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Efficient and Provably Secure Generic Construction of Client-to-Client Password-Based Key Exchange Protocol

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**Abstract**

Client-to-client password authenticated key exchange (C2C-PAKE) protocol enables two clients who only share their passwords with their own servers to establish a shared key for their secure communications. Recently, Byun *et al.* and Yin-Li respectively proposed first provably secure C2C-PAKE protocols. However, both protocols are found to be vulnerable to undetectable online dictionary attacks and other attacks. In this paper, we present an efficient generic construction for cross-realm C2C-PAKE protocols and prove its security in the Random-or-Real model due to Abdalla *et al.*, without making use of the Random Oracle model.

*Keywords:* Password-authenticated key exchange, cross realm, client-to-client, provably secure, general construction.

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# Introduction

Client-to-client password-authenticated key exchange protocols (C2C-PAKE) are important cryptographic techniques for secure communications. Conceptually, a typical C2C-PAKE protocol works as follows. It is required that each client should share a human-memorable password with his own trusted server. When two clients want to establish a shared session key, they resort to their own trusted server for authenticating each other. Therefore, a communicating party who wants to build secure communications with other parties does not need to remember so many pass- words whose number would be large linearly in the number of all possible partners, instead it only holds a password shared with his trusted server. Due to this advan- tage, it has attracted a lot of attention and many C2C-PAKE protocols have been proposed [[1](#_bookmark4),[2](#_bookmark5),[3](#_bookmark6),[4](#_bookmark7),[5](#_bookmark8),[6](#_bookmark9),[7](#_bookmark10)] in recent years.

Byun *et al.* [[1](#_bookmark4)] first proposed a C2C-PAKE protocol in the cross-realm setting by using the key distribution centers(KDCs) in the different realms as the go-between. They have heuristically proved that the schemes were secure against all consid- ered attacks. Such protocols are more popularly known as cross-realm C2C-PAKE protocols. For simplicity, we will call these C2C-PAKEs for the rest of this paper.

Nevertheless, most of the existing C2C-PAKE protocols were only analyzed in ad hoc without a formal security model. Hitherto, only Byun *et al.* [[6](#_bookmark9)] and Yin-Li

[[7](#_bookmark10)] respectively proposed provably secure C2C-PAKE protocols, with security based on computationally intractable assumptions. However, Phan and Goi [[8](#_bookmark11)] found that both protocols fall to undetectable online dictionary attacks by any adversary and

that the protocol of Byun *et al.* [[6](#_bookmark9)] can not keep the malicious servers from launching

a successful man-in-the-middle attack and the Yin-Li [[7](#_bookmark10)] scheme inherits a weakness against unknown key-share attacks.

To our knowledge, there exists no generic construction of C2C-PAKE in the cross-realm setting. Recently, Abdalla *et al.* [[9](#_bookmark12)] proposed a generic method to construct provably secure single-server C2C-PAKE protocol. However, Wang and

Hu [[10](#_bookmark13)] found their scheme suffer from undetectable on-line dictionary attacks, and they introduced a new efficient generic construction scheme for the 3-party PAKE protocols. In this paper, based on Wang-Hu’s scheme we presented a new generic construction for the cross-realm C2C-PAKE protocols which is not only efficient but also resistant to both off-line and undetectable on-line dictionary attacks. Moreover,

we prove its security in Abdalla *et al.*’s Real-or-Random(ROR) model [[9](#_bookmark12)].

The paper is organized as follows. In Section 2, we describe our generic con- struction for the cross-realm C2C-PAKE protocols. To prove its security, in Section 3, we recall the ROR model, necessary basic assumptions and the definition of secu- rity. In Section 4, we focus on the security of the new scheme and provides details of the security proof. Finally, concluding remarks are given in Section 5.

# General Construction of C2C-PAKE Protocols

In this section, we present a generic construction for client-to-client password-based key exchange protocols (referred as C2C-GPAKE) in the scenario in which we have an honest-but-curious server. The construction could be viewed as an extension of the scheme proposed in [[10](#_bookmark13)], which in turn is an enhancing of Abdalla *et al.*’s generic construction[[9](#_bookmark12)] which is designed for 3-party PAKE. More precisely, we ex- tend Wang-Hu’s scheme to two separate servers, and present the construction using a 2-party password-based key exchange and a 2-party MAC-based key exchange protocol. Similarly to the construction of Abdalla *et al.*, the proposed scheme is essentially a form of compiler transforming any secure 2-party PAKE protocol into a secure C2C-PAKE protocol, and thus can be used to create a series of provably secure C2C-PAKE protocols.

* 1. *Scheme Description*

The general construction involves in four participants, denoted as *A*, *S*1, *B* and *S*2, respectively, where *A* is a client in the realm of server *S*1, *B* is a client in the realm of server *S*2. We assume that the key *K* is pre-distributed between *S*1 and *S*2 by using a two party key exchange protocol. The detailed steps of the C2C-GPAKE, as shown in Figure [1](#_bookmark1), are described as follows:

*A*(*pwA*)

*S*1(*pwA*)

*S*2(*pwB*)

*B*(*pwB*)

2*P AKE*(*skA*)

*⇐⇒*

2*P AKE*(*skB*)

*⇐⇒*

*ga,MACsk* (*ga,A,B*)

*−−−−−−−A−−−−→*

*gb,MACsk* (*gb,B,A*)

*←−−−−−B−−−−−−*

*ga,MACK* (*ga,A,B*)

*−−−−−−−−−→*

*gb,MACK* (*gb,B,A*)

*←−−−−−−−−−*

*gb,MACsk* (*gb,B,A*)

*←−−−−−−A−−−−−*

*ga,MACsk* (*ga,A,B*)

*−−−−−−−B−−−−→*

Fig. 1. C2C-GPAKE: a generic client-to-client password-based key exchange

* + - Step 1: The users *A* and *B* establish two secure high-entropy session keys *skA* and *skB* with the trusted server *S*1 and *S*2, respectively, by using any semantic secure 2-party PAKE protocol.
    - Step 2: Using the session keys *skA* and *skB* generated in the first step as the MAC key, *A* and *B* can concurrently authenticate and send their respective temporary Diffie-Hellman public keys to their own server *S*1 and *S*2, respectively.
    - Step 3: Upon receiving and confirming the temporary public key from the client *A*, the server *S*1 authenticates and transfers a temporary public key of *A* to *S*2 by using the MAC scheme with the symmetrical key *K* between *S*1 and *S*2. Similarly, the server *S*2 authenticates and transfers a temporary public key of *B* to *S*1 in

the same way.

* Step 4: Finally, *S*1 and *S*2 send the temporary public keys of *B* and *A* to *A* and *B*, respectively. In this manner, *A* and *B* establish a session key in an authenticated way, with the cooperation of the trusted servers *S*1 and *S*2.

# Formal Models for Cross-Realm C2C-PAKE Protocol

The first security model about key exchange protocol was proposed by Bellare and Rogaway in [[11](#_bookmark14)]. After that, Bellare *et al.* extended their model to password-based key exchange protocol [[12](#_bookmark15)] in 2000. Recently, Abdalla *et al.* provided a new and stronger security model [[9](#_bookmark12)] by modifying the previous one [[12](#_bookmark15)] slightly and called it Real-or-Random (ROR) model. They suggested to use the ROR model for proving the security of their password-based schemes. In this section, we utilize this formal model to prove the security of our generic construction for our cross-realm client- to-client password-based key exchange.

* 1. *Communication Model*

We denote *A*, *B* as two clients belonging to two different realms. Client *A* shares his password *pwA* with server *S*1, and client *B* shares his password *pwB* with another server *S*2. *S*1 and *S*2 share the common key *K* which is pre-distributed between them by using a 2-party key exchange protocol. All clients’ passwords are chosen from the same small dictionary *D* whose distribution is *Dpw*.

The generic construction of cross-realm C2C-PAKE is an interactive scheme among four participants’ instances: *Ai*, *Bj* , *Ss*, *St* . In the end, *Ai* and *Bj* establish

1 2

a session key *sk*. In the model, it is assumed that an adversary *A* has full control over the communication channels and can create several concurrent instances of the protocol. During the execution of the protocol, adversary *A* interacts with participants only via oracle queries, which model adversary’s possible attacks in the real execution. All possible oracle queries are listed in the following, where *Ui* (*Sj* , respectively) denotes the *i*-th (*j*-th, respectively) instance of a participant *U* (*S*, respectively):

* + - *Execute*(*Ai*, *Bj* , *Ss*, *St* ): This query models passive attacks in which the at-

1 2

tacker eavesdrops on honest executions. The output of this query consists of the messages that were exchanged during the honest execution of the protocol.

* + - *SendClient*(*Ui*, *m*): This query models an active attack. After querying the oracle, a message *m* is sent to the client instance *Ui*. Finally, client instance *Ui* forwards its response to *A*.
    - *SendServer*(*Si*, *m*): This query models an active attack against a server. It out- puts the message that server instance *Si* would generate upon receipt of message *m*.
    - *Test*(*Ui*): If a *Test* query is asked to a client instance that has not *accepted*, then return the undefined *⊥*. If a *Test* query is asked to an instance of an honest

client whose intended partner is dishonest or to an instance of a dishonest client, then returns the real session key. Otherwise, returns either the real session key if *b* = 1 or a random one if *b* = 0, where *b* is the hidden bit selected at random prior to the first call.

**Partnering:** The definition of partnering uses the session identifications(*sid*). More specifically, two instances *Ui* and *Uj* are said to be partners if the following conditions are satisfied:

1. Both *Ui* and *Uj* accept;
2. Both *Ui* and *Uj* own the same *sid*;
3. *Ui* is *Uj* ’s partner and vice-verse; and
4. No instance other than *Ui* and *Uj* accepts with a partner identity equal to

*Ui* or *Uj* .

**Freshness.** An instance *Ui* is said to be fresh if it has accepted and no *Reveal*

queries have been made to it or its partner.

* 1. *Building Blocks*

In our generic construction for the client-to-client PAKE protocols, two crypto- graphic primitives are used as building blocks: decisional Diffie-Hellman assumption and message authentication codes.

**Decisional Diffie-Hellman assumption: DDH**. The DDH assumption can

be precisely defined by two experiments, Exp*ddh−real*(*A*) and Exp*ddh−rand*(*A*). An

G G

adversary *A* is provided with *gx*, *gy* and *gxy* in the former experiment, and *gx*, *gy*

and *gz* in the latter one, where *x*, *y* and *z* are drawn at random from *{*1, ..., G*}*.

Define the advantage of *A* in violating the DDH assumption as follows:

*Advddh*(*t*) = *max{|* Pr[*Expddh−real*(*A*) = 1] *−* Pr[*Expddh−rand*(*A*) = 1]*|}*.

G G G

where the maximum is over all adversaries *A* running in time at most *t*. The DDH assumption in G holds if *Advddh*(*t*) is a negligible function of *t*.

G

**Message authentication codes.** A message authentication code scheme MAC=(Key,Tag,Ver) is composed of a MAC key generation algorithm Key, a MAC generation algorithm Tag and a MAC verification algorithm Ver. A secure MAC should prevent existential forgeries under chosen-message attacks(EUF-CMA) if ad- versaries has access to the generation and verification oracles. That is, it can not create a new valid message-tag pair, even after obtaining many valid message-tag pairs. The maximal value of the advantage *Adveuf−cma*(*A*) with at most *t* time complexity and at most *qg* and *qv* queries to its MAC generation and verification oracles, respectively, is a negligible function of the parameters above.

*MAC*

* 1. *Security Deﬁnition*

According to [[7](#_bookmark10)], a secure generic construction of cross-realm C2C-PAKE should satisfy the following security requirements: (1) The session key cannot be distin- guished from a random number by an adversary; (2) The servers do not know the

session key between clients; (3) The client can authenticate his server and vice-verse;

(4) The client does not know other client’s password; and (5) Clients’ passwords are not revealed to other servers except for their own servers. We define the following security notions:

**Semantic Security in the ROR model:** During the executing, the adversary *A* is allowed to send multiple queries to the *Execute*, *SendClient*, *SendServer*, and *Test* oracles as it wants, while it is no longer allowed to ask *Reveal* queries which is allowed in the model of Abdalla *et al.* [[9](#_bookmark12)]. Notice that, when *b*=0, the same random key value should be returned for *Test* queries that are asked to two instances which are partnered.

We say the adversary *A* succeeds if he correctly guesses the bit *b* hidden in the *Test* oracle. Let *Succ* denote the event that *A* succeeds. Provided that passwords are drawn from dictionary *D*, we define the advantage of *A* as:

*Advror−ake*(*A*) = 2 *·* Pr[*Succ*] *−* 1*, Advror−ake*(*t, R*) = *max{Advror−ake*(*A*)*}*,

*P,D*

*P,D P,D*

where the maximum is over all adversaries with time-complexity at most *t* and using at most *R* times oracle queries.

The scheme of C2C-GPAKE is said to be semantically secure if the advantage *Advror−ake*(*t, R*) is only negligibly larger than *kn/|D|*, where *n* is number of active sessions and *k* is a constant.

*P,D*

**Key Privacy with respect to the server:** This security requires no infor- mation about the session key revealed to the server who knows all passwords of his members but behaves in an honest-but-curious manner. The adversary *A* has access to all the passwords. To capture the adversary’s ability to tell apart the real session key shared between any two instances from a random one, Abdalla *et al.*[[9](#_bookmark12)] introduced a new type of oracle, called *TestPair*, defined as follows, where *b* is a bit chosen uniformly at random at the beginning of the experiment.

TestPair(*Ai, Bj* ): If client instances *Ai* and *Bj* do not share the same key, then return the undefined symbol *⊥*. Otherwise, return the real session key shared be- tween *Ai* and *Bj* if *b*=1 or a random key of the same size if *b*=0.

During the executing, the adversary *A* has access to the passwords of all users and multiple queries to the *Execute*, *SendClient* and *TestPair* oracles as it wants, and let *b*0 be its output. Such an adversary is said to win the experiment if *b*0 = *b*, where *b* is the hidden bit used by the *TestPair* oracle. Let *Succ* denote the event in which the adversary guesses *b* correctly. We can then define the kp-advantage *Advkp−ake*(*A*) of *A* in violating the key privacy of the key exchange protocol P and

*P,D*

the advantage function *Advkp*(*t, R*) of P as in previous definitions.

*D*

Finally, we say an adversary *A* succeeds in breaking the key privacy of a protocol P if its advantage *Advkp−ake*(*A*) is non-negligible.

*P,D*

**Authentication Security:** Most of the existing password-based authenticated key exchange protocols are vulnerable to the undetectable on-line dictionary at-

tacks due to the absence of authentication of messages between the client and the server. In order to solve this problem, we introduce the definition of the unilat- eral authentication from the client to the trusted server as [[10](#_bookmark13)] does. We denote by *Succauth*(*c→s*)(*A*) the probability that an adversary *A* successfully impersonates a client instance during executing the protocol P while the trusted server does

*P*

not detect it. Further, *Succauth*(*c→s*)(*A*) = *max{Advauth*(*c→s*)(*A*)*}* is defined as

*P P*

the maximum over all *A* running in time at most *t* and using resources at most

*R*. We say a scheme of C2C-GPAKE is client-to-server authentication secure if

*Succauth*(*c→s*)(*t, R*) is negligible in the security parameter.

*P*

**Password Protection Against Malicious Client:** The malicious client *C* succeeds if he successfully learns another client’s password. Since *Test* oracle query is used to define the session key’s security, the malicious client does not have access to *Test* query. Let *D* be user’s password dictionary. For any malicious client *C*, define his advantage *Succpw−mc* as

*D*

*Advpw−mc*(*C*) = Pr[*Succpw−mc*],

*D*

*Advpw−mc*(*t, R*) = *max{Advpw−mc*(*C*)*}*,

*D D*

where the maximum is over all adversaries with time-complexity at most *t* and querying oracles at most *R* times. We say P satisfies password protection against malicious client if the advantage *Advpw−mc* is only negligibly larger than *O*(*qs*)*·Dpw*, where *qs* is the number of all send queries, *Dpw* is the distribution of password dictionary.

**Password Protection Against Honest-but-Curious Server:** An honest- but-curious server *S* succeeds if he successfully learns the passwords of the clients which belongs to other servers. For any honest-but-curious server *S*, we define his advantage *Advpw−ms*(*S*) as

*D*

*Advpw−ms*(*S*) = Pr[*Succpw−ms*],

*D*

*Advpw−ms*(*t, R*) = *max{Advpw−ms*(*S*)*}*,

*D D*

where the maximum is over all adversaries with time-complexity at most *t* and querying oracles at most *R* times.

We say P satisfies password protection against malicious server if the advantage *Advpw−ms* is only negligibly larger than *O*(*qs*) *· Dpw*, where *qs* is the number of all send queries, *Dpw* is the distribution of password dictionary.

# Security proof

In this section, we examine all security requirements proposed in the subsection 3.2 and show they are all met.

**Semantic Security in the ROR model.** As the following theorem states, the generic scheme C2C-GPAKE is a secure client-to-client password-based key exchange protocol as long as the Decisional Diffie-Hellman assumption holds in G and the underlying primitives it uses are secure.

**Theorem 4.1** *Let 2PAKE be a semantic secure 2-party PAKE protocol and MAC be a secure MAC algorithm. Let qexe and qtest denote the numbers of queries to*

*Execute and Test oracles, and qA*

*send*

*, q*

*B*

*send*

*, and qake be the numbers of queries to*

*the SendClient and SendServer oracles with respect to each of the two 2PAKE protocols and the MAC-based authenticated key exchange protocols. Then,*

*ror−ake C*2*C−GPAKE,D*

*Adv*

(*t, qexe, qtest, qA*

*B*

*send*

*, q*

*, qake*)

*ror−ake*

*send*

*≤* 2 *· Adv*

2*PAKE,D*

(*t, qexe, qexe* + *qA*

*A*

*send*

*, q*

)

*ror−ake*

*send*

+2 *· Adv*

2*PAKE,D*

(*t, qexe, qexe* + *qB*

*B*

*send*

*, q*

)

+2 *· qake · Adveuf−cma*(*t,* 2*,* 0)

*send*

*MAC*

+2 *· Advddh*(*t* + 8(*qexe* + *qake*) *· τG*)

G

*where τG denotes the exponentiation computational time in* G*.*

**Proof.** We follow the proof of Wang-Hu, which in turn is of Abdalla *et al.*[[9](#_bookmark12)]. Without loss of generality, we assume the set of honest users contains only users *A* and *B*. It can be easily extended to the more general case. Let *A* be an adversary against the semantic security of C2C-GPAKE in the Real-or-Random model with time-complexity at most *t*, and asking at most *qexe* queries to its *Execute* oracle,

, *q*

*qtest* queries to its *Test* oracle, *qA*

*send*

*B*

*send*

queries to *SendClient* and *SendServer*

oracles corresponding to the 2PAKE protocol between *A* and the trusted server *S*1,

and between *B* and the trusted server *S*2, respectively. *qAS* queries to *SendClient*

*ake*

and *SendSever* oracles corresponding to the authenticated key exchange protocol

between *A* and *S*1, and *qBS* queries to the oracles corresponding to the protocol

*ake*

between *B* and *S*2. Our proof consists of a sequence of hybrid experiments, starting

with the real attack against C2C-GPAKE scheme and ending in a game in which the adversary’s advantage is 0. For each game *Gi*, define an event *Succi* corresponding to the case in which the adversary correctly guesses the hidden bit *b* involved in the *Test* queries in game *Gi*.

**Game** *G*0. This game corresponds to the real attack. By definition, we have

*ror−ake C*2*C−GPAKE,D*

*Adv*

(*A*) = 2 *·* Pr[*Succ*0] *−* 1.

**Game** *G*1. We now modify the simulation of the oracles as the proof of Wang- Hu which uses a random session key *sk'* , instead of the session key *skA*, as the MAC key in all of the sessions between *A* and *S*1. So, we have the following lemma:

*A*

**Lemma 4.2** *|* Pr[*Succ*1] *−* Pr[*Succ*0]*|≤* 2 *· Advror−ake*

2*PAKE,D*

(*t, qexe, qexe* + *qA*

*send*)*.*

**Game** *G*2**.** This game is the same as the previous one except that we replace

*send*

*, q*

*A*

the session key *skB* with a random session key *sk'* in all of the sessions between *B*

*B*

and *S*2. So, we have the similar argument:

*, q*

*B*

**Lemma 4.3** *|* Pr[*Succ*2] *−* Pr[*Succ*1]*|≤* 2 *· Advror−ake*

2*PAKE,D*

(*t, qexe, qexe* + *qB*

*send*

*send*)*.*

**Game** *G*3**.** In this game, we use a random key *K'*, instead of the key *K* in all of the sessions between *S*1 and *S*2. In fact, since *K* is pre-distributed between *S*1 and *S*2 by using two party key exchange protocol, we can view it as a random and independent value, so this game is equivalent to the previous one. Thus, we have Pr[*Succ*3] = Pr[*Succ*2].

**Game** *G*4**.** This game is modified as follows. If the adversary asks a *SendClient* or *SendServer* query for AKE between *A* and *S*1 involving a new pair of message tag not previously generated by an oracle, then we consider the MAC tag invalid and abort the game. So we have the following arguments:

**Lemma 4.4** *|* Pr[*Succ*4] *−* Pr[*Succ*3]*|≤ qAS · Adveuf−cma*(*t,* 2*,* 0)*.*

*ake MAC*

**Game** *G*5**.** This game is the same as the previous one except that the adversary asks a *SendClient* or *SendServer* query for AKE between *B* and *S*2. Hence

**Lemma 4.5** *|* Pr[*Succ*5] *−* Pr[*Succ*4]*|≤ qBS · Adveuf−cma*(*t,* 2*,* 0)*.*

*ake MAC*

The following two games *G*6 and *G*7 is the same as the last two games of proof of Wang-Hu. So we have the following two conclusions:

Pr[*Succ*6] = Pr[*Succ*5] *and*

**Lemma 4.6** *|* Pr[*Succ*7] *−* Pr[*Succ*6]*|≤ Advddh*(*t* + 8(*qexe* + *qake*)*τG*)*, where qake* =

*G*

*qAS* + *qBS.*

*ake ake*

Since no information on the bit *b* in the *Test* oracle is leaked to the adversary, Pr[*Succ*7] = 1*/*2. This result combined with the previous lemmas yields the result in Theorem [4.1](#_bookmark2).

**Key Privacy respect to Server:** An honest-but-curious server only has access to *Sendclient*, *Execute* and *Testpair* oracles. As the following theorem states, the generic scheme C2C-GPAKE has key privacy with respect to the server as long as the DDH assumption holds in G.

**Theorem 4.7** *In our cross-realm C2C-GPAKE protocol, an honest-but-curious server cannot learn the session key between clients as long as the DDH assump- tion holds in the group* G*. Formally,*

*kp−ake C*2*C−GPAKE,D*

*Adv*

(*t, qexe, qtest, qA*

*B*

*send*

*, q*

*, qake*) *≤* 2 *· Advddh*(*t* + 8(*qexe* + *qake*) *· τe*)

*where the parameters are deﬁned as in Theorem* [*4.1*](#_bookmark2)*.*

*send*

G

**Proof.** The proof is similar to the games *G*6 and *G*7 in the proof of semantic security of C2C-GPAKE. Let *Akp* be an adversary against the key privacy of C2C-GPAKE whose time-complexity is at most *t*. Moreover, *Akp* asks at most *qexe* queries to

its *Execute* oracle, *qtest* queries to its *TestPair* oracle, *qAS* queries to *SendClient*

*ake*

and *SendSever* oracles corresponding to the authenticated key exchange protocol

between *A* and *S*1, and *qBS* queries to the oracles corresponding to the protocol

*ake*

between *B* and *S*2. We show that if *Akp* exists, we can construct an adversary *Addh*

to solve the DDH problem with non-negligible probability.

Given an instance of the DDH problem (*X, Y, Z*), *Addh* first chooses the pass- words for all users according to the distribution of *D*, then it chooses a bit *b* at random used in the *TestPair* oracle. Now it starts running *Akp* giving the pre- distributed key *K* and all the passwords of all users to it. Since *Addh* knows the password of all users, it can easily answer queries made by *Akp*. To deal with the security of the key privacy respect to server, we only consider the last flows of C2C-GPAKE. Like Abdalla’s *et al.*[[9](#_bookmark12)] proof, here we introduce the input triple in the answers to *SendClient*, *Execute*, and *TestPair* queries by using the classical random self-reducibility of the Diffie-Hellman problem.

We simulate the *Execute* oracle by using the passwords that have been chosen and *SendClient* queries, and simulate the *SendClient* and *TestPair* as follows:

R1: When a *SendClient*(*Ai, Start*) query is asked, *Addh* picks two random values *a*0 and *x*0 in *Zq*, computes *X*0 = *Xa*0 *gx*0 and stores them in a list Λ*A*. For *SendClient*(*Bj, Start*) in the same session, the simulator selects *b*0 and *y*0, computers *Y*0 and stores them in a list Λ*B* in the same measure.

R2: Upon receipt of both *SendClient*(*Ai,* (*Y*0*, mb*)) and *SendClient*(*Bj,* (*X*0*, ma*)) of the same session, the simulator checks the exis- tence of *X*0 and *Y*0 by using Λ*A* and Λ*B*, respectively. If their existence is exact, it computes *Z*0 = *Za*0*b*0 *× Y x*0*b*0 *× Xa*0*y*0 *× gx*0*y*0 in preparation for answering the *TestPair* query. Otherwise, it proceeds with the simulation as it would in a real attack.

R3: When a *TestPair*(*Ui,Uj* ) query is asked, *Addh* first checks whether *Ui* and

1 2 1

*Uj* have both accepted and have the same key. If the check fails, then *Addh* returns

2

*⊥*. If the check passes, then *Addh* knows the corresponding value *Z*0 for the secret key and can answer it based on the hidden bit *b* it had previously chosen.

Let *b*0 be the output of *Akp*. If *b*0 = *b*, then *Addh* returns 1 and 0, otherwise. As analyzed as the game *G*6 of the proof of Wang-Hu, we have the result of

Theorem [4.7](#_bookmark3).

**Authentication security:** This security aims to resist the undetectable on- line dictionary attacks which stem from an absence of authentication of messages between the client and the server, so it has nothing to do with the messages be- tween the servers. From this viewpoint, we can treat *S*1 and *S*2 as a single server. According to the games from *G*0 to *G*5, we have the following theorem:

**Theorem 4.8** *The cross-realm C2C-GPAKE satisﬁes the client-to-server authen- tication security as long as the DDH assumption holds in G and the underlying primitives it uses are secure. Formally,*

*auth*(*C→S*)

*Adv*

*C*2*C−GPAKE,D*

(*t, qexe, qtest, qA*

*B*

*send*

*, q*

*, qake*)

*ror−ake*

*send*

*≤ Adv*

2*PAKE,D*

(*t, qexe, qexe* + *qA*

*A*

*send*

*, q*

)

*ror−ake*

*send*

+*Adv*

2*PAKE,D*

(*t, qexe, qexe* + *qB*

*B*

*send*

*, q*

)

+*qake · Adveuf−cma*(*t,* 2*,* 0)

*send*

*MAC*

*where the parameters are deﬁned as in Theorem* [*4.1*](#_bookmark2)*.*

**Password Protection Against Malicious Client:** In the cross-realm C2C- GPAKE protocol, a malicious client may want to learn other client’s password. In our protocol, we suppose client *B* is malicious and his goal is to learn client *A*’s password *pwA*. This security notion is ensured by the following theorem.

**Theorem 4.9** *In our cross-realm C2C-GPAKE scheme, the malicious client B cannot learn the client A’s password as long as our cross-realm C2C-GPAKE sat- isﬁes the client-to-server authentication security. Formally,*

*pw−mc*

*Adv*

*C*2*C−GPAKE,D*

(*t, qexe, qtest, qA*

*B*

*send*

*, q*

*, qake*)

*ror−ake*

*send*

*≤ Adv*

2*PAKE,D*

(*t, qexe, qexe* + *qA*

*A*

*send*

*, q*

)

*ror−ake*

*send*

+*Adv*

2*PAKE,D*

(*t, qexe, qexe* + *qB*

*B*

*send*

*, q*

)

+*qake · Adveuf−cma*(*t,* 2*,* 0)+ (*qA*

*send*

+ *qB*

+ *qake*)*/N*

*MAC*

*send*

*send*

*where the parameters are deﬁned as in Theorem* [*4.1*](#_bookmark2)*.*

**Proof.** Since the C2C-GPAKE satisfies the client-to-server authentication security, it can resist undetectable on-line dictionary attacks. Moreover, from the execution of the protocol, since *a* is a random number and the 2PAKE is secure, so the malicious client *B* thinks the values of *ga* and *M AC*(*ga, skA, A, B*) are two independent ran- dom numbers from which no information about *pwA* is revealed to him. As a result, the probability that client *B* correctly guesses *pwA* is exactly *qs/N* after *qs* times

+ *q*

*send* queries, where *N* is the size of the dictionary and *qs* = *qA*

*send*

*B*

*send*

+ *qake*.

**Password Protection Against Malicious Server:** In our protocol, we sup- pose *S*2 is malicious and his goal is to learn client *A*’s password *pwA*. This theorem’s proof is similar to that of Theorem 4.9.

**Theorem 4.10** *In our cross-realm C2C-GPAKE protocol, the malicious server S*2

*cannot learn the client A’s password. Formally,*

*pw−ms C*2*C−GPAKE,D*

*Adv*

(*t, qexe, qtest, qA*

*B*

*send*

*, q*

*, qake*)

*ror−ake*

*send*

*≤ Adv*

2*PAKE,D*

(*t, qexe, qexe* + *qA*

*A*

*send*

*, q*

)

*ror−ake*

*send*

+*Adv*

2*PAKE,D*

(*t, qexe, qexe* + *qB*

*B*

*send*

*, q*

)

+*qake · Adveuf−cma*(*t,* 2*,* 0)+ (*qA*

*send*

+ *qB*

+ *qake*)*/N*

*MAC*

*send*

*send*

*where the parameters are deﬁned as in Theorem* [*4.1*](#_bookmark2)*.*

# Conclusion

Some generic constructions for 3-party PAKE protocols [[9](#_bookmark12),[10](#_bookmark13)] were proposed re- cently, but they do not accommodate client-to-client PAKE. Byun *et.al* [[6](#_bookmark9)] suggested

to design a generic construction of C2C-PAKE in the cross-realm setting by using 2-party PAKE and key distribution protocols, but they were not able to provide a scheme. In this paper, we present a general construction for the client-to-client PAKE protocols based on the generic construction for 3-party scenario. Moreover, we are able to prove its security by using the existing efficient protocols based on standard assumption instead of the random oracle models.

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