

Workgroup: Network Working Group
Internet-Draft:
draft-mattsson-cfrg-det-sigs-with-noise-04
Updates: [6979](#), [8032](#) (if approved)
Published: 15 February 2022
Intended Status: Informational
Expires: 19 August 2022
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Deterministic ECDSA and EdDSA Signatures with Additional Randomness

Abstract

Deterministic elliptic-curve signatures such as deterministic ECDSA and EdDSA have gained popularity over randomized ECDSA as their security do not depend on a source of high-quality randomness. Recent research has however found that implementations of these signature algorithms may be vulnerable to certain side-channel and fault injection attacks due to their determinism. One countermeasure to such attacks is to re-add randomness to the otherwise deterministic calculation of the per-message secret number. This document updates RFC 6979 and RFC 8032 to recommend constructions with additional randomness for deployments where side-channel attacks and fault injection attacks are a concern. The updates are invisible to the validator of the signature and compatible with existing ECDSA and EdDSA validators.

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1. Introduction

In Elliptic-Curve Cryptography (ECC) signature algorithms, the per-message secret number has traditionally been generated from a random number generator (RNG). The security of such algorithms depends on the cryptographic quality of the random number generation and biases in the randomness may have catastrophic effects such as compromising private keys (see e.g., [Bernstein19]). Repeated per-message secret numbers have caused several severe security accidents in practice. As stated in [RFC6979], the need for a cryptographically secure source of randomness is also a hindrance to deployment of randomized ECDSA [FIPS-186-4] in architectures where secure random number generation is challenging, in particular, embedded IoT systems and smartcards. [ABFJLM17] does however state that smartcards typically have a high-quality RNG on board, which makes it significantly easier and faster to use the RNG instead of doing a hash computation.

In deterministic ECC signatures schemes such as Deterministic Elliptic Curve Digital Signature Algorithm (ECDSA) [RFC6979] and Edwards-curve Digital Signature Algorithm (EdDSA) [RFC8032], the per-message secret number is instead generated in a fully deterministic way as a function of the message and the private key. Except for key generation, the security of such deterministic signatures does not depend on a source of high-quality randomness.

This makes verification of implementations easier. As they are presumed to be safer, deterministic signatures have gained popularity and are referenced and recommended by a large number of recent RFCs [[RFC8037](#)] [[RFC8080](#)] [[RFC8152](#)] [[RFC8225](#)] [[RFC8387](#)] [[RFC8410](#)] [[RFC8411](#)] [[RFC8419](#)] [[RFC8420](#)] [[RFC8422](#)] [[RFC8446](#)] [[RFC8463](#)] [[RFC8550](#)] [[RFC8591](#)] [[RFC8624](#)] [[RFC8208](#)] [[RFC8608](#)].

Side-channel attacks are potential attack vectors for implementations of cryptographic algorithms. Side-Channel attacks can in general be classified along three orthogonal axes: passive vs. active, physical vs. logical, and local vs. remote [[SideChannel](#)]. It has been demonstrated how side-channel attacks such as power analysis [[BCPST14](#)] and timing attacks [[Minerva19](#)] [[TPM-Fail19](#)] allow for practical recovery of the private key in some existing implementations of randomized ECDSA. [[BSI](#)] summarizes minimum requirements for evaluating side-channel attacks of elliptic curve implementations and writes that deterministic ECDSA and EdDSA requires extra care. The deterministic ECDSA specification [[RFC6979](#)] notes that the deterministic generation of per-message secret numbers may be useful to an attacker in some forms of side-channel attacks and as stated in [[Minerva19](#)], deterministic signatures like [[RFC6979](#)] and [[RFC8032](#)] might help an attacker to reduce the noise in the side-channel when the same message is signed multiple times. Recent research [[SH16](#)] [[BP16](#)] [[RP17](#)] [[ABFJLM17](#)] [[SBBDS17](#)] [[PSSLR17](#)] [[SB18](#)] [[WPB19](#)] [[AOTZ19](#)] [[FG19](#)] have theoretically and experimentally analyzed the resistance of deterministic ECC signature algorithms against side-channel and fault injection attacks. The conclusions are that deterministic signature algorithms have theoretical weaknesses against certain instances of these types of attacks and that the attacks are practically feasible in some environments. These types of attacks may be of particular concern for hardware implementations such as embedded IoT devices and smartcards where the adversary can be assumed to have access to the device to induce faults and measure its side-channels such as timing information, power consumption, electromagnetic leaks, or sound with low signal-to-noise ratio. A good summary of fault attacks is given by [[Cao20](#)]. See also the discussions and references in [[Comments-186-5](#)].

Fault attacks may also be possible without physical access to the device. RowHammer [[RowHammer14](#)] showed how an attacker can induce DRAM bit-flips in memory areas the attacker should not have access to. Plundervolt [[Plundervolt19](#)] showed how an attacker with root access can use frequency and voltage scaling interfaces to induce faults that bypass even secure execution technologies. RowHammer can e.g., be used in operating systems with several processes or cloud scenarios with virtualized servers. Protocols like TLS, SSH, and IKEv2 that add a random number to the message to be signed mitigate some types of attacks [[PSSLR17](#)].

Government agencies are clearly concerned about these attacks. In [[Notice-186-5](#)] and [[Draft-186-5](#)], NIST warns about side-channel and fault injection attacks, but states that deterministic ECDSA may be desirable for devices that lack good randomness. BSI has published [[BSI](#)] and researchers from BSI have co-authored two research papers [[ABFJLM17](#)] [[PSSLR17](#)] on attacks on deterministic signatures. For many industries it is important to be compliant with both RFCs and government publications, alignment between IETF, NIST, and BSI recommendations would be preferable.

Note that deriving per-message secret number deterministically, is also insecure in a multi-party signature setting [[I-D.irtf-cfrg-frost](#)].

One countermeasure to entropy failures, side-channel attacks, and fault injection attacks recommended by [[Langley13](#)] [[RP17](#)] [[ABFJLM17](#)] [[SBBDS17](#)] [[PSSLR17](#)] [[SB18](#)] [[AOTZ19](#)] [[FG19](#)] and implemented in [[OpenSSL13a](#)] [[OpenSSL13b](#)] [[XEdDSA](#)] [[libSodium](#)] [[libHydrogen](#)] is to generate the per-message secret number from a random string, a secret key, and the message. This combines the security benefits of fully randomized per-message secret numbers with the security benefits of fully deterministic secret numbers. Such a construction protects against key compromise due to weak random number generation, but still effectively prevents many side-channel and fault injection attacks that exploit determinism. Such a construction require minor changes to the implementation and does not increase the number of elliptic curve point multiplications and is therefore suitable for constrained IoT. Adding randomness to EdDSA is not compliant with [[RFC8032](#)]. [[Kampanakis16](#)] describes an alternative [[FIPS-186-4](#)] compliant approach where message specific pseudo-random information is used as an additional input to the random number generation to create per-message secret number. [[Bernstein14](#)] states that generation of the per-message secret number from a subset of a random string, a secret key, the message, and a message counter is common in DSA/ECDSA implementations.

This document updates [[RFC6979](#)] and [[RFC8032](#)] to recommend constructions with additional randomness for deployments where side-channel and fault injection attacks are a concern. The updates are invisible to the validator of the signature. Produced signatures remain fully compatible with unmodified ECDSA and EdDSA verifiers and existing key pairs can continue to be used. As the precise use of the noise is specified, test vectors can still be produced and implementations can be tested against them.

2. Conventions Used in This Document

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. Updates to RFC 8032 (EdDSA)

For Ed25519ph, Ed25519ctx, and Ed25519: In deployments where side-channel and fault injection attacks are a concern, the following step is RECOMMENDED instead of step (2) in Section 5.1.6 of [[RFC8032](#)]:

2. Compute $\text{SHA-512}(\text{dom2}(F, C) \parallel Z \parallel \text{prefix} \parallel 000\dots \parallel \text{PH}(M))$, where M is the message to be signed, Z is 32 octets of random data, the number of zeroes 000... is chosen so that the length of $(\text{dom2}(F, C) \parallel Z \parallel \text{prefix} \parallel 000\dots)$ is a multiple of 128 octets. Interpret the 64-octet digest as a little-endian integer r.

For Ed448ph and Ed448: In deployments where side-channel and fault injection attacks are a concern, the following step is RECOMMENDED instead of step (2) in Section 5.3.6 of [[RFC8032](#)]:

2. Compute $\text{SHAKE256}(\text{dom4}(F, C) \parallel Z \parallel \text{prefix} \parallel 000\dots \parallel \text{PH}(M), 114)$, where M is the message to be signed, and Z is 57 octets of random data, the number of zeroes 000... is chosen so that the length of $(\text{dom4}(F, C) \parallel Z \parallel \text{prefix} \parallel 000\dots)$ is a multiple of 136 octets. F is 1 for Ed448ph, 0 for Ed448, and C is the context to use. Interpret the 114-octet digest as a little-endian integer r.

4. Updates to RFC 6979 (Deterministic ECDSA)

For Deterministic ECDSA: In existing ECDSA deployments where side-channel and fault injection attacks are a concern, the following steps are RECOMMENDED instead of steps (d) and (f) in Section 3.2 of [[RFC6979](#)]:

d. Set:

$K = \text{HMAC_K}(V \parallel 0x00 \parallel Z \parallel \text{int2octets}(x) \parallel 000\dots \parallel \text{bits2octets}(h1))$ where '||' denotes concatenation. In other words, we compute HMAC with key K, over the concatenation of the following, in order: the current value of V, a sequence of eight bits of value 0, random data Z (of the same length as $\text{int2octets}(x)$), the encoding of the (EC)DSA private key x, a sequence of zero bits 000... chosen so that the length of $(V \parallel 0x00 \parallel Z \parallel \text{int2octets}(x) \parallel 000\dots)$ is equal to the block size of the hash function, and the hashed message (possibly truncated and extended as specified by the bits2octets transform). The HMAC result is the new value of K. Note that the private key x is in the $[1, q-1]$ range, hence a proper input for int2octets , yielding rlen bits of output, i.e., an integral number of octets (rlen is a multiple of 8).

f. Set:

$K = \text{HMAC_K}(V \parallel 0x01 \parallel Z \parallel \text{int2octets}(x) \parallel 000\dots \parallel \text{bits2octets}(h1))$

When ECDSA is used with SHAKE [[SHA3](#)] the HMAC construction above MAY be used but it is RECOMMENDED to use the more efficient KMAC construction [[KMAC](#)]. SHAKE is a variable-length hash function defined as $\text{SHAKE}(M, d)$ where the output is a d-bits-long digest of message M. When ECDSA is used with $\text{SHAKE128}(M, d)$, it is RECOMMENDED to replace $\text{HMAC}(K, M)$ with $\text{KMAC128}(K, M, d, "")$. When ECDSA is used with $\text{SHAKE256}(M, d)$, it is RECOMMENDED to replace $\text{HMAC}(K, M)$ with $\text{KMAC256}(K, M, d, "")$. [[RFC8692](#)] and [[Draft-186-5](#)] define the use of SHAKE128 with an output length of 256 bits and SHAKE256 with an output length of 512 bits.

In new deployments, where side-channel and fault injection attacks are a concern, EdDSA with additional randomness as specified in [Section 3](#) is RECOMMENDED.

5. Security Considerations

The constructions in this document follows the high-level approach in [[XEdDSA](#)] to calculate the per-message secret number from the hash of the private key and the message, but add additional randomness into the calculation for greater resilience. This does not re-introduce the strong security requirement of randomness needed by randomized ECDSA [[FIPS-186-4](#)]. The randomness of Z does not need to be perfect, but SHALL be generated by a cryptographically secure pseudo random number generator (PRNG) and SHALL be secret. Even if the same random number Z is used to sign two different messages, the security will be the same as deterministic ECDSA and EdDSA and an

attacker will not be able to compromise the private key with algebraic means as in fully randomized ECDSA [[FIPS-186-4](#)]. With the construction specified in this document, two signatures over two equal messages are different which prevents information leakage in use cases where signatures but not messages are public. The construction in this document place the additional randomness before the message to align with randomized hashing methods.

[[SBBDS17](#)] states that [[XEdDSA](#)] would not prevent their attack due to insufficient mixing of the hashed private key with the additional randomness. [[SBBDS17](#)] suggest a construction where the randomness is padded with zeroes so that the first 1024-bit SHA-512 block is composed only of the hashed private key and the random value, but not the message. The construction in this document follows this recommendation and pads with zeroes so that the first block is composed only of the hashed private key and the random value, but not the message.

Another countermeasure to fault attacks is to force the signer to verify the signature in the last step of the signature generation or to calculate the signature twice and compare the results. These countermeasure would catch a single fault but would not protect against attackers that are able to precisely inject faults several times [[RP17](#)] [[PSSLR17](#)] [[SB18](#)]. Adding an additional sign or verification operation would also significantly affect performance, especially verification which is a heavier operation than signing in ECDSA and EdDSA.

[[ABFJLM17](#)] suggests using both additional randomness and a counter, which makes the signature generation stateful. While most used signatures have traditionally been stateless, stateful signatures like XMSS [[RFC8391](#)] and LMS [[RFC8554](#)] have now been standardized and deployed. [[RFC8937](#)] specifies a PRNG construction with a random seed, a secret key, a context string, and a nonce, which makes the random number generation stateful. The generation of the per-message secret number in this document is not stateful, but it can be used with a stateful PRNG. The exact construction in [[RFC8937](#)] is however not recommended in deployments where side-channel and fault injection attacks are a concern as it relies on deterministic signatures.

With the construction in this document, the repetition of the same per-message secret number for two different messages is highly unlikely even with an imperfect random number generator, but not impossible. As an extreme countermeasure, previously used secret numbers can be tracked to ensure their uniqueness for a given key, and a different random number can be used if a collision is detected. This document does not mandate nor stop an implementation from taking such a precaution.

Implementations need to follow best practices on how to protect against all side-channel attacks, not just attacks that exploit determinism, see for example [BSI].

6. For discussion (to be removed in the future)

*removal of "noise" from filename. Will be done if/when the draft is uploaded as adopted (draft-irtf-....)

*Strong consensus to change the name "Deterministic ECDSA and EdDSA Signatures with Additional Randomness". The signatures are obviously not deterministic anymore. Several suggestions for new names: "message-dependent", "message-keyed", "entropy stealing", "entropy combining", "whitening", "keyed entropy whitening", "hedged", "noise".

*Ordering of the parameters in "dom2(F, C) || Z || prefix || 000... || PH(M)" in Ed25519 and similar in Ed448 and ECDSA. There has also been suggestion to use a larger Z and to use several paddings 000....

*Ilari Liusvaara pointed out attacks using the context that needs to be considered. Some statements "first block is composed only of the hashed private key and the random value" in the document are not true for Ed25519ctx and Ed448ctx.

*Jim Schaad: Is there any advantage to stealing one of the zeros from the end padding and using it to pad between 'Z' and 'x' in the construction? I would assume that it should use the '0'/'1' construction between steps d and f.

*Jim Schaad: Is there any advantage to padding with 0x01 in step f rather than 0x00?

*Rene Stuik: MUST instead of RECOMMENDED.

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Acknowledgments

The authors want to thank Tony Arcieri, Uri Blumenthal, Carsten Bormann, Phillip Hallam-Baker, Chelsea Komlo, Quynh Dang, Janos Follath, Ilari Liusvaara, Jim Schaad, and Ruggero Susella for their valuable comments and feedback.

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