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Augmented Password-Authenticated Key Exchange (AugPAKE) draft-irtf-cfrg-augpake-03

Abstract

This document describes a secure and highly-efficient augmented password-authenticated key exchange (AugPAKE) protocol where a user remembers a low-entropy password and its verifier is registered in the intended server. In general, the user password is chosen from a small set of dictionary whose space is within the off-line dictionary attacks. The AugPAKE protocol described here is secure against passive attacks, active attacks and off-line dictionary attacks (on the obtained messages with passive/active attacks). Also, this protocol provides resistance to server compromise in the context that an attacker, who obtained the password verifier from the server, must at least perform off-line dictionary attacks to gain any advantage in impersonating the user. The AugPAKE protocol is not only provably secure in the random oracle model but also the most efficient over the previous augmented PAKE protocols (SRP and AMP).

Status of This Memo

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1. Introduction

In the real world, many applications such as web mail, Internet banking/shopping/trade require secure channels between participating parties. Such secure channels can be established by using an authenticated key exchange (AKE) protocol, which allows the involving parties to authenticate each other and to generate a temporary session key. The temporary session key is used to protect the subsequent communications between the parties.

Until now, password-only AKE (called, PAKE) protocols have attracted much attention because password-only authentication is very convenient to the users. However, it is not trivial to design a secure PAKE protocol due to the existence of off-line dictionary attacks on passwords. These attacks are possible since passwords are chosen from a relatively-small dictionary that allows for an attacker to perform the exhaustive searches. This problem was brought forth by Bellovin and Merritt [BM92], and many following works have been conducted in the literature (see some examples in [IEEEP1363.2]). A PAKE protocol is said to be secure if the best attack an active attacker can take is restricted to the on-line dictionary attacks, which allow to check a guessed password only by interacting with the honest party.

An augmented PAKE protocol (e.g., [BM93], [RFC2945], [ISOIEC11770-4], [IEEEP1363.2]) provides extra protection for server compromise in the sense that an attacker, who obtained a password verifier from a server, cannot impersonate the corresponding user without performing off-line dictionary attacks on the password verifier. This additional security is known as "resistance to server compromise". The AugPAKE protocol described in this document is an augmented PAKE which also achieves highly efficiency over the previous works (SRP [RFC2945], [ISOIEC11770-4], and AMP [ISOIEC11770-4]). In summary, 1) The AugPAKE protocol is secure against passive attacks, active attacks and off-line dictionary attacks on the obtained messages with passive/active attacks (see [SKI10] for the formal security proof), and 2) It provides resistance to server compromise. At the same time, the AugPAKE protocol has similar computational efficiency to the plain Diffie-Hellman key exchange [DH76] that does not provide authentication by itself. Specifically, the user and the server need to compute 2 and 2.17 modular exponentiations, respectively, in the AugPAKE protocol. After excluding pre-computable costs, the user and the server are required to compute only 1 and 1.17 modular exponentiations, respectively. Compared with SRP [RFC2945], [ISOIEC11770-4], and AMP [ISOIEC11770-4], the AugPAKE protocol is more efficient 1) than SRP in terms of the user's computational costs and 2) than AMP in terms of the server's computational costs.

1.1. Keywords

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119].

2. AugPAKE Specification

2.1. Underlying Group

The AugPAKE protocol can be implemented over the following group.

- Let p and q be sufficiently large primes such that q is a divisor of ((p - 1) / 2) and every factors of ((p - 1) / 2) are also primes comparable to q in size. This p is called a "secure" prime. We denote by G a multiplicative subgroup of prime order q over the field GF(p), the integers modulo p. Let g be a generator for the subgroup G so that all the subgroup elements are generated by g. The group operation is denoted multiplicatively (in modulo p).

By using a secure prime p, the AugPAKE protocol has computational efficiency gains. Specifically, it does not require the order check of elements, received from the counterpart party. Note that the groups, defined in Discrete Logarithm Cryptography [SP800-56A] and RFC 5114 [RFC5114], are not necessarily the above secure prime groups.

Alternatively, one can implement the AugPAKE protocol over the following groups.

- Let p and q be sufficiently large primes such that p = (2 * q) + 1. This p is called a "safe" prime. We denote by G a multiplicative subgroup of prime order q over the field GF(p), the integers modulo p. Let g be any element of G other than 1. For example, g = h^2 mod p where h is a primitive element. The group operation is denoted multiplicatively (in modulo p).

- Let p and q be sufficiently large primes such that q is a divisor of ((p - 1) / 2). We denote by G a multiplicative subgroup of prime order q over the field GF(p), the integers modulo p. Let g be a generator for the subgroup G so that all the subgroup elements are generated by g. The group operation is denoted multiplicatively (in modulo p). If p is not a "secure" prime, the AugPAKE protocol MUST perform the order check of received elements.

2.2. Notation

The AugPAKE protocol is a two-party protocol where a user and a server authenticate each other and generate a session key. The following notation is used in this document:

U
: The user's identity (e.g., defined in [RFC4282]). It is a string in {0,1}^* where {0,1}^* indicates a set of finite binary strings.

S
: The server's identity. It is a string in {0,1}^*.

b = H(a)
: A binary string a is given as input to a secure one-way hash function H (e.g., SHA-2 family [FIPS180-3]) which produces a fixed-length output b. The hash function H maps {0,1}^* to {0,1}^k where {0,1}^k indicates a set of binary strings of length k and k is a security parameter.

b = H'(a)
: A binary string a is given as input to a secure one-way hash function H' which maps the input a in {0,1}^* to the output b in Z_q^* where Z_q^* is a set of positive integers modulo prime q.

a | b
: It denotes a concatenation of binary strings a and b in {0,1}^*.

0x
: A hexadecimal value is shown preceded by "0x".

X * Y mod p
: It indicates a multiplication of X and Y modulo prime p.

X = g^x mod p
: The g^x indicates a multiplication computation of g by x times. The resultant value modulo prime p is assigned to X. The discrete logarithm problem says that it is computationally hard to compute the discrete logarithm x from X, g and p.

w
: The password remembered by the user. This password may be used as an effective password (instead of itself) in the form of H'(0x00 | U | S | w).

W

The password verifier registered in the server. This password verifier is computed as follows: W = g^w mod p where the user's password w is used itself, or W = g^w' mod p where the effective password w' = H'(0x00 | U | S | w) is used.

bn2bin(X)
It indicates a conversion of a multiple precision integer X to the corresponding binary string. If X is an element over GF(p), its binary representation MUST have the same bit length as the binary representation of prime p.

U -> S: msg
It indicates a message transmission that the user U sends a message msg to the server S.

U:
It indicates a local computation of user U (without any out-going messages).

2.2.1. Password Processing

The input password MUST be processed according to the rules of the [RFC4013] profile of [RFC3454]. The password SHALL be considered a "stored string" per [RFC3454] and unassigned code points are therefore prohibited. The output SHALL be the binary representation of the processed UTF-8 character string. Prohibited output and unassigned code points encountered in SASLprep pre-processing SHALL cause a failure of pre-processing and the output SHALL NOT be used with the AugPAKE protocol.

The following table shows examples of how various character data is transformed by the rules of the [RFC4013] profile.

#	Input	Output	Comments
1	I<U+00AD>X	IX	SOFT HYPHEN mapped to nothing
2	user	user	no transformation
3	USER	USER	case preserved, will not match #2
4	<U+00AA>	a	output is NFKC, input in ISO 8859-1
5	<U+2168>	IX	output is NFKC, will match #1
6	<U+0007>		Error - prohibited character
7	<U+0627><U+0031>		Error - bidirectional check

2.3. Protocol

The AugPAKE protocol consists of two phases: initialization and actual protocol execution. The initialization phase SHOULD be

finished in a secure manner between the user and the server, and it is performed all at once. Whenever the user and the server need to establish a secure channel, they can run the actual protocol execution through an open network (i.e., the Internet) in which an active attacker exists.

2.3.1. Initialization

U -> S: (U, W)
The user U computes W = g^w mod p (instead of w, the effective password w' may be used), and transmits W to the server S. The W is registered in the server as the password verifier of user U. Of course, user U just remembers the password w only.

If resistance to server compromise is not necessary, the server can store w' instead of W. In either case, server S SHOULD NOT store any plaintext passwords.

As noted above, this phase SHOULD be performed securely and all at once.

2.3.2. Actual Protocol Execution

The actual protocol execution of the AugPAKE protocol allows the user and the server to share an authenticated session key through an open network (see Figure 1).

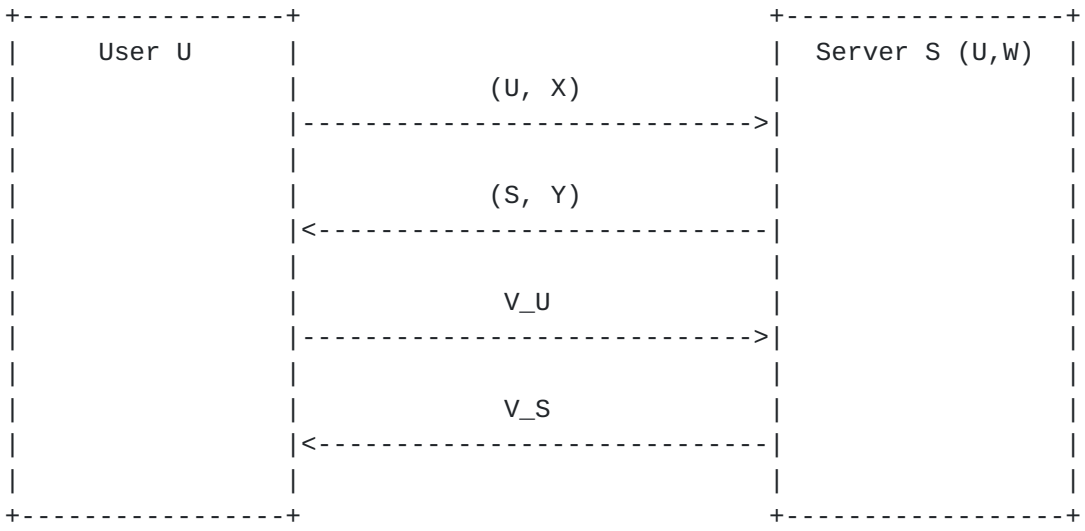

Figure 1: Actual Protocol Execution of AugPAKE

U -> S: (U, X)

The user U chooses a random element x from Z_q^* and computes its Diffie-Hellman public value X = g^x mod p. The user sends the first message (U, X) to the server S.

S -> U: (S, Y)

If the received X from user U is 0, 1 or -1 (mod p), server S MUST terminate the protocol execution. Otherwise, the server chooses a random element y from Z_q^* and computes Y = (X * (W^r))^y mod p where r = H'(0x01 | U | S | bn2bin(X)). Note that X^y * g^(w * r * y) mod p can be computed from y and (w * r * y) efficiently using Shamir's trick [MOV97]. Then, server S sends the second message (S, Y) to the user U.

U -> S: V_U

If the received Y from server S is 0, 1 or -1 (mod p), user U MUST terminate the protocol execution. Otherwise, the user computes K = Y^z mod p where z = 1 / (x + (w * r)) mod q and r = H'(0x01 | U | S | bn2bin(X)). Also, user U generates an authenticator V_U = H(0x02 | U | S | bn2bin(X) | bn2bin(Y) | bn2bin(K)). Then, the user sends the third message V_U to the server S.

S -> U: V_S

If the received V_U from user U is not equal to H(0x02 | U | S | bn2bin(X) | bn2bin(Y) | bn2bin(K)) where K = g^y mod p, server S MUST terminate the protocol execution. Otherwise, the server generates an authenticator V_S = H(0x03 | U | S | bn2bin(X) | bn2bin(Y) | bn2bin(K)) and a session key SK = H(0x04 | U | S | bn2bin(X) | bn2bin(Y) | bn2bin(K)). Then, server S sends the fourth message V_S to the user U.

U:

If the received V_S from server S is not equal to H(0x03 | U | S | bn2bin(X) | bn2bin(Y) | bn2bin(K)), user U MUST terminate the protocol execution. Otherwise, the user generates a session key SK = H(0x04 | U | S | bn2bin(X) | bn2bin(Y) | bn2bin(K)).

In the actual protocol execution, the sequential order of message exchanges is very important in order to avoid any possible attacks. For example, if the server S sends the second message (S, Y) and the fourth message V_S together, any attacker can easily derive the correct password w with off-line dictionary attacks.

The session key SK, shared only if the user and the server authenticate each other successfully, MAY be generated by using a key derivation function (KDF) [SP800-108]. After generating SK, the user and the server MUST delete all the internal states (e.g., Diffie-Hellman exponents x and y) from memory.

For the formal proof [SKI10] of the AugPAKE protocol, we need to change slightly the computation of Y (in the above S -> U: (S, Y)) and K (in the above S -> U: V_S) as follows: Y = (X * (W^r))^y' and K = g^y' where y' = H'(0x05 | bn2bin(y)).

3. Security Considerations

This section shows why the AugPAKE protocol (i.e., the actual protocol execution) is secure against passive attacks, active attacks and off-line dictionary attacks, and also provides resistance to server compromise.

3.1. General Assumptions

- An attacker is computationally-bounded.
- Any hash functions, used in the AugPAKE protocol, are secure in terms of pre-image resistance (one-wayness), second pre-image resistance and collision resistance.

3.2. Security against Passive Attacks

An augmented PAKE protocol is said to be secure against passive attacks in the sense that an attacker, who eavesdrops the exchanged messages, cannot compute an authenticated session key (shared between the honest parties in the protocol).

In the AugPAKE protocol, an attacker can get the messages (U, X), (S, Y), V_U, V_S by eavesdropping, and then wants to compute the session key SK. That is, the attacker's goal is to derive the correct K from the obtained messages X and Y because the hash functions are secure and the only secret in the computation of SK is K = g^y mod p. Note that

X = g^x mod p and

Y = (X * (W^r))^y = X^y * W^(r * y) = X^y * (g^y)^t = X^y * K^t

hold where t = w * r mod q. Though t is determined from possible password candidates and X, the only way for the attacker to extract K from X and Y is to compute X^y. However, the probability for the attacker to compute X^y is negligible in the security parameter for

the underlying groups since both x and y are random elements chosen from Z_q^*. Therefore, the AugPAKE protocol is secure against passive attacks.

3.3. Security against Active Attacks

An augmented PAKE protocol is said to be secure against active attacks in the sense that an attacker, who completely controls the exchanged messages, cannot compute an authenticated session key (shared with the honest party in the protocol) with the probability better than that of on-line dictionary attacks. In other words, the probability for an active attacker to compute the session key is restricted by the on-line dictioinary attacks where it grows linearly to the number of interactions with the honest party.

In the AugPAKE protocol, the user (resp., the server) computes the session key SK only if the received authenticator V_S (resp., V_U) is valid. There are three cases to be considered in the active attacks.

3.3.1. Impersonation Attacks on User U

When an attacker impersonates the user U, the attacker can compute the same SK (to be shared with the server S) only if the authenticator V_U is valid. For a valid authenticator V_U, the attacker has to compute the correct K from X and Y because the hash functions are secure. In this impersonation attack, the attacker of course knows the discrete logarithm x of X and guesses a password w'' from the password dictionary. So, the probability for the attacker to compute the correct K is bounded by the probability of w = w''. That is, this impersonation attack is restricted by the on-line dictionary attacks where the attacker can try a guessed password communicating with the honest server S. Therefore, the AugPAKE protocol is secure against impersonation attacks on user U.

3.3.2. Impersonation Attacks on Server S

When an attacker impersonates the server S, the attacker can compute the same SK (to be shared with the user U) only if the authenticator V_S is valid. For a valid authenticator V_S, the attacker has to compute the correct K from X and Y because the hash functions are secure. In this impersonation attack, the attacker chooses a random element y and guesses a password w'' from the password dictionary so that

Y = (X * (W'^r))^y = X^y * W'^(r * y) = X^y * (g^y)^t'

where t' = w'' * r mod q. The probability for the attacker to compute the correct K is bounded by the probability of w = w''.

Also, the attacker knows whether the guessed password is equal to w or not by seeing the received authenticator V_U. However, when w is not equal to w'', the probability for the attacker to compute the correct K is negligible in the security parameter for the underlying groups since the attacker has to guess the discrete logarithm x (chosen by user U) as well. That is, this impersonation attack is restricted by the on-line dictionary attacks where the attacker can try a guessed password communicating with the honest user U. Therefore, the AugPAKE protocol is secure against impersonation attacks on server S.

3.3.3. Man-in-the-Middle Attacks

When an attacker performs the man-in-the-middle attack, the attacker can compute the same SK (to be shared with the user U or the server S) only if one of the authenticators V_U, V_S is valid. Note that if the attacker relays the exchanged messages honestly, it corresponds to the passive attacks. In order to generate a valid authenticator V_U or V_S, the attacker has to compute the correct K from X and Y because the hash functions are secure. So, the attacker is in the same situation as discussed above. Though the attacker can test two passwords (one with user U and the other with server S), it does not change the fact that this attack is restricted by the on-line dictionary attacks where the attacker can try a guessed password communicating with the honest party. Therefore, the AugPAKE protocol is also secure against man-in-the-middle attacks.

3.4. Security against Off-line Dictionary Attacks

An augmented PAKE protocol is said to be secure against off-line dictionary attacks in the sense that an attacker, who completely controls the exchanged messages, cannot reduce the possible password candidates better than on-line dictionary attacks. Note that, in the on-line dictionary attacks, an attacker can test one guessed password by running the protocol execution (i.e., communicating with the honest party).

As discussed in Section 3.2, an attacker in the passive attacks does not compute X^y (and the correct K = g^y mod p) from the obtained messages X, Y. This security analysis also indicates that, even if the attacker can guess a password, the K is derived independently from the guessed password. Next, we consider an active attacker whose main goal is to perform the off-line dictionary attacks in the AugPAKE protocol. As in Section 3.3, the attacker can 1) test one guessed password by impersonating the user U or the server S, or 2) test two guessed passwords by impersonating the server S (to the honest user U) and impersonating the user U (to the honest server S) in the man-in-the-middle attacks. Whenever the honest party receives

an invalid authenticator, the party terminates the actual protocol execution without sending any message. In fact, this is important to prevent an attacker from testing more than one password in the active attacks. Since passive attacks and active attacks cannot remove the possible password candidates efficiently than on-line dictionary attacks, the AugPAKE protocol is secure against off-line dictionary attacks.

3.5. Resistance to Server Compromise

We consider an attacker who has obtained a (user's) password verifier from a server. In the (augmented) PAKE protocols, there are two limitations [BJKMRSW00]: 1) the attacker can find out the correct password from the password verifier with the off-line dictionary attacks because the verifier has the same entropy as the password; and 2) if the attacker impersonates the server with the password verifier, this attack is always possible because the attacker has enough information to simulate the server. An augmented PAKE protocol is said to provide resistance to server compromise in the sense that the attacker cannot impersonate the user without performing off-line dictionary attacks on the password verifier.

In order to show resistance to server compromise in the AugPAKE protocol, we consider an attacker who has obtained the password verifier W and then tries to impersonate the user U without off-line dictionary attacks on W. As a general attack, the attacker chooses two random elements c and d from Z_q^*, and computes

X = (g^c) * (W^d) mod p

and sends the first message (U, X) to the server S. In order to impersonate user U successfully, the attacker has to compute the correct K = g^y mod p where y is randomly chosen by server S. After receiving Y from the server, the attacker's goal is to find out a value e satisfying Y^e = K mod p. That is,

log_g (Y^e) = log_g K mod q

(c + (w * d) + (w * r)) * y * e = y mod q

(c + w * (d + r)) * e = 1 mod q

where log_g K indicates the logarithm of K to the base g. Since there is no off-line dictionary attacks on W, the above solution is that e = 1 / c mod q and d = -r mod q. However, the latter is not possible since r is determined by X (i.e., r = H'(0x01 | U | S | bn2bin(X))) and H' is a secure hash function. Therefore, the AugPAKE protocol provides resistance to server compromise.

4. Implementation Consideration

As discussed in Section 3, the AugPAKE protocol is secure against passive attacks, active attacks and off-line dictionary attacks, and provides resistance to server compromise. However, an attacker in the on-line dictionary attacks can check whether one password (guessed from the password dictionary) is correct or not by interacting with the honest party. Let N be a dictionary size of passwords. Certainly, the attacker's success probability grows with the probability of (I / N) where I is the number of interactions with the honest party. In order to provide a reasonable security margin, implementation SHOULD take a countermeasure to the on-line dictionary attacks. For example, it would take about 90 years to test 2^(25.5) passwords with one minute lock-out for 3 failed password guesses (see Appendix A in [SP800-63]).

5. IANA Considerations

This document has no request to IANA.

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Appendix A. Features of AugPAKE

Below are some features of the AugPAKE protocol.

Security:

- AugPAKE is zero knowledge (password) proof. It is secure against passive/active/off-line dictionary attacks. It is also resistant to server-compromise impersonation attacks.
- AugPAKE provides Perfect Forward Secrecy (PFS) and is secure against Denning-Sacco attack.
- Any cryptographically secure Diffie-Hellman groups can be used.
- The formal security proof of AugPAKE can be found at [SKI10].
- AugPAKE can be easily used with strong credentials.
- In the case of server compromise, an attacker has to perform off-line dictionary attacks while computing modular exponentiation with a password candidate.

Intellectual Property:

- AugPAKE was publicly disclosed on Oct. 2008.
- AIST applied for a patent in Japan on July 10, 2008. AIST would provide royal-free license of AugPAKE.
- IPR disclosure (see https://datatracker.ietf.org/ipr/2037/)

Miscellaneous:

- The user needs to compute only 2 modular exponentiation computations while the server needs to compute 2.17 modular exponentiation computations. AugPAKE needs to exchange 2 group elements and 2 hash values. This is almost the same computation/ communication costs as the plain Diffie-Hellman key exchange. If we use a large (e.g., 2048/3072-bits) parent group, the hash size would be relatively small.
- AugPAKE can be easily converted to 'balanced' PAKE.
- AugPAKE has the same performance for any type of secret.
- Internationalization of character-based passwords can be supported.
- AugPAKE can be implemented over any ECP (Elliptic Curve Group over GF[P]), EC2N (Elliptic Curve Group over GF[2^N]), and MODP (Modular Exponentiation Group) groups.
- AugPAKE has request/response nature.
- No Trusted Third Party (TTP) and clock synchronization
- No additional primitive (e.g., Full Domain Hash (FDH) and/or ideal cipher) is needed.
- Easy implementation. We already implemented AugPAKE and have been testing in AIST.

Appendix B. Test Vector of AugPAKE

Here is a test vector of the AugPAKE protocol.

```
p = 0x FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
       4300000000000000000000000000000000000000000000000000000000000000
       0000000000000000000000000000000000000000000000000000000000000000
       0000000000000000000000000000000000000000000000000000000000000000
```

```
        0000000000000000000000000000000000000000000000000000000000000000
        0000000000000000000000000000000000000000000000000000000000000000
        0000000000000000000000000000000000000000000000000000000000000000
        0000000000000000000000000000000000000000000000000000000000000000
        0000000000000000000000000000000000000000000000000000000000000000
        0000000000000000000000000000000000000000000000000000000000000000
        0000000000000000330A0DFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
        FFFFFFFFFFFFFFFFDA5193AB

q = 0x FFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFFF
        43

g = 0x F1AC99884ABBBBCC9BAA19BF375607FD14570B3019A03871147032445ADA7F
        A5B8BDC399C1889BBDA197ADB1E3939D55361241F5CD5ED529B0ADD921B274
        44BD2EB698DC962A9F7D202EAB98BC0C8CC950CA13BC6B1E632D0876A4E796
        26FDE85F06A46C9991EB02A6D6096E0DF6BCA2CAA12E838BEC47A7CB4AF2B0
        D94107B9CDBD67327238ECAF84DF292E776AF0F76288B39F9D9E4DDF3A9731
        CC832D70F150A0F29E7A1E193D1D21CBE8A84B56B0A4692CB39D3048086782
        85A23F08F9DB402487746F7E2A19CAF2171E55C76337E359217516213FF3BF
        616F8B20586A8B3168DA444AEA862BB76B9EA2BF8CB84773D29D4EFE511C53
        95F89CB547EFBBAE333E0BDB22DA40CE0B942A59841A12790910CC1332699D
        64BBF667E0DF3791C4E29CEB48E8397D50C72F7765C5A18809E3497F6BD374
        F5D185BBC8F57E36051E11E8DD0C5DD385A9DA442F22598111960CC2B83CBA
        0A1D980745562F6C62DD6D81B7BAEA7650B1E6E57AB9CC4C95EF17256A79B1
        31859E1BAC81FF1E

U =    augpakeuser@aist.go.jp

S =    augpakeserver@aist.go.jp

X = 0x AF261CB6FD99E2E3B4FCDE8A9C538A872EBB54CC82845E8038EA34804DD739
        90689F2191BF6436BFFD13459DC5FF1FBD56734CA6347ADF52AFAB85EC98A0
        4D27C122EBAF1840229C2F74E9AEEB79C27ECAF6C8B88FCD5FB3F9C8F20F8F
        88D45CEBB56D6CAB251DC34D3656DB73E4DF77B71420565D4696DBF8D27023
        36E909F4C33B2F14605BDEB535423F02B779D7AF0CCB4F3705E177C4334F14
        707140218197845C708E6ABC025BCA954AA2FDAA352D284DE41D33F7CCFCFD
        99CAB3CFD34361B6D0551C6D8AEE604316F99758A9C58A96C39AA811E8BA10
        2E4D21D8F5EFC26920B3F95E6C800D8EBE9914B53144B038BE0E0B43D86479
        E3CBE623FD148CC90784548C1C7C522C6C71FD4A095B15CBF3EB74C7759493
        38AC7691A3763C0A3AB97E9E2B439192C49470BF90F292C4A8D336D86780FD
        DC7DC3C2CC04A6E3AB632788D97D4FDDEE5B117DCF76D91CEA1794FAD91CA1
        7C9715D83589A00CBB72DD513F6A30E4DB31ACA8DA5D6ECD0E20307D70D6DD
        0C2D6D3D7962694B5E1B0848

Y = 0x 39033C00E1C30FF1A945DD699C516D3BB194FABBB46ADF54A2ED0820FEE0A4
        DE52128E2126A4393E3040E07D90432B8C19433EC920274E5A7C165DC89AA2
        C6D77E801A0C7676BC71955A52E74775C57C63B97304C73211C2035BD7B6D1
```

8844A28AC50DD2DA96B257236A6090CCB08D2006BF57AC69EA14ABC5D71BA0
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957205C228FAC57B9A1589B8FF2B134980504F56B8A84809B8FF70EFF67520
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8DDFB77D0DF4C1932F1FE63389F3B1F29AE99F34BC39EF0AD04BC3A6A129DE
E66E50B6768EDECC529F06FE5F7AD3825E8ECFCB12DB579C40F19D12BF6F60
4621F60413DAEB77FE48C136518C57D02A2C6BB596EDFA0DACC127C2FD5FE1
9B72580A722307C3F86C0EB1

V_U = 0x 490C7CE33DCC3EBE8D0406EEB97CA154882DCBBA0A728F3B870263BCA36
9DB6

V_S = 0x D70D2CAA821B9D84E29D75EB5E9B2DB038BA1256ECFC35C553832743A6E
36F

Appendix C. AugPAKE over EC Groups

The AugPAKE protocol can be implemented over elliptic curve groups as follows.

Let p and q be sufficiently large primes, and let m be some positive integer. An elliptic curve E is defined by one of the following two curve equations

y^2 = x^3 + a * x + b over the prime field GF(p) or

y^2 + x * y = x^3 + a * x^2 + b over the binary field GF(2^m)

together with the point at infinity 0_E where x, y, and two coefficients a and b are elements of GF(p) or GF(2^m). Let #E be the number of points on E, and prime q be the order of the desired group. The cofactor k is the value (#E / q) satisfying k = 2^n * q_1 * q_2 ... q_t where n = {0,1,2,3} and every primes q_i > q for i = 1, 2, ..., t. Optionally, k = 2^n. Also, n can be 3 for good performance and security. Let G be a generator for a subgroup of q points on E so that all the subgroup elements are generated by G. The group operation is denoted additively. For example, (X = [x] * G) indicates that an addition computation of G by x times and the resultant value is assigned to X.

By using the above elliptic curve groups, the AugPAKE protocol has computational efficiency gains. Specifically, it does not require the order check of elements, received from the counterpart party.

The AugPAKE protocol consists of two phases: initialization and actual protocol execution. The initialization phase SHOULD be

finished in a secure manner between the user and the server, and it is performed all at once. Whenever the user and the server need to establish a secure channel, they can run the actual protocol execution through an open network (i.e., the Internet) in which an active attacker exists.

Initialization

U -> S: (U, W)
The user U computes W = [w] * G (instead of w, the effective password w' may be used), and transmits W to the server S. The W is registered in the server as the password verifier of user U. Of course, user U just remembers the password w only.

Actual Protocol Execution

U -> S: (U, X)
The user U chooses a random element x from Z_q^* and computes its elliptic curve Diffie-Hellman public value X = [x] * G. The user sends the first message (U, X) to the server S.

S -> U: (S, Y)
If the received X from user U is not a point on E or [2^n] * X = 0_E, server S MUST terminate the protocol execution. Otherwise, the server chooses a random element y from Z_q^* and computes Y = [y] * (X + ([r] * W)) where r = H'(0x01 | U | S | bn2bin(X)). Then, server S sends the second message (S, Y) to the user U.

U -> S: V_U
If the received Y from server S is not a point on E or [2^n] * Y = 0_E, user U MUST terminate the protocol execution. Otherwise, the user computes K = [z] * Y where z = 1 / (x + (w * r)) mod q and r = H'(0x01 | U | S | bn2bin(X)). Also, user U generates an authenticator V_U = H(0x02 | U | S | bn2bin(X) | bn2bin(Y) | bn2bin(K)). Then, the user sends the third message V_U to the server S.

S -> U: V_S
If the received V_U from user U is not equal to H(0x02 | U | S | bn2bin(X) | bn2bin(Y) | bn2bin(K)) where K = [y] * G, server S MUST terminate the protocol execution. Otherwise, the server generates an authenticator V_S = H(0x03 | U | S | bn2bin(X) | bn2bin(Y) | bn2bin(K)) and a session key SK = H(0x04 | U | S | bn2bin(X) | bn2bin(Y) |

bn2bin(K)). Then, server S sends the fourth message V_S to the user U.

U:

If the received V_S from server S is not equal to H(0x03 | U | S | bn2bin(X) | bn2bin(Y) | bn2bin(K)), user U MUST terminate the protocol execution. Otherwise, the user generates a session key SK = H(0x04 | U | S | bn2bin(X) | bn2bin(Y) | bn2bin(K)).

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