Generating Just-in-Time Shared Keys (JIT-SK) for TLS 1.3 Zero RoundTrip Time (0-RTT)

Eslam G. AbdAllah, Randy Kuang, and Changcheng Huang

Abstract—**The main goal of Transport Layer Security (TLS) protocol is to provide a secure communication channel between communicating pairs. A new version of the protocol, TLS 1.3, is introduced to improve security and performance for customers. One of the major advantages of TLS 1.3 over earlier versions is that it introduces Zero RoundTrip Time (0-RTT) feature, that saves a round trip at connection setup stage. 0-RTT data security properties are weaker than other kinds of TLS data because the data is not forward secret and it is vulnerable to replay attacks. Existing solutions such as single-use tickets, client hello recording, and freshness checks provide inefficient solutions for 0-RTT problems.**

In this paper, we propose an efficient technique to utilize 0-RTT feature with forward secrecy and prevent replay attacks. Our technique uses a synchronized pseudorandom number generator (PRNG) that depends on initial shared secret between communicating pairs. The initial secret can be shared using TLS 1.3 three basic key exchange modes. In our technique, the PRNG also uses session shared information such as session ID to dynamically provide Just-in-Time Shared Keys (JIT-SK) for 0-RTT. Client and server sides change the keys in each session and hence securely and efficiently use the 0-RTT. We implement a proof of concept for our technique using our private PRNG, named Quantum Entropy Expansion and Propagation (QEEP), and WolfSSL implementation for TLS 1.3 and show the differences using our solution.

Index Terms—**Transport Layer Security (TLS v1.3), Zero RoundTrip Time (0-RTT), pseudorandom number generator (PRNG), Quantum Entropy Expansion and Propagation (QEEP).**

I. INTRODUCTION

The Transport Layer Security (TLS) protocol consists of two primary protocols: a handshake protocol and a record protocol. The handshake protocol main goals are to authenticate the communicating pairs, negotiate cryptographic parameters, and establish shared keys. A record protocol protects the traffic between the communicating pairs using the handshake parameters. The Internet Engineering Task Force (IETF) introduced a new version of Transport Layer Security (TLS) protocol, TLS 1.3,

in August 2018 [1]. TLS 1.3 includes a lot of security and performance improvements that can be summarized in the following points: (1) TLS 1.3 introduces Zero RoundTrip Time (0-RTT) feature, (2) current symmetric encryption algorithms in TLS 1.3 are Authenticated Encryption with Associated Data (AEAD) algorithms, (3) all public-key based key exchange mechanisms support forward secrecy, and (4) other updates including adding or removing cryptographic algorithms and modifying some functions in the protocol [1]-[6].

One of the biggest advantages of TLS 1.3 is the 0-RTT. Based on Cloudflare [2], the connections can be classified to two different groups. Around 60% of the connections are from people who are visiting a website for the first time or revisiting after an extended period of time. For this group, TLS 1.3 improves the speed of these connections significantly. Around 40% of the connections are from people who are resuming a previous connection. For this group, TLS 1.3 uses 0-RTT. 0-RTT speeds up resumed connections, and hence leads to a faster response for web sites that people visit regularly.

0-RTT feature was added in TLS 1.3 to save a round trip at connection setup for some application data, however it comes with some security vulnerabilities. 0-RTT data is not forward secret, because the data is encrypted under keys derived using the offered Preshared keys (PSK). By using 0-RTT, there are no guarantees of non-replay between connections. In ordinary TLS 1.3 1-RTT data, the date is protected using servers' random value, whereas 0-RTT data does not depend on the ServerHello random value and hence has weaker guarantee. Additionally, more attacks can be performed based on replay attacks such as reordering of 0-RTT messages and cache timing attacks. As 0-RTT is a new feature in TLS 1.3, it is noncompatible with earlier TLS versions, which also can cause security risks. To overcome 0-RTT security vulnerabilities, TLS 1.3 uses different mitigation techniques such as single-use tickets, client hello recording, and freshness checks, however these techniques provide inefficient solutions for 0- RTT problems.

In this paper, we propose to use a synchronized pseudorandom number generator (PRNG) that can provide Just-in-Time Shared Keys (JIT-SK) for 0-RTT. Client and server sides dynamically change the keys each session. The PRNG depends on initial shared secret key that can be provided using TLS 1.3 key exchange modes in addition to session shared information such as session ID. Then the PRNG generates random keys for each session to secure 0-RTT messages. Using fresh random key with each session provides forward secrecy for 0-RTT data and also prevents replay attacks as the key cannot be reused for multiple

Eslam. G. AbdAllah was at the Department of Systems and Computer Engineering, Carleton University, Ottawa, ON, Canada. He is now with the Master of Information Systems Security Management (MISSM), Faculty of Management, Concordia University of Edmonton, AB, Canada (e-mail: eslam.abdallah@concordia.ab.ca).

Randy Kuang is with Quantropi Inc., Ottawa, ON, Canada (e-mail: randy.kuang@quantropi.com).

Changcheng Huang is with the Department of Systems and Computer Engineering, Carleton University, Ottawa, ON, Canada (e-mail: huang@sce.carleton.ca).

sessions. We implement our technique using a private PRNG, named Quantum Entropy Expansion and Propagation (QEEP) [4] and WolfSSL libraries for TLS 1.3. We show the differences between WolfSSL basic implementation that depends on static keys and our approach that provides JIT-SK for 0-RTT.
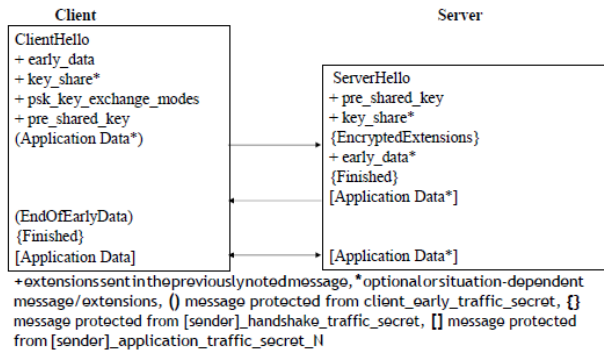

Fig. 1. 0-RTT handshake [1].

II. PROBLEM STATEMENT AND EXISTING COUNTERMEASURES

In TLS 1.3, clients and servers share a PSK, which can be obtained externally or using a previous handshake. TLS 1.3 allows clients to send 0-RTT data on the first flight (early data), as shown in Fig. 1. The client uses the PSK to authenticate the server and to encrypt the early data. 0-RTT messages have the same types as other messages in handshake and application date, but 0-RTT messages are encrypted using 0-RTT keys.

The security attributes for 0-RTT data are weaker than other kinds of TLS data [1]-[3]. The main reasons for this weakness can be summarized in the following points. 0-RTT data is not forward secret. Forward security can be defined as the security of past communications even when a certain message is compromised at a later stage. 0-RTT is encrypted using keys derived using the offered PSK, and hence it is not forward secret.

Replay attacks can be easily performed by network attackers by duplicating a flight of 0-RTT data. Additionally, network attackers can use client retry behavior to send multiple copies of an application message. 0-RTT increases this attack especially for any system that does not maintain consistent server state. For example, if a server has multiple zones, in which tickets from zone 1 will not be accepted in zone 2, then the attacker can duplicate 0-RTT for multiple zones. This enforces the server to reject lots of 0-RTT messages and clients need to complete full handshake, which makes 0-RTT feature useless. Performing replay attacks can also cause more potential attacks. The duplication of actions causes side effects (e.g., buying an item or sending money) to be duplicated, thus harming the communicating pairs. Attackers can also reorder 0-RTT messages. Attackers can perform cache timing attacks in order to discover the content of 0-RTT messages. This can be performed by redirecting a 0-RTT message to malicious cache nodes and figure out the requested resource.

Another issue in 0-RTT data is coming from the non-compatibility with older servers. This can cause a downgrade attack especially in multi-server environments,

where some servers implement TLS 1.3 and others implement TLS 1.2 or earlier versions. A countermeasure for this issue in the multi-server environments is to ensure a deployment of TLS 1.3 without 0-RTT prior to enabling 0-RTT.

Existing solutions to overcome 0-RTT security challenges can be summarized in the following three techniques. These techniques provide partial solutions and limit the capabilities of 0-RTT feature [1].

Single-use tickets. This technique proposes anti-replay defense mechanism that allows each session ticket to be used once. The server can have a database of all valid tickets and deletes each ticket once it is used. When unregistered ticket is provided, the server forces the connection to use the full handshake. This technique requires the session database to be shared between server nodes in environments with multiple distributed servers, and hence it is hard to achieve high rates of successful PSK 0-RTT connections.

Client hello recording. In this technique, the anti-replay mechanism is to record a unique value derived from the ClientHello message and reject duplicates. It is infeasible to record all ClientHellos, but a server can record ClientHellos within a given time window by using "obfuscated_ticket_age" attribute to make sure that tickets cannot be reused outside that window. This technique is suitable to be implemented in distributed systems with high rates of resumption and 0-RTT, because client hello recording mechanism does not require storing all outstanding tickets. In these distributed systems, it is impractical to have large scale reliable and consistent storage of all the received ClientHellos. In this case, the best anti-replay strategy for this mechanism is by using a single storage zone to be responsible for granting or refusing 0-RTT for a ticket in any zone. This simply prevents replay attacks because there is only one zone that will accept or reject 0-RTT data. Another design approach is to implement a storage for each zone, and hence limits the number of replays to once per zone.

Freshness checks. ClientHello message includes the time at which the client sent the message. The freshness check technique can use this time to efficiently determine whether a ClientHello was sent reasonably recently or not. This technique only accepts 0-RTT for such a recent ClientHello message, otherwise return to a 1-RTT handshake. For the implementation of this mechanism, a server has to store the time of the generated session ticket and an estimation of the roundtrip time between client and server. This freshness checking is not sufficient to prevent replay attacks because of the following reasons: (1) it does not detect replay attacks during the error window, and (2) it is only performed at the time the ClientHello is received not when continuous early data records are received.

Generally, TLS 1.3 servers are responsible to protect themselves against 0-RTT data replication attacks. The existing countermeasures try to prevent replay at the TLS layer, however they do not provide complete protection against receiving multiple copies of client data. Application protocols need a profile that defines 0-RTT usage. In this profile, the application protocols identify the allowed messages to be used with 0-RTT and what should happen when the server rejects 0-RTT.

III. Proposed Solution (JIT-SK for 0-RTT)

In order to access a web page using HTTPS for the first time, there are four basic steps.

DNS lookup. DNS is operated by Internet Service Provider (ISP), who caches the IP address for popular domains. The latency in this step is negligible.

TCP handshake. This step takes one roundtrip. In this step, the data is sent from a client to server and back using SYN and ACK packets, respectively.

TLS handshake. This step requires two roundtrips. The client and server agree on the cryptographic key and establish an encrypted connection.

HTTP. This step requires one roundtrip. After establishing the secure connection in TLS handshake step, the browser sends GET request as encrypted HTTP request and the server replies with HTTP response.

In general, there are four roundtrips before the client can access the website. In case the client revisits the site again (resumed connections), the total required roundtrips become three because one of TLS handshakes can be removed using TLS session resumption. A big advantage for TLS 1.3 is that it requires only one roundtrip in TLS handshake for new or revisited website so the total number in each case is just three roundtrips. With TLS 0-RTT another roundtrip can be eliminated for resumed connections. Table I summarizes the required roundtrips in TLS 1.2, TLS 1.3, and TLS1.3 0-RTT.

TABLE I: Required Roundtrips for Different TLS Versions

TLS version	New Connection	Resumed Connection
TLS 1.2 (and earlier)	4	3
TLS 1.3	3	3
TLS 1.3 with 0-RTT	3	2

TLS 1.3 supports three basic key exchange modes: Diffie-Hellman over either finite fields or elliptic curves abbreviated as (EC)DHE, PSK-only, and PSK with (EC)DHE. Our solution does not require any modification to the standard TLS 1.3. Instead of using the pre-shared key for 0-RTT, we use the pre-shared key as initial secret key (seed) for a synchronized PRNG, that can generate a large number of random keys. A random key can be generated for each session to provide JIT- SK. The client can use the random key to encrypt the first flight (early data). Instead of using PSK just once for 0-RTT as defined in TLS 1.3, we use random keys for each session to extend 0-RTT usage multiple times. Using PRNG, a client and server need to have pre-shared secret for authentication to avoid man-in-the-middle attack. This secret is needed only once in our approach. The pre-shared key from TLS 1.3 can be used as our seed. The client encrypts the early data using the generated random number (session key) and securely transmits the encrypted data. The receiver uses a synchronized algorithm to generate the same random number (session key) to decrypt the received message.

In this paper as a PRNG, we use QEEP, which is a software-based technique that depends on unitary permutation matrices. QEEP uses a large key space, which enables QEEP to generate random outputs that is indistinguishable from true randomness. In QEEP, each row in the matrix consists of a permutation of all numbers between 0 to 255. There are total 256! unique states for an 8-bit system and Shannon's entropy is 1684 bits. Fig. 2 shows the steps of our technique. We use PSK and session ID to randomly select the permutation matrix and then use PSK to generate the session key (SK) that can be used to encrypt/decrypt the early data. Generally, any good high entropy PRNG such as QEEP, or SHA-256 [7], or a certified private PRNG can be used. The PRNG should have entropy of 256 bits or more to prevent advanced cryptographic attacks coming from classical or quantum computers [8], [9]. The quality of the generated randomness is tested using various tools such as National Institute of Standards and Technology Statistical Test Suite (NIST STS), specifically SP 800-22 [10], Dieharder [11], and entropy and randomness online tester [12]. QEEP passes all NIST STS SP 800-22 and Dieharder tests and generates random output that follows a Gaussian normal distribution.
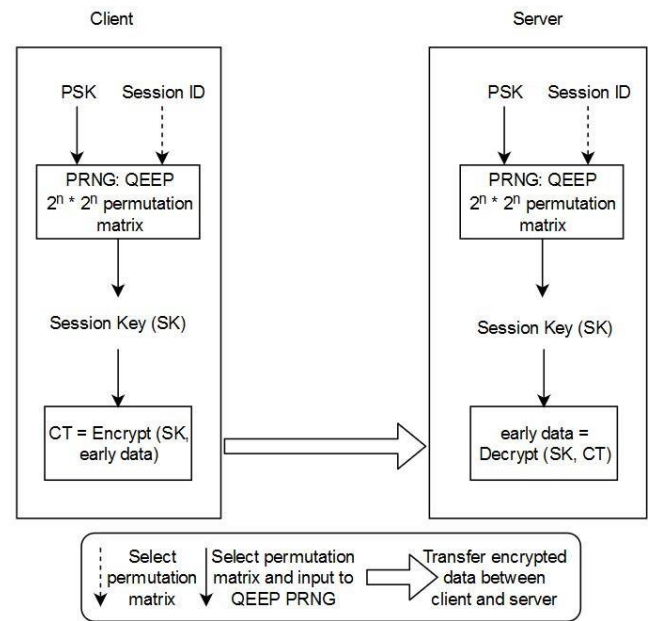

Fig. 2. JIT-SK steps for 0-RTT.

For the server to accept TLS 1.3 0-RTT early data, the server first must accept a PSK cipher suite and select the first available key in the "pre_shared_key" extension. Second, the server must verify that TLS version number, selected cipher suite, and selected Application-Layer Protocol Negotiation (ALPN) protocol are the same as the selected PSK. In case of PSK exchanged using NewSessionTicket message, the server verifies the values that are negotiated in the connection when the ticket was established. In case of externally established PSKs, the server verifies the values that are provisioned with the key. When a client uses a PSK and early data is allowed for that PSK, this enables the client to send application data in the first flight of messages. In this case, the client provides "pre_shared_key" and "early_data" extensions. The client uses "EarlyDataIndication" value for "extension_data" field of this extension. Our proposed solution does not change TLS 1.3 standard specifications because the PSK and a session shared information (session ID) will be used as inputs to the PRNG and then the server decrypts using the generated random. If the generated randoms between the server and the client are not verified, the server forces the communication to return to

1-RTT handshake.

Using synchronized PRNG can achieve the following goals:

Forward security. When a communication is compromised at any stage, forward security property guarantees the security of past communications. Imagine that a communication is exposed, using our technique that depends on dynamic random keys, the attacker still cannot infer any information from previous sessions.

Prevention of replay attacks. In our proposed solution, the early and application data for 0-RTT are encrypted with JIT-SK for each session. An attacker cannot replay any message as the key is used only once. This simplifies the detection of replay attacks for communicating pairs. The prevention of replay attacks removes the side effects of these attacks such as duplication of actions, reordering of 0-RTT messages, and cache timing attacks.

Reusing 0-RTT feature. Using our technique allows TLS 1.3 to continuously use 0-RTT for multiple sessions. Each session has a fresh shared random number.

IV. IMPLEMENTATION

TLS 1.3 has been supported and implemented across multiple browsers such as Google Chrome v67+, Mozilla Firefox v61+, and Apple Mac OS v10.3 and iOS v11 [2]. A number of service providers such as Cloudflare, Akamai, and Facebook support TLS 1.3 connections. Also, TLS 1.3 has been implemented using software libraries such as OpenSSL and WolfSSL.

As a proof of concept, we use WolfSSL open source libraries for TLS 1.3. WolfSSL provides static shared key between a server and a client as shown in Fig. 3 and Fig. 4. The two tests in Fig. 5 show that the client and server share and use the same key every time. In order to use PSK in WolfSSL, the following defines should be added to the header file in IDE\WIN\user_settings.h

```
#define WOLFSSL_TLS13
#define
HAVE_TLS_EXTENSIONS

#define HAVE_SUPPORTED_CURVES

#define
HAVE_SESSION_TICKET
#define HAVE_HKDF

#define HAVE_FFDHE_2048
#define WC_RSA_PSS
```

We build with a –enable-psk configure option to remove *#define   NO_PSK* from *options.h* as in the following command.

```
$./configure --enable-tls13
--enable-aesccm --enable-keygen
--enable-psk && make
```

Examples to run WolfSSL server and client are shown in the following commands (option-s is used for preshared keys)

```
$./examples/server/server -s -v 4
-l TLS13-AES128-GCM-SHA256
```

```
$./examples/client/client -s -v 4
-l TLS13-AES128-GCM-SHA256
```

In TLS 1.3 the cipher suite parameter can be one of the following five group of algorithms

```
TLS_AES_256_GCM_SHA384
TLS_CHACHA20_POLY1305_SHA256
TLS_AES_128_GCM_SHA256
TLS_AES_128_CCM_8_SHA256
TLS_AES_128_CCM_SHA256
```


Fig. 3. Server side JIT-SK using WolfSSL implementation.

Fig. 4. Client side JIT-SK using WolfSSL implementation.

Fig. 5. Static keys at server and client sides.

Replay attacks and side effects are applicable in current TLS 1.3 implementation and there is no forward secrecy. As shown in our update in Fig. 3 and Fig. 4, we dynamically replace these static keys with JIT-SK for 0-RTT by using QEEP. We read the dynamic key from a file each session. This file can be generated offline and be ready for use next session. The client and server can do that using preshared key and session share information such as session ID. Then QEEP will generate random session keys for securing early data in 0-RTT manner as shown in Fig. 6 and Fig. 7. These figures show that for each message the client and server use the same JIT-SK. Algorithm 1 shows the steps for generating JIT-SK. Line 1 selects the permutation matrix using PSK and session ID. The session ID can be replaced with any session shared information. Line 2 generates the session key using

PSK. Lines 3 and 4 show the encryption and decryption processes for the early data at the transmitter and receiver sides. Lines 1-4 are repeated for each session.

Test 1 (server side)

Test 2 (server side)

Test 3 (server side)

Fig. 6. JIT-SK for 0-RTT data (server side).

Algorithm 1 JIT-SK generation for 0-RTT for each session
Input: PSK, Session_ID
Output: Encrypted/decrypted early_data
1. Select_permutation_matrix (PSK, Session_ID)
2. Session_key = QEEP(PSK)
3. CT = Enc(Session_key, early_data) → for transmitter
4. → for receiver: early_data = Dec (Session_key, CT)

Test 1 (client side)

Test 2 (client side)

Test 3 (client side)

Fig. 7. JIT-SK for 0-RTT data (client side).

V. CONCLUSION

Transport Layer Security (TLS) provides a secure channel between two communicating peers that provides the following properties: authentication, confidentiality, and integrity. The Internet Engineering Task Force (IETF) introduced TLS 1.3, which is a big step forward for Internet performance and security. In this paper, we focus on one of the new concepts in TLS 1.3, which is Zero RoundTrip Time (0-RTT) feature. By using TLS 1.3 with 0-RTT, the performance gains are more dramatic. 0-RTT data has security challenges and the existing solutions cannot efficiently mitigate these challenges. In this paper, we use a novel approach that depends on a synchronized pseudorandom number generator (PRNG) to efficiently and securely use 0-RTT feature. We implement our approach using a private PRNG, named Quantum Entropy Expansion and Propagation (QEEP) and WolfSSL libraries for TLS 1.3.

The implementation shows that using our approach enables 0-RTT with forward secrecy and without replay attacks.

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Eslam G. AbdAllah is an assistant professor in Concordia University of Edmonton, AB, Canada. During 2019 to 2020, he was a postdoctoral fellow in Carleton University, ON, Canada. In 2018, Dr. AbdAllah worked as an assistant professor at the Faculty of Computer and Information Sciences in Ain Shams University in Egypt. Dr. AbdAllah received his PhD from the School of Computing, Queen's University in Kingston, Ontario in 2017. Eslam has contributed to a number of journals, technical papers and reports and his research interests include cryptography, network security, post-quantum cryptography, information centric networking (ICN), Radio Frequency IDentification (RFID), and autonomous vehicles. He won the best paper award at IEEE-DASC 2015 conference in Liverpool, UK.

Changcheng Huang received his B. Eng. in 1985 and M. Eng. in 1988 both in electronic engineering from Tsinghua University, Beijing, China. He received a Ph.D. degree in electrical engineering from Carleton University, Ottawa, Canada in 1997. From 1996 to 1998, he worked for Nortel Networks, Ottawa, Canada where he was a systems engineering specialist. He was a systems engineer and network architect in the Optical Networking Group of Tellabs, Illinois, USA during the period of 1998 to 2000. Since July 2000, he has been with the Department of Systems and Computer Engineering at Carleton University, Ottawa, Canada where he is currently a full professor. Dr. Huang won the CFI new opportunity award for building an optical network laboratory in 2001. He is an associate editor of Springer Photonic Network Communications.

Randy Kuang holds a doctorate in quantum physics. His research findings have been published in top international journals named "Kuang's Semi-Classical Formalism" by NASA in 2012. With a career spanning IT, including with Nortel as a senior researcher and developer, he co-founded inBay technologies in 2009, serving as a CTO of the cybersecurity platform. As the first recipient of a patent for two-level authentication (2013), Randy is a prolific inventor, with 30+ U.S. patents in broad technology fields, such as WiMAX, optical networks, multi-factor identity authentication, transaction authorization, as well as concepts, technologies and industrial applications for quantum cryptography.