

Workgroup: tls
Internet-Draft:
draft-ietf-tls-external-psk-guidance-01
Published: 2 November 2020
Intended Status: Informational
Expires: 6 May 2021
Authors: R. Housley J. Hoyland M. Sethi
 Vigil Security Cloudflare Ltd. Ericsson
 C.A. Wood
 Cloudflare
Guidance for External PSK Usage in TLS

Abstract

This document provides usage guidance for external Pre-Shared Keys (PSKs) in TLS. It lists TLS security properties provided by PSKs under certain assumptions and demonstrates how violations of these assumptions lead to attacks. This document also discusses PSK use cases, provisioning processes, and TLS stack implementation support in the context of these assumptions. It provides advice for applications in various use cases to help meet these assumptions. Privacy and security properties not provided by PSKs are also included.

Discussion Venues

This note is to be removed before publishing as an RFC.

Source for this draft and an issue tracker can be found at <https://github.com/tlswg/external-psk-design-team>.

Status of This Memo

This Internet-Draft is submitted in full conformance with the provisions of BCP 78 and BCP 79.

Internet-Drafts are working documents of the Internet Engineering Task Force (IETF). Note that other groups may also distribute working documents as Internet-Drafts. The list of current Internet-Drafts is at <https://datatracker.ietf.org/drafts/current/>.

Internet-Drafts are draft documents valid for a maximum of six months and may be updated, replaced, or obsoleted by other documents at any time. It is inappropriate to use Internet-Drafts as reference material or to cite them other than as "work in progress."

This Internet-Draft will expire on 6 May 2021.

Copyright Notice

Copyright (c) 2020 IETF Trust and the persons identified as the document authors. All rights reserved.

This document is subject to BCP 78 and the IETF Trust's Legal Provisions Relating to IETF Documents (<https://trustee.ietf.org/license-info>) in effect on the date of publication of this document. Please review these documents carefully, as they describe your rights and restrictions with respect to this document. Code Components extracted from this document must include Simplified BSD License text as described in Section 4.e of the Trust Legal Provisions and are provided without warranty as described in the Simplified BSD License.

Table of Contents

- [1. Introduction](#)
- [2. Conventions and Definitions](#)
- [3. Notation](#)
- [4. PSK Security Properties](#)
- [5. Privacy Properties](#)
- [6. External PSK Use Cases and Provisioning Processes](#)
 - [6.1. Provisioning Examples](#)
 - [6.2. Provisioning Constraints](#)
- [7. Recommendations for External PSK Usage](#)
 - [7.1. Stack Interfaces](#)
 - [7.1.1. PSK Identity Encoding and Comparison](#)
 - [7.1.2. PSK Identity Collisions](#)
- [8. Security Considerations](#)
- [9. IANA Considerations](#)
- [10. References](#)
 - [10.1. Normative References](#)
 - [10.2. Informative References](#)
- [Appendix A. Acknowledgements](#)
- [Authors' Addresses](#)

1. Introduction

There are many resources that provide guidance for password generation and verification aimed towards improving security. However, there is no such equivalent for external Pre-Shared Keys (PSKs) in TLS. This document aims to reduce that gap. It lists TLS security properties provided by PSKs under certain assumptions and demonstrates how violations of these assumptions lead to attacks. This document also discusses PSK use cases, provisioning processes, and TLS stack implementation support in the context of these assumptions. It provides advice for applications in various use cases to help meet these assumptions.

The guidance provided in this document is applicable across TLS [[RFC8446](#)], DTLS [[I-D.ietf-tls-dtls13](#)], and Constrained TLS [[I-D.ietf-tls-ctls](#)].

2. Conventions and Definitions

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [[RFC2119](#)] [[RFC8174](#)] when, and only when, they appear in all capitals, as shown here.

3. Notation

For purposes of this document, a "logical node" is a computing presence that other parties can interact with via the TLS protocol. A logical node could potentially be realized with multiple physical instances operating under common administrative control, e.g., a server farm. An "endpoint" is a client or server participating in a connection.

4. PSK Security Properties

External PSK authentication in TLS allows endpoints to authenticate connections using previously established keys. These keys do not provide protection of endpoint identities (see [Section 5](#)), nor do they provide non-repudiation (one endpoint in a connection can deny the conversation). PSK authentication security implicitly assumes one fundamental property: each PSK is known to exactly one client and one server, and that these never switch roles. If this assumption is violated, then the security properties of TLS are severely weakened.

As discussed in [Section 6](#), there are use cases where it is desirable for multiple clients or multiple servers to share a PSK. If this is done naively by having all members share a common key, then TLS only authenticates the entire group, and the security of the overall system is inherently rather brittle. There are a number of obvious weaknesses here:

1. Any group member can impersonate any other group member.
2. If PSK with DH is used, then compromise of a group member that actively completes connections with other group members can read (and modify) traffic.
3. If PSK without DH is used, then compromise of any group member allows the attacker to passively read (and modify) all traffic.

4. If a group member is compromised, then the attacker can perform all of the above attacks.

Additionally, a malicious non-member can reroute handshakes between honest group members to connect them in unintended ways, as described below. (Note that this class of attack is not possible if each member uses the SNI extension [[RFC6066](#)] and terminates the connection on mismatch. See [[Selfie](#)] for details.) Let the group of peers who know the key be A, B, and C. The attack proceeds as follows:

1. A sends a ClientHello to B.
2. The attacker intercepts the message and redirects it to C.
3. C responds with a ServerHello to A.
4. A sends a Finished message to B. A has completed the handshake, ostensibly with B.
5. The attacker redirects the Finished message to C. C has completed the handshake with A.

This attack violates the peer authentication property, and if C supports a weaker set of cipher suites than B, this attack also violates the downgrade protection property. This rerouting is a type of identity misbinding attack [[Krawczyk](#)][[Sethi](#)]. Selfie attack [[Selfie](#)] is a special case of the rerouting attack against a group member that can act both as TLS server and client. In the Selfie attack, a malicious non-member reroutes a connection from the client to the server on the same endpoint.

Finally, in addition to these weaknesses, sharing a PSK across nodes may negatively affects deployments. For example, revocation of individual group members is not possible without changing the authentication key for all members.

Entropy properties of external PSKs may also affect TLS security properties. In particular, if a high entropy PSK is used, then PSK-only key establishment modes are secure against both active and passive attack. However, they lack forward security. Forward security may be achieved by using a PSK-DH mode.

In contrast, if a low entropy PSK is used, then PSK-only key establishment modes are subject to passive exhaustive search passive attacks which will reveal the traffic keys. PSK-DH modes are subject to active attacks in which the attacker impersonates one side. The exhaustive search phase of these attacks can be mounted offline if the attacker captures a single handshake using the PSK, but those attacks will not lead to compromise of the traffic keys for that

connection because those also depend on the Diffie-Hellman (DH) exchange. Low entropy keys are only secure against active attack if a PAKE is used with TLS. The Crypto Forum Research Group (CFRG) is currently working on specifying a standard PAKE (see [[I-D.irtf-cfrg-cpace](#)] and [[I-D.irtf-cfrg-opaque](#)]).

5. Privacy Properties

PSK privacy properties are orthogonal to security properties described in [Section 4](#). Traditionally, TLS does little to keep PSK identity information private. For example, an adversary learns information about the external PSK or its identifier by virtue of it appearing in cleartext in a ClientHello. As a result, a passive adversary can link two or more connections together that use the same external PSK on the wire. Depending on the PSK identity, a passive attacker may also be able to identify the device, person, or enterprise running the TLS client or TLS server. An active attacker can also use the PSK identity to oppress handshakes or application data from a specific device by blocking, delaying, or rate-limiting traffic. Techniques for mitigating these risks require analysis and are out of scope for this document.

In addition to linkability in the network, external PSKs are intrinsically linkable by PSK receivers. Specifically, servers can link successive connections that use the same external PSK together. Preventing this type of linkability is out of scope.

6. External PSK Use Cases and Provisioning Processes

PSK ciphersuites were first specified for TLS in 2005. Now, PSKs are an integral part of the TLS version 1.3 specification [[RFC8446](#)]. TLS 1.3 also uses PSKs for session resumption. It distinguishes these resumption PSKs from external PSKs which have been provisioned out-of-band (OOB). Below, we list some example use-cases where pair-wise external PSKs (i.e., external PSKs that are shared between only one server and one client) have been used for authentication in TLS.

- *Device-to-device communication with out-of-band synchronized keys. PSKs provisioned out-of-band for communicating with known identities, wherein the identity to use is discovered via a different online protocol.
- *Intra-data-center communication. Machine-to-machine communication within a single data center or PoP may use externally provisioned PSKs, primarily for the purposes of supporting TLS connections with early data.
- *Certificateless server-to-server communication. Machine-to-machine communication may use externally provisioned PSKs, primarily for the purposes of establishing TLS connections

without requiring the overhead of provisioning and managing PKI certificates.

- *Internet of Things (IoT) and devices with limited computational capabilities. [[RFC7925](#)] defines TLS and DTLS profiles for resource-constrained devices and suggests the use of PSK ciphersuites for compliant devices. The Open Mobile Alliance Lightweight Machine to Machine Technical Specification [[LwM2M](#)] states that LwM2M servers MUST support the PSK mode of DTLS.
- *Use of PSK ciphersuites are optional when securing RADIUS [[RFC2865](#)] with TLS as specified in [[RFC6614](#)].
- *The Generic Authentication Architecture (GAA) defined by 3GPP mentions that TLS-PSK can be used between a server and user equipment for authentication [[GAA](#)].
- *Smart Cards. The electronic German ID (eID) card supports authentication of a card holder to online services with TLS-PSK [[SmartCard](#)].
- *Quantum resistance: Some deployments may use PSKs (or combine them with certificate-based authentication as described in [[RFC8773](#)]) because of the protection they provide against quantum computers.

There are also use cases where PSKs are shared between more than two entities. Some examples below (as noted by Akhmetzyanova et al. [[Akhmetzyanova](#)]):

- *Group chats. In this use-case, group participants may be provisioned an external PSK out-of-band for establishing authenticated connections with other members of the group.
- *Internet of Things (IoT) and devices with limited computational capabilities. Many PSK provisioning examples are possible in this use-case. For example, in a given setting, IoT devices may all share the same PSK and use it to communicate with a central server (one key for n devices), have their own key for communicating with a central server (n keys for n devices), or have pairwise keys for communicating with each other (n^2 keys for n devices).

The exact provisioning process depends on the system requirements and threat model. Generally, use of a single PSK shared between more than one node is not recommended, even if other accommodations are made, such as client certificate authentication after PSK-based connection establishment. See [Section 7](#).

6.1. Provisioning Examples

*Many industrial protocols assume that PSKs are distributed and assigned manually via one of the following approaches: typing the PSK into the devices, or via web server masks (using a Trust On First Use (TOFU) approach with a device completely unprotected before the first login did take place). Many devices have very limited UI. For example, they may only have a numeric keypad or even less number of buttons. When the TOFU approach is not suitable, entering the key would require typing it on a constrained UI.

*Some devices provision PSKs via an out-of-band, cloud-based syncing protocol.

*Some secrets may be baked into or hardware or software device components. Moreover, when this is done at manufacturing time, secrets may be printed on labels or included in a Bill of Materials for ease of scanning or import.

6.2. Provisioning Constraints

PSK provisioning systems are often constrained in application-specific ways. For example, although one goal of provisioning is to ensure that each pair of nodes has a unique key pair, some systems do not want to distribute pair-wise shared keys to achieve this. As another example, some systems require the provisioning process to embed application-specific information in either PSKs or their identities. Identities may sometimes need to be routable, as is currently under discussion for EAP-TLS-PSK [[I-D.mattsson-emu-eap-tls-psk](#)].

7. Recommendations for External PSK Usage

If an application uses external PSKs, the external PSKs MUST adhere to the following requirements:

1. Each PSK SHOULD be derived from at least 128 bits of entropy, MUST be at least 128 bits long, and SHOULD be combined with a DH exchange, e.g., by using the "psk_dhe_ke" Pre-Shared Key Exchange Mode in TLS 1.3, for forward secrecy. As discussed in [Section 4](#), low entropy PSKs, i.e., those derived from less than 128 bits of entropy, are subject to attack and SHOULD be avoided. If only low-entropy keys are available, then key establishment mechanisms such as Password Authenticated Key Exchange (PAKE) that mitigate the risk of offline dictionary attacks SHOULD be employed. Note that no such mechanisms have yet been standardised, and further that these mechanisms will not necessarily follow the same architecture as the process for

incorporating EPSKs described in [[I-D.ietf-tls-external-psk-importer](#)].

2. Unless other accommodations are made, each PSK MUST be restricted in its use to at most two logical nodes: one logical node in a TLS client role and one logical node in a TLS server role. (The two logical nodes MAY be the same, in different roles.) Two acceptable accommodations are described in [[I-D.ietf-tls-external-psk-importer](#)]: (1) exchanging client and server identifiers over the TLS connection after the handshake, and (2) incorporating identifiers for both the client and the server into the context string for an EPSK importer.
3. Nodes using TLS 1.3 SHOULD use external PSK importers [[I-D.ietf-tls-external-psk-importer](#)] when configuring PSKs for a client-server pair. Importers make provisioning external PSKs easier and less error prone by deriving a unique, imported PSK from the external PSK for each key derivation function a node supports. See the Security Considerations in [[I-D.ietf-tls-external-psk-importer](#)] for more information.
4. Where possible the main PSK (that which is fed into the importer) SHOULD be deleted after the imported keys have been generated. This protects an attacker from bootstrapping a compromise of one node into the ability to attack connections between any node; otherwise the attacker can recover the main key and then re-run the importer itself.

7.1. Stack Interfaces

Most major TLS implementations support external PSKs. Stacks supporting external PSKs provide interfaces that applications may use when supplying them for individual connections. Details about existing stacks at the time of writing are below.

***OpenSSL and BoringSSL:** Applications can specify support for external PSKs via distinct ciphersuites in TLS 1.2 and below. They also then configure callbacks that are invoked for PSK selection during the handshake. These callbacks must provide a PSK identity and key. The exact format of the callback depends on the negotiated TLS protocol version, with new callback functions added specifically to OpenSSL for TLS 1.3 [[RFC8446](#)] PSK support. The PSK length is validated to be between [1, 256] bytes. The PSK identity may be up to 128 bytes long.

***mbedTLS:** Client applications configure PSKs before creating a connection by providing the PSK identity and value inline. Servers must implement callbacks similar to that of OpenSSL. Both PSK identity and key lengths may be between [1, 16] bytes long.

*gnutls: Applications configure PSK values, either as raw byte strings or hexadecimal strings. The PSK identity and key size are not validated.

*wolfSSL: Applications configure PSKs with callbacks similar to OpenSSL.

7.1.1. PSK Identity Encoding and Comparison

Section 5.1 of [\[RFC4279\]](#) mandates that the PSK identity should be first converted to a character string and then encoded to octets using UTF-8. This was done to avoid interoperability problems (especially when the identity is configured by human users). On the other hand, [\[RFC7925\]](#) advises implementations against assuming any structured format for PSK identities and recommends byte-by-byte comparison for any operation. When PSK identities are configured manually it is important to be aware that due to encoding issues visually identical strings may, in fact, differ.

TLS version 1.3 [\[RFC8446\]](#) follows the same practice of specifying the PSK identity as a sequence of opaque bytes (shown as opaque identity<1..2¹⁶-1> in the specification). [\[RFC8446\]](#) also requires that the PSK identities are at least 1 byte and at the most 65535 bytes in length. Although [\[RFC8446\]](#) does not place strict requirements on the format of PSK identities, we do however note that the format of PSK identities can vary depending on the deployment:

*The PSK identity MAY be a user configured string when used in protocols like Extensible Authentication Protocol (EAP) [\[RFC3748\]](#). gnutls for example treats PSK identities as usernames.

*PSK identities MAY have a domain name suffix for roaming and federation.

*Deployments should take care that the length of the PSK identity is sufficient to avoid collisions.

7.1.2. PSK Identity Collisions

It is possible, though unlikely, that an external PSK identity may clash with a resumption PSK identity. The TLS stack implementation and sequencing of PSK callbacks influences the application's behaviour when identity collisions occur. When a server receives a PSK identity in a TLS 1.3 ClientHello, some TLS stacks execute the application's registered callback function before checking the stack's internal session resumption cache. This means that if a PSK identity collision occurs, the application will be given precedence over how to handle the PSK.

8. Security Considerations

It is NOT RECOMMENDED to share the same PSK between more than one client and server. However, as discussed in [Section 6](#), there are application scenarios that may rely on sharing the same PSK among multiple nodes. [\[I-D.ietf-tls-external-psk-importer\]](#) helps in mitigating rerouting and Selfie style reflection attacks when the PSK is shared among multiple nodes. This is achieved by correctly using the node identifiers in the ImportedIdentity.context construct specified in [\[I-D.ietf-tls-external-psk-importer\]](#). It is RECOMMENDED that each endpoint selects one globally unique identifier and uses it in all PSK handshakes. The unique identifier can, for example, be one of its MAC addresses, a 32-byte random number, or its Universally Unique Identifier (UUID) [\[RFC4122\]](#). Each endpoint SHOULD know the identifier of the other endpoint with which it wants to connect and SHOULD compare it with the other endpoint's identifier used in ImportedIdentity.context. It is however important to remember that endpoints sharing the same group PSK can always impersonate each other.

9. IANA Considerations

This document makes no IANA requests.

10. References

10.1. Normative References

[I-D.ietf-tls-dtls13] Rescorla, E., Tschofenig, H., and N. Modadugu, "The Datagram Transport Layer Security (DTLS) Protocol Version 1.3", Work in Progress, Internet-Draft, draft-ietf-tls-dtls13-38, 29 May 2020, <<http://www.ietf.org/internet-drafts/draft-ietf-tls-dtls13-38.txt>>.

[I-D.ietf-tls-external-psk-importer]
Benjamin, D. and C. Wood, "Importing External PSKs for TLS", Work in Progress, Internet-Draft, draft-ietf-tls-external-psk-importer-05, 19 May 2020, <<http://www.ietf.org/internet-drafts/draft-ietf-tls-external-psk-importer-05.txt>>.

[RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <<https://www.rfc-editor.org/info/rfc2119>>.

[RFC6066] Eastlake 3rd, D., "Transport Layer Security (TLS) Extensions: Extension Definitions", RFC 6066, DOI 10.17487/RFC6066, January 2011, <<https://www.rfc-editor.org/info/rfc6066>>.

[RFC8174]

Leiba, B., "Ambiguity of Uppercase vs Lowercase in RFC 2119 Key Words", BCP 14, RFC 8174, DOI 10.17487/RFC8174, May 2017, <<https://www.rfc-editor.org/info/rfc8174>>.

[RFC8446]

Rescorla, E., "The Transport Layer Security (TLS) Protocol Version 1.3", RFC 8446, DOI 10.17487/RFC8446, August 2018, <<https://www.rfc-editor.org/info/rfc8446>>.

10.2. Informative References

[Akhmetzyanova]

Akhmetzyanova, L., Alekseev, E., Smyshlyaeva, E., and A. Sokolov, "Continuing to reflect on TLS 1.3 with external PSK", 2019, <<https://eprint.iacr.org/2019/421.pdf>>.

[GAA]

"TR33.919 version 12.0.0 Release 12", n.d., <https://www.etsi.org/deliver/etsi_tr/133900_133999/133919/12.00.00_60/tr_133919v120000p.pdf>.

[I-D.ietf-tls-ctls]

Rescorla, E., Barnes, R., and H. Tschofenig, "Compact TLS 1.3", Work in Progress, Internet-Draft, draft-ietf-tls-ctls-01, 2 November 2020, <<http://www.ietf.org/internet-drafts/draft-ietf-tls-ctls-01.txt>>.

[I-D.irtf-cfrg-cpace]

Abdalla, M., Haase, B., and J. Hesse, "CPace, a balanced composable PAKE", Work in Progress, Internet-Draft, draft-irtf-cfrg-cpace-00, 28 July 2020, <<http://www.ietf.org/internet-drafts/draft-irtf-cfrg-cpace-00.txt>>.

[I-D.irtf-cfrg-opaque]

Krawczyk, H., Lewi, K., and C. Wood, "The OPAQUE Asymmetric PAKE Protocol", Work in Progress, Internet-Draft, draft-irtf-cfrg-opaque-00, 28 September 2020, <<http://www.ietf.org/internet-drafts/draft-irtf-cfrg-opaque-00.txt>>.

[I-D.mattsson-emu-eap-tls-psk]

Mattsson, J., Sethi, M., Aura, T., and O. Friel, "EAP-TLS with PSK Authentication (EAP-TLS-PSK)", Work in Progress, Internet-Draft, draft-mattsson-emu-eap-tls-psk-00, 9 March 2020, <<http://www.ietf.org/internet-drafts/draft-mattsson-emu-eap-tls-psk-00.txt>>.

[Krawczyk]

Krawczyk, H., "SIGMA: The 'SIGn-and-MAC' Approach to Authenticated Diffie-Hellman and Its Use in the IKE Protocols", Annual International Cryptology Conference. Springer, Berlin, Heidelberg, 2003, <<https://>

link.springer.com/content/pdf/10.1007/978-3-540-45146-4_24.pdf>.

- [LwM2M] "Lightweight Machine to Machine Technical Specification", n.d., <http://www.openmobilealliance.org/release/LightweightM2M/V1_0-20170208-A/OMA-TS-LightweightM2M-V1_0-20170208-A.pdf>.
- [RFC2865] Rigney, C., Willens, S., Rubens, A., and W. Simpson, "Remote Authentication Dial In User Service (RADIUS)", RFC 2865, DOI 10.17487/RFC2865, June 2000, <<https://www.rfc-editor.org/info/rfc2865>>.
- [RFC3748] Aboba, B., Blunk, L., Vollbrecht, J., Carlson, J., and H. Levkowetz, Ed., "Extensible Authentication Protocol (EAP)", RFC 3748, DOI 10.17487/RFC3748, June 2004, <<https://www.rfc-editor.org/info/rfc3748>>.
- [RFC4122] Leach, P., Mealling, M., and R. Salz, "A Universally Unique IDentifier (UUID) URN Namespace", RFC 4122, DOI 10.17487/RFC4122, July 2005, <<https://www.rfc-editor.org/info/rfc4122>>.
- [RFC4279] Eronen, P., Ed. and H. Tschofenig, Ed., "Pre-Shared Key Ciphersuites for Transport Layer Security (TLS)", RFC 4279, DOI 10.17487/RFC4279, December 2005, <<https://www.rfc-editor.org/info/rfc4279>>.
- [RFC6614] Winter, S., McCauley, M., Venaas, S., and K. Wierenga, "Transport Layer Security (TLS) Encryption for RADIUS", RFC 6614, DOI 10.17487/RFC6614, May 2012, <<https://www.rfc-editor.org/info/rfc6614>>.
- [RFC7925] Tschofenig, H., Ed. and T. Fossati, "Transport Layer Security (TLS) / Datagram Transport Layer Security (DTLS) Profiles for the Internet of Things", RFC 7925, DOI 10.17487/RFC7925, July 2016, <<https://www.rfc-editor.org/info/rfc7925>>.
- [RFC8773] Housley, R., "TLS 1.3 Extension for Certificate-Based Authentication with an External Pre-Shared Key", RFC 8773, DOI 10.17487/RFC8773, March 2020, <<https://www.rfc-editor.org/info/rfc8773>>.
- [Selfie] Drucker, N. and S. Gueron, "Selfie: reflections on TLS 1.3 with PSK", 2019, <<https://eprint.iacr.org/2019/347.pdf>>.
- [Sethi] Sethi, M., Peltonen, A., and T. Aura, "Misbinding Attacks on Secure Device Pairing and Bootstrapping", Proceedings

of the 2019 ACM Asia Conference on Computer and Communications Security , 2019, <<https://arxiv.org/pdf/1902.07550>>.

[SmartCard] "Technical Guideline TR-03112-7 eCard-API-Framework – Protocols", 2015, <https://www.bsi.bund.de/SharedDocs/Downloads/DE/BSI/Publikationen/TechnischeRichtlinien/TR03112/TR-03112-api_teil7.pdf?blob=publicationFile&v=1>.

Appendix A. Acknowledgements

This document is the output of the TLS External PSK Design Team, comprised of the following members: Benjamin Beurdouche, Bjoern Haase, Christopher Wood, Colm MacCarthaigh, Eric Rescorla, Jonathan Hoyland, Martin Thomson, Mohamad Badra, Mohit Sethi, Oleg Pekar, Owen Friel, and Russ Housley.

Authors' Addresses

Russ Housley
Vigil Security

Email: housley@vigilsec.com

Jonathan Hoyland
Cloudflare Ltd.

Email: jonathan.hoyland@gmail.com

Mohit Sethi
Ericsson

Email: mohit@piuha.net

Christopher A. Wood
Cloudflare

Email: caw@heapingbits.net