}$  is able to trivially expose a fresh session key by asking a Reveal query to either  $A$  or  $B$ , and has a non-negligible advantage in distinguishing the Test key (i.e.  $\text{Adv}^{\mathcal{A}}(k)$  is non-negligible). Furthermore, session keys comprise keying material contributed by  $\mathcal{A}$ ,  $x_E$ , in violation of the key integrity property described in Definition 5.

### 3.4 Remarks

In recent work [20], we demonstrate that the McCullagh–Barreto 2P-IDAKA protocol can be proven secure in the BR93 model without restricting the adversary,  $\mathcal{A}$ , from asking the Reveal queries in most situations (i.e.,  $\mathcal{A}$  is restricted from asking Reveal queries to any sessions associated with the owner of the target Test session), by simply making a small change to the way that session keys are constructed in the protocol. However, if the Gap Bilinear Diffie-Hellman (GBDH) assumption due to Okamoto & Pointcheval [32] is used, then the improved McCullagh–Barreto 2P-IDAKA protocol can be proven secure in the BR93 model without any restriction.

## 4 Conclusion

Through a detailed study of the McCullagh–Barreto 2P-IDAKA protocol and its variant, we had demonstrated why the protocol and its variant are insecure if the adversary is allowed to reveal non-partner players who share the same session key and obtain a fresh session key, in violation of the definition of security in the BR93 model (in which the protocol is proven secure). We also demonstrated that the protocols do not achieve the key integrity property.

## Acknowledgments

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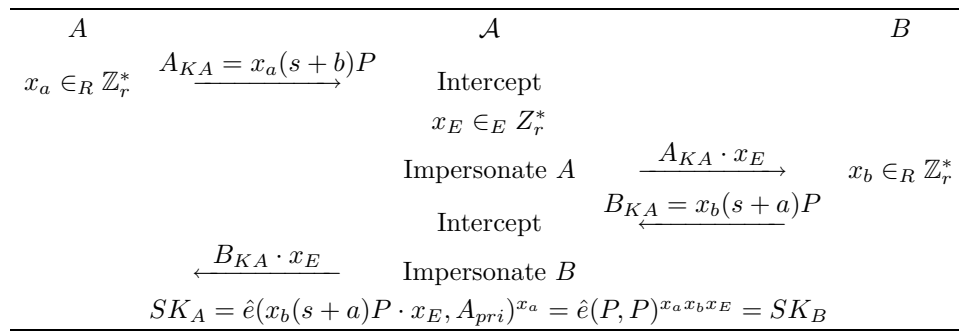


Figure 5: Execution of the 2P-IDAKA protocol in the presence of a malicious adversary,  $A$

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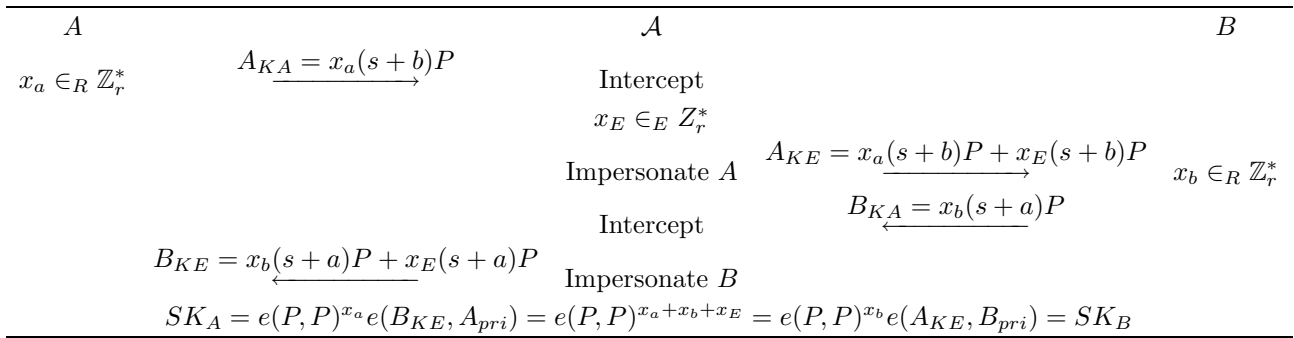


Figure 6: Execution of the variant protocol in the presence of a malicious adversary,  $\mathcal{A}$

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**Kim-Kwang Raymond Choo** received his BSc Maths, BAppSci (Hons) Industrial & Applied Maths, and Master of Information Technology degrees in Dec 2000, Dec 2002, and May 2002 respectively. He is currently a full-time Ph.D. candidate with Information Security Institute, Queensland University of Technology, Australia; and a part-time MBA student with the University of Queensland. His research interests include formal specification and analysis of mutual authentication and/or key establishment protocols, and provably-secure protocols.