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HIP Diet EXchange (DEX)
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Abstract

This document specifies the Host Identity Protocol Diet EXchange (HIP DEX), a variant of the Host Identity Protocol Version 2 (HIPv2). The HIP DEX protocol design aims at reducing the overhead of the employed cryptographic primitives by omitting public-key signatures and hash functions.

The HIP DEX protocol is primarily designed for computation or memory-constrained sensor/actuator devices. Like HIPv2, it is expected to be used together with a suitable security protocol such as the Encapsulated Security Payload (ESP) for the protection of upper layer protocol data. Unlike HIPv2, HIP DEX does not support Perfect Forward Secrecy (PFS), and MUST only be used on devices where PFS is prohibitively expensive. In addition, HIP DEX can also be used as a keying mechanism for security primitives at the MAC layer, e.g., for IEEE 802.15.4 networks.

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1. Introduction

This document specifies the Host Identity Protocol Diet EXchange (HIP DEX). HIP DEX builds on the Base EXchange (BEX) of the Host Identity Protocol Version 2 (HIPv2) [RFC7401]. HIP DEX preserves the protocol semantics as well as the general packet structure of HIPv2. Hence, it is recommended that [RFC7401] is well-understood before reading this document.

The main differences between HIP BEX and HIP DEX are:

1. HIP DEX uses a different set of cryptographic primitives compared to HIP BEX with the goal to reduce the protocol overhead:

   * Peer authentication and key agreement in HIP DEX are based on static Elliptic Curve Diffie-Hellman (ECDH) key pairs. This replaces the use of public-key signatures and ephemeral Diffie-Hellman key pairs in HIPv2.

   * HIP DEX uses AES-CTR for symmetric-key encryption and AES-CMAC as its MACing function. In contrast, HIPv2 currently supports AES-CBC for encryption and HMAC-SHA-1, HMAC-SHA-256, or HMAC-SHA-384 for MACing.

   * HIP DEX defines a simple fold function to efficiently generate HITs, whereas the HIT generation of HIPv2 is based on SHA-1, SHA-256, or SHA-384.

2. HIP DEX forfeits the HIPv2 Perfect Forward Secrecy property of HIPv2 due to the removal of the ephemeral Diffie-Hellman key agreement. As this weakens the security properties of HIP DEX, it MUST be used only with constrained devices where this is prohibitively expensive as further explained in Section 1.2.

3. HIP DEX forfeits the use of digital signatures with the removal of a hash function. Peer authentication with HIP DEX, therefore, is based on the use of the ECDH derived key in the HIP_MAC parameter.

4. With HIP DEX, the ECDH derived key is only used to protect HIP packets. Separate session key(s) are used to protect the transmission of upper layer protocol data. These session key(s) are established via a new secret exchange during the handshake.

5. HIP DEX introduced a new, optional retransmission strategy that is specifically designed to handle potentially extensive processing times of the employed cryptographic operations on computationally constrained devices.

By eliminating the need for public-key signatures and the ephemeral DH key agreement, HIP DEX reduces the computational, energy, transmission, and memory requirements for public-key cryptography (see [LN08]) in the HIPv2 protocol design. This makes HIP DEX especially suitable for constrained devices as defined in [RFC7228].

This document focuses on the protocol specifications related to differences between HIP BEX and HIP DEX. Where differences are not called out explicitly, the protocol specification of HIP DEX is the same as defined in [RFC7401].

1.1. The HIP Diet EXchange (DEX)

The HIP Diet EXchange is a two-party cryptographic protocol used to establish a secure communication context between hosts. The first party is called the Initiator and the second party the Responder. The four-packet exchange helps to make HIP DEX Denial of Service (DoS) resilient. The Initiator and the Responder exchange their static Elliptic Curve Diffie-Hellman (ECDH) keys in the R1 and I2 handshake packet. The parties then authenticate each other in the I2 and R2 handshake packet based on the ECDH-derived keying material. The Initiator and the Responder additionally transmit keying material for the session key in these last two handshake packets (I2 and R2). This is to prevent overuse of the static ECDH-derived keying material. Moreover, the Responder starts a puzzle exchange in the R1 packet and the Initiator completes this exchange in the I2 packet before the Responder performs computationally expensive operations or stores any state from the exchange. Given this handshake structure, HIP DEX operationally is very similar to HIP BEX. Moreover, the employed model is also fairly equivalent to 802.11-2007 [IEEE.802-11.2007] Master Key and Pair-wise Transient Key, but handled in a single exchange.

HIP DEX does not have the option to encrypt the Host Identity of the Initiator in the I2 packet. The Responder's Host Identity also is not protected. Thus, contrary to HIPv2, HIP DEX does not provide for end-point anonymity and any signaling (i.e., HOST_ID parameter contained with an ENCRYPTED parameter) that indicates such anonymity should be ignored.

As in [RFC7401], data packets start to flow after the R2 packet. The I2 and R2 packets may carry a data payload in the future. The details of this may be defined later.

An existing HIP association can be updated with the update mechanism defined in [RFC7401]. Likewise, the association can be torn down with the defined closing mechanism for HIPv2 if it is no longer needed. In doing so, HIP DEX does so even in the absence of the HIP_SIGNATURE that is used in standard HIPv2.

Finally, HIP DEX is designed as an end-to-end authentication and key establishment protocol. As such, it can be used in combination with Encapsulated Security Payload (ESP) [RFC7402] as well as with other end-to-end security protocols. In addition, HIP DEX can also be used as a keying mechanism for security primitives at the MAC layer, e.g., for IEEE 802.15.4 networks [IEEE.802-15-4.2011]. It is worth mentioning that the HIP DEX base protocol does not cover all the fine-grained policy control found in Internet Key Exchange Version 2 (IKEv2) [RFC7296] that allows IKEv2 to support complex gateway policies. Thus, HIP DEX is not a replacement for IKEv2.

1.2. Applicability

HIP DEX achieves its lightweight nature in large part due to the intentional removal of Forward Secrecy (FS) from the key exchange. Current mechanisms to achieve FS use an authenticated ephemeral Diffie-Hellman exchange (e.g., SIGMA or PAKE). HIP DEX targets usage on devices where even the most lightweight ECDH exchange is prohibitively expensive for recurring (ephemeral) use. For example, experience with the 8-bit 8051-based ZWAVE ZW0500 microprocessor has shown that EC25519 keypair generation exceeds 10 seconds and consumes significant energy (i.e., battery resources). Even the ECDH multiplication for the HIP DEX static-static key exchange takes 8-9 seconds, again with measurable energy consumption. This resource consumption is tolerable as a one-time event during provisioning, but would render the protocol unsuitable for use on these devices if it was required to be a recurring part of the protocol. For devices constrained in this manner, a FS-enabled protocol will likely provide little gain. The resulting "FS" key, likely produced during device provisioning, would typically end up being used for the remainder of the device's lifetime.

With such a usage pattern, the inherent benefit of ephemeral keys is not realized. The security properties of such usage are very similar to those of using a statically provisioned symmetric pre-shared key, in that there remains a single PSK in static storage that is susceptible to exfiltration/compromise, and compromise of that key in effect compromises the entire protocol for that node. HIP DEX achieves marginally better security properties by computing the effective long-term PSK from a DH exchange, so that the provisioning service is not required to be part of the risk surface due to also possessing the PSK.

Due to the substantially reduced security guarantees of HIP DEX compared to HIP BEX, HIP DEX MUST only be used when at least one of the two endpoints is a class 0 or 1 constrained device defined in Section 3 of [RFC7228]). HIP DEX MUST NOT be used when both endpoints are class 2 devices or unconstrained.

1.3. Memo Structure

The rest of this memo is structured as follows. Section 2 defines the central keywords, notation, and terms used throughout this document. Section 3 defines the structure of the Host Identity and its various representations. Section 4 gives an overview of the HIP Diet EXchange protocol. Sections 5 and 6 define the detailed packet formats and rules for packet processing. Finally, Sections 7, 8, 9, and 10 discuss policy, interoperability between HIPv2 vs DEX, security, and IANA considerations, respectively. Appendix A defines a two factor authentication scheme and Appendix B highlights some discussions with the IESG.

2. Terms, Notation and Definitions

2.1. Requirements Terminology

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.

2.2. Notation

[x] indicates that x is optional.

{x} indicates that x is encrypted.

X(y) indicates that y is a parameter of X.

<x>i indicates that x exists i times.

--> signifies "Initiator to Responder" communication (requests).

<-- signifies "Responder to Initiator" communication (replies).

| signifies concatenation of information - e.g., X | Y is the concatenation of X and Y.

FOLD (X, K) denotes the partitioning of X into n K-bit segments and the iterative folding of these segments via XOR. I.e., X = x_1,

x_2, ..., x_n, where x_i is of length K and the last segment x_n is padded to length K by appending 0 bits. FOLD then is computed as FOLD(X, K) = t_n, where t_i = t_i-1 XOR x_i and t_1 = x_1.

Ltrunc (M(x), K) denotes the lowest order K bits of the result of the MAC function M on the input x.

sort (HIT-I | HIT-R) is defined as the network byte order concatenation of the two HITs, with the smaller HIT preceding the larger HIT, resulting from the numeric comparison of the two HITs interpreted as positive (unsigned) 128-bit integers in network byte order.

2.3. Definitions

CKDF: CMAC-based Key Derivation Function.

CMAC: The Cipher-based Message Authentication Code with the 128-bit Advanced Encryption Standard (AES) defined in RFC 4493 [RFC4493].

HIP association: The shared state between two peers after completion of the HIP DEX handshake.

HIP DEX (Diet EXchange): The ECDH-based HIP handshake for establishing a new HIP association.

HIT Suite: A HIT Suite groups all algorithms that are required to generate and use an HI and its HIT. In particular for HIP DEX, these algorithms are: 1) ECDH and 2) FOLD.

HI (Host Identity): The static ECDH public key that represents the identity of the host. In HIP DEX, a host proves ownership of the private key belonging to its HI by creating a HIP_MAC with the derived ECDH key (see Section 3).

HIT (Host Identity Tag): A shorthand for the HI in IPv6 format. It is generated by folding the HI (see Section 3).

Initiator: The host that initiates the HIP DEX handshake. This role is typically forgotten once the handshake is completed.

KEYMAT: Keying material. That is, the bit string(s) used as cryptographic keys.

Length of the Responder's HIT Hash Algorithm (RHASH_len): The natural output length of RHASH in bits.

Nonce #I: Nonce #I refers to the corresponding field in the PUZZLE parameter (see section 5.2.4 in [RFC7401]. It is also referred to as "random value #I" in this document.

OGA (Orchid Generation Algorithm): Hash function used in generating the ORCHID.

ORCHID (Overlay Routable Cryptographic Hash Identifiers): IPv6 addresses intended to be used as endpoint identifiers at applications and Application Programming Interfaces (APIs) and not as identifiers for network location at the IP layer.

Puzzle difficulty K: The Initiator has to compute a solution for the puzzle. The level of computational difficulty is denoted by the #K field in the puzzle parameter (see section 5.2.4 in [RFC7401].

Responder: The host that responds to the Initiator in the HIP DEX handshake. This role is typically forgotten once the handshake is completed.

RHASH (Responder's HIT Hash Algorithm): In HIP DEX, RHASH is redefined as CMAC. Still, note that CMAC is a message authentication code (MAC) and not a cryptographic hash function. Thus, a mapping from CMAC(x,y) to RHASH(z) must be defined where RHASH is used. Moreover, RHASH has different security properties in HIP DEX and is not used for HIT generation.

3. Host Identity (HI) and its Structure

In this section, the properties of the Host Identity and Host Identity Tag are discussed, and the exact format for them is defined. In HIP, the public key of an asymmetric key pair is used as the Host Identity (HI). Correspondingly, the host itself is defined as the entity that holds the private key of the key pair. See the HIP architecture specification [I-D.ietf-hip-rfc4423-bis] for more details on the difference between an identity and the corresponding identifier.

HIP DEX implementations use the Elliptic Curve Diffie-Hellman (ECDH) [RFC6090] key exchange for generating the HI as defined in Section 5.2.3. No alternative algorithms are defined at this time.

A compressed encoding of the HI, the Host Identity Tag (HIT), is used in the handshake packets to represent the HI. The DEX Host Identity Tag (HIT) is different from the BEX HIT in two ways:

o The HIT suite ID MUST only be a DEX HIT ID (see Section 5.2.4).

- The DEX HIT is not generated via a cryptographic hash. Rather, it is a compression of the HI.

Due to the latter property, an attacker may be able to find a collision with a HIT that is in use. Hence, policy decisions such as access control MUST NOT be based solely on the HIT. Instead, the HI of a host SHOULD be considered.

Carrying HIs or HITs in the header of user data packets would increase the overhead of packets. Thus, it is not expected that these parameters are carried in every packet, but other methods are used to map the data packets to the corresponding HIs. In some cases, this allows use of HIP DEX without any additional headers in the user data packets. For example, if ESP is used to protect data traffic, the Security Parameter Index (SPI) carried in the ESP header can be used to map the encrypted data packet to the correct HIP DEX association. When other user data packet formats are used, the corresponding extensions need to define a replacement for the ESP_TRANSFORM [RFC7402] parameter along with associated semantics, but this procedure is outside the scope of this document.

3.1. Host Identity Tag (HIT)

With HIP DEX, the HIT is a 128-bit value - a compression of the HI prepended with a specific prefix. There are two advantages of using this compressed encoding over the actual variable-sized public key in protocols. First, the fixed length of the HIT keeps packet sizes manageable and eases protocol coding. Second, it presents a consistent format for the protocol, independent of the underlying identity technology in use.

The structure of the HIT is based on RFC 7343 [RFC7343], called Overlay Routable Cryptographic Hash Identifiers (ORCHIDs), and consists of three parts: first, an IANA assigned prefix to distinguish it from other IPv6 addresses. Second, a four-bit encoding of the algorithms that were used for generating the HI and the compressed representation of the HI. Third, a 96-bit hashed representation of the HI. In contrast to HIPv2, HIP DEX employs HITs that are NOT generated by means of a cryptographic hash. Instead, the HI is compressed to 96 bits as defined in the following section.

3.2. Generating a HIT from an HI

The HIT does not follow the exact semantics of an ORCHID as there is no hash function in HIP DEX. Still, its structure is strongly aligned with the ORCHID design. The same IPv6 prefix used in HIPv2 is used for HIP DEX. The HIP DEX HIT suite (see Section 10) is used for the four bits of the Orchid Generation Algorithm (OGA) field in

the ORCHID. The hash representation in an ORCHID is replaced with FOLD(HI,96).

3.2.1. Why Introduce FOLD

HIP DEX, by design lacks a cryptographic hash function. The generation of the HIT is one of the few places in the protocol where this presents a challenge. CMAC was first considered for this purpose, but to use CMAC for HIT generation would require using a static key, either ZERO or some published value. NIST does not consider CMAC an approved cryptograhic hash as:

> It is straightforward to demonstrate that CMAC is not collision-resistant for any choice of a published key.

Since collision-resistance is not possible with the tools at hand, any reasonable function (e.g. FOLD) that takes the full value of the HI into generating the HIT can be used, provided that collision detection is part of the HIP-DEX deployment design. This is achieved here through either an ACL or some other lookup process that externally binds the HIT and HI.

4. Protocol Overview

This section gives a simplified overview of the HIP DEX protocol operation and does not contain all the details of the packet formats or the packet processing steps. Section 5 and Section 6 describe these aspects in more detail and are normative in case of any conflicts with this section. Importantly, the information given in this section focuses on the differences between the HIPv2 and HIP DEX protocol specifications.

4.1. Creating a HIP Association

By definition, the system initiating a HIP Diet EXchange is the Initiator, and the peer is the Responder. This distinction is typically forgotten once the handshake completes, and either party can become the Initiator in future communications.

The HIP Diet EXchange serves to manage the establishment of state between an Initiator and a Responder. The first packet, I1, initiates the exchange, and the last three packets, R1, I2, and R2, constitute an authenticated Diffie-Hellman [DH76] key exchange for the Master Key SA generation. This Master Key SA is used by the Initiator and the Responder to wrap secret keying material in the I2 and R2 packets. Based on the exchanged keying material, the peers then derive a Pair-wise Key SA if cryptographic keys are needed, e.g., for ESP-based protection of user data.

The Initiator first sends a trigger packet, I1, to the Responder. This packet contains the HIT of the Initiator and the HIT of the Responder, if it is known. Moreover, the I1 packet initializes the negotiation of the Diffie-Hellman group that is used for generating the Master Key SA. Therefore, the I1 packet contains a list of Diffie-Hellman Group IDs supported by the Initiator.

The second packet, R1, starts the actual authenticated Diffie-Hellman key exchange. It contains a puzzle - a cryptographic challenge that the Initiator must solve before continuing the exchange. The level of difficulty of the puzzle can be adjusted based on level of knowledge of the Initiator, current load, or other factors. In addition, the R1 contains the Responder's Diffie-Hellman parameter and lists of cryptographic algorithms supported by the Responder. Based on these lists, the Initiator can continue, abort, or restart the handshake with a different selection of cryptographic algorithms.

In the I2 packet, the Initiator MUST display the solution to the received puzzle. Without a correct solution, the I2 packet is discarded. The I2 also contains a key wrap parameter that carries secret keying material of the Initiator. This keying material is only half of the final session key. The packet is authenticated by the sender (Initiator) via a MAC.

The R2 packet acknowledges the receipt of the I2 packet and completes the handshake. The R2 contains a key wrap parameter that carries the rest of the keying material of the Responder. The packet is authenticated by the sender (Responder) via a MAC.

The HIP DEX handshake is illustrated below. The terms "ENC(DH,x)" and "ENC(DH,y)" refer to the random values x and y that are wrapped based on the Master Key SA (indicated by ENC and DH). Note that x and y each constitute half of the final session key material. The packets also contain other parameters that are not shown in this figure.

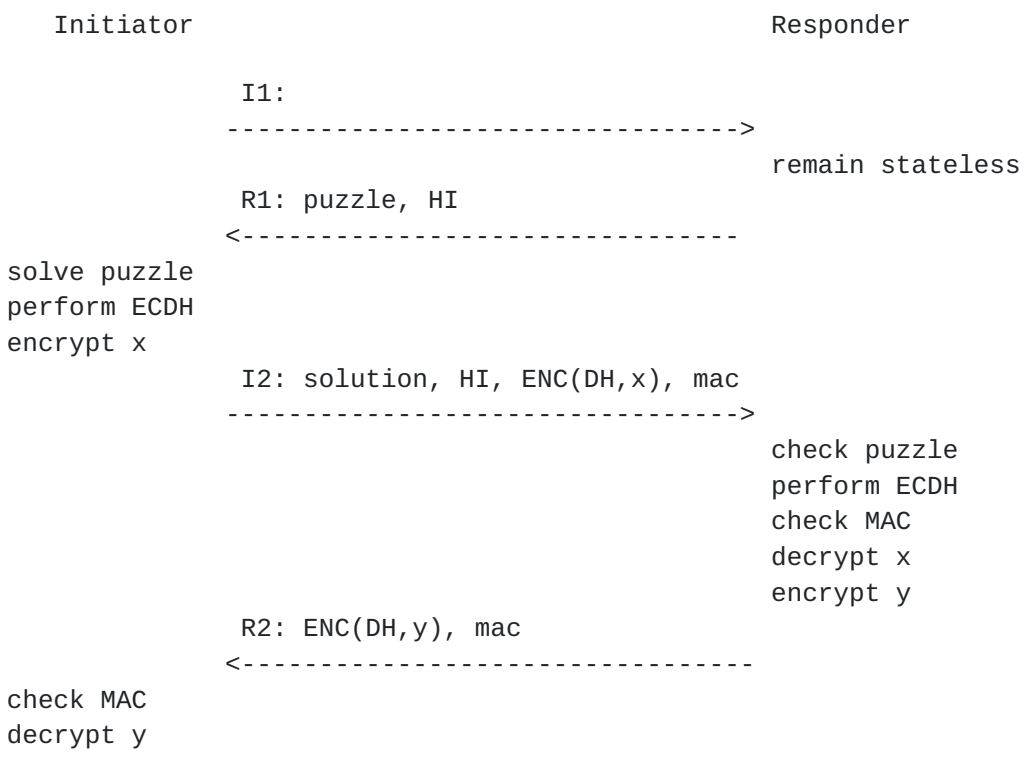


Figure 1: High-level overview of the HIP Diet EXchange

4.1.1. HIP Puzzle Mechanism

The purpose of the HIP puzzle mechanism is to protect the Responder from a number of denial-of-service threats. It allows the Responder to delay state creation until receiving the I2 packet. Furthermore, the puzzle allows the Responder to use a fairly cheap calculation to check that the Initiator is "sincere" in the sense that it has churned enough CPU cycles in solving the puzzle.

The puzzle mechanism enables a Responder to immediately reject an I2 packet if it does not contain a valid puzzle solution. To verify the puzzle solution, the Responder only has to compute a single CMAC operation. After a successful puzzle verification, the Responder can securely create session-specific state and perform CPU-intensive operations such as a Diffie-Hellman key generation. By varying the difficulty of the puzzle, the Responder can frustrate CPU or memory targeted DoS attacks. Under normal network conditions, the puzzle difficulty SHOULD be zero, thus effectively reverting the puzzle mechanism to a cookie-based DoS protection mechanism. Without setting the puzzle difficulty to zero under normal network conditions, potentially scarce computation resources at the Initiator would be churned unnecessarily.

Conceptually, the puzzle mechanism in HIP DEX is the same as in HIPv2. Hence, this document refers to Sections 4.1.1 and 4.1.2 in [RFC7401] for more detailed information about the employed mechanism. Notably, the only differences between the puzzle mechanism in HIP DEX and HIPv2 are that HIP DEX does not employ pre-computation of R1 packets and uses CMAC instead of a hash function for solving and verifying a puzzle. The implications of these changes on the puzzle implementation are discussed in Section 6.1.

4.1.2. HIP State Machine

The HIP DEX state machine has the same states as the HIPv2 state machine (see Section 4.4. in [RFC7401]). However, HIP DEX features a retransmission strategy with an optional reception acknowledgement for the I2 packet. The goal of this additional acknowledgement is to reduce premature I2 retransmissions in case of devices with low computation resources [HWZ13]. As a result, there are minor changes regarding the transitions in the HIP DEX state machine. The following section documents these differences compared to HIPv2.

4.1.2.1. HIP DEX Retransmission Mechanism

For the retransmission of I1 and I2 packets, the Initiator adopts the retransmission strategy of HIPv2 (see Section 4.4.3. in [RFC7401]). This strategy is based on a timeout that is set to a value larger than the worst-case anticipated round-trip time (RTT). For each received I1 or I2 packet, the Responder sends an R1 or R2 packet, respectively. This design trait enables the Responder to remain stateless until the reception and successful processing of the I2 packet. The Initiator stops retransmitting I1 or I2 packets after the reception of the corresponding R1 or R2. If the Initiator did not receive an R1 packet after I1_RETRIES_MAX tries, it stops I1 retransmissions. Likewise, it stops retransmitting the I2 packet after I2_RETRIES_MAX unsuccessful tries.

For repeatedly received I2 packets, the Responder SHOULD NOT perform operations related to the Diffie-Hellman key exchange or the keying material wrapped in the ENCRYPTED_KEY parameters. Instead, it SHOULD re-use the previously established state to re-create the corresponding R2 packet in order to prevent unnecessary computation overhead.

The potentially high processing time of an I2 packet at a (resource-constrained) Responder may cause premature retransmissions if the time required for I2 transmission and processing exceeds the RTT-based retransmission timeout. Thus, the Initiator should also take the processing time of the I2 packet at the Responder into account for retransmission purposes. To this end, the Responder MAY notify

the Initiator about the anticipated delay once the puzzle solution was successfully verified and if the remaining I2 packet processing incurs a high processing delay. The Responder MAY therefore send a NOTIFY packet (see Section 5.3.6. in [RFC7401]) to the Initiator before the Responder commences the ECDH operation. The NOTIFY packet serves as an acknowledgement for the I2 packet and consists of a NOTIFICATION parameter with Notify Message Type I2_ACKNOWLEDGEMENT (see Section 5.2.19. in [RFC7401]). The NOTIFICATION parameter contains the anticipated remaining processing time for the I2 packet in milliseconds as two-octet Notification Data. This processing time can, e.g., be estimated by measuring the computation time of the ECDH key derivation operation during the Responder start-up procedure. After the I2 processing has finished, the Responder sends the regular R2 packet.

When the Initiator receives the NOTIFY packet, it sets the I2 retransmission timeout to the I2 processing time indicated in the NOTIFICATION parameter plus half the RTT-based timeout value. In doing so, the Initiator MUST NOT set the retransmission timeout to a higher value than allowed by a local policy. This is to prevent unauthenticated NOTIFY packets from maliciously delaying the handshake beyond a well-defined upper bound in case of a lost R2 packet. At the same time, this extended retransmission timeout enables the Initiator to defer I2 retransmissions until the point in time when the Responder should have completed its I2 packet processing and the network should have delivered the R2 packet according to the employed worst-case estimates.

4.1.2.2. HIP State Processes

HIP DEX clarifies or introduces the following new transitions.

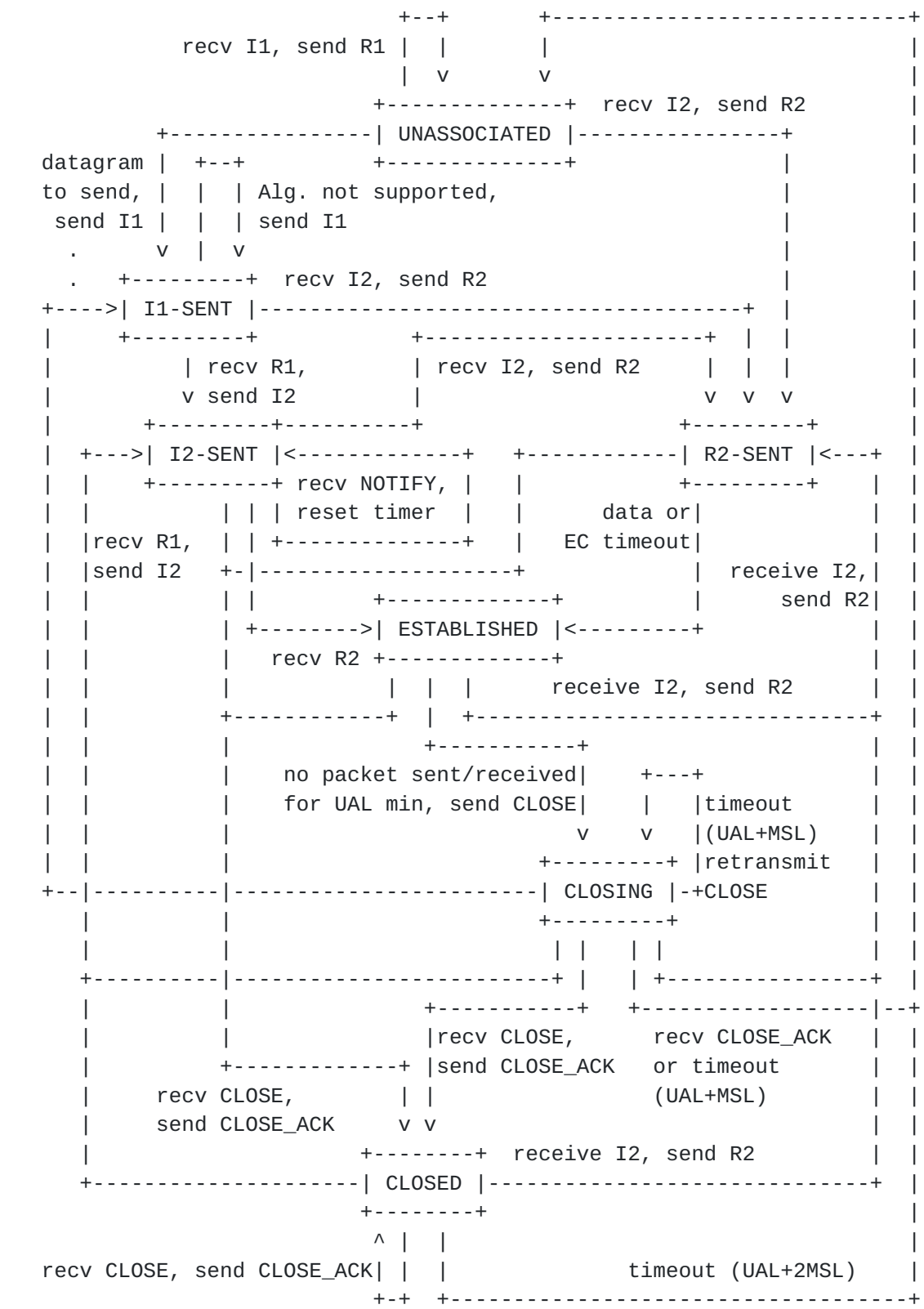
System behavior in state I2-SENT, Table 1.

Trigger	Action
Receive NOTIFY, process	Set I2 retransmission timer to value in I2_ACKNOWLEDGEMENT Notification Data plus 1/2 RTT-based timeout value and stay at I2-SENT
Timeout	Increment trial counter
	If counter is less than I2_RETRIES_MAX, send I2, reset timer to RTT-based timeout, and stay at I2-SENT
	If counter is greater than I2_RETRIES_MAX, go to E-FAILED

Table 1: I2-SENT - Waiting to finish the HIP Diet EXchange

4.1.2.3. Simplified HIP State Diagram

The following diagram shows the major state transitions. Transitions based on received packets implicitly assume that the packets are successfully authenticated or processed.


recv I1, send R1
UNASSOCIATED
datagram to send, send I1
Alg. not supported, send I1
recv I2, send R2
I1-SENT
recv R1, send I2
recv I2, send R2
I2-SENT
R2-SENT
recv NOTIFY, reset timer
recv R1, send I2
data or EC timeout
receive I2, send R2
ESTABLISHED
recv R2
receive I2, send R2
no packet sent/received for UAL min, send CLOSE
timeout (UAL+MSL) retransmit
CLOSING
CLOSE
recv CLOSE, send CLOSE_ACK
recv CLOSE_ACK or timeout (UAL+MSL)
CLOSED
receive I2, send R2
timeout (UAL+2MSL)

4.1.3. HIP DEX Security Associations

HIP DEX establishes two Security Associations (SA), one for the Diffie-Hellman derived key, or Master Key, and one for the session key, or Pair-wise Key.

4.1.3.1. Master Key SA

The Master Key SA is used to authenticate HIP packets and to encrypt selected HIP parameters in the HIP DEX packet exchanges. Since only a small amount of data is protected by this SA, it can be long-lived with no need for rekeying. At the latest, the system MUST initiate rekeying when its incoming ESP sequence counter is going to overflow, and the system MUST NOT replace its keying material until the rekeying packet exchange successfully completes as described in Section 6.8 in [RFC7402].

The Master Key SA contains the following elements:

- Source HIT
- Destination HIT
- HIP_Encrypt Key
- HIP_MAC Key

The HIP_Encrypt and HIP_MAC keys are extracted from the Diffie-Hellman derived key as described in Section 6.3. Their length is determined by the HIP_CIPHER.

4.1.3.2. Pair-wise Key SA

The Pair-wise Key SA is used to authenticate and to encrypt user data. It is refreshed (or rekeyed) using an UPDATE packet exchange. The Pair-wise Key SA elements are defined by the data transform (e.g., ESP_TRANSFORM [RFC7402]).

The keys for the Pair-wise Key SA are derived based on the wrapped keying material exchanged in the ENCRYPTED_KEY parameter (see Section 5.2.5) of the I2 and R2 packets. Specifically, the exchanged keying material of the two peers is concatenated. This concatenation forms the input to a Key Derivation Function (KDF). If the data transform does not specify its own KDF, the key derivation function defined in Section 6.3 is used. Even though the concatenated input is randomly distributed, a KDF Extract phase may be needed to get the proper length for the input to the KDF Expand phase.

4.1.4. User Data Considerations

The User Data Considerations in Section 4.5. of [RFC7401] also apply to HIP DEX. There is only one difference between HIPv2 and HIP DEX. Loss of state due to system reboot may be a critical performance issue for resource-constrained devices. Thus, implementors MAY choose to use non-volatile, secure storage for HIP states in order for them to survive a system reboot as discussed in Section 6.11. Using non-volatile storage will limit state loss during reboots to only those situations with an SA timeout.

5. Packet Formats

5.1. Payload Format

HIP DEX employs the same fixed HIP header and payload structure as HIPv2. As such, the specifications in Section 5.1 of [RFC7401] also apply to HIP DEX.

5.2. HIP Parameters

The HIP parameters carry information that is necessary for establishing and maintaining a HIP association. For example, the peer's public keys as well as the signaling for negotiating ciphers and payload handling are encapsulated in HIP parameters. Additional information, meaningful for end-hosts or middleboxes, may also be included in HIP parameters. The specification of the HIP parameters and their mapping to HIP packets and packet types is flexible to allow HIP extensions to define new parameters and new protocol behavior.

In HIP packets, HIP parameters are ordered according to their numeric type number and encoded in TLV format.

HIP DEX reuses the HIP parameters of HIPv2 defined in Section 5.2. of [RFC7401] where possible. Still, HIP DEX further restricts and/or extends the following existing parameter types:

- DH_GROUP_LIST and HOST_ID are restricted to ECC-based suites.
- HIP_CIPHER is restricted to AES-128-CTR and NULL-ENCRYPT.
- HIT_SUITE_LIST is limited to the HIT suite ECDH/FOLD.
- RHASH and RHASH_len are redefined to CMAC for the PUZZLE, SOLUTION, and HIP_MAC parameters (see Section 6.1 and Section 6.2).

In addition, HIP DEX introduces the following new parameter:

TLV	Type	Length	Data
ENCRYPTED_KEY	TBD1 (suggested value 643)	variable	Encrypted container for the session key exchange
I_NONCE	TBD6 (suggested value 644)	variable	Nonce from Initator for Master Key

5.2.1. DH_GROUP_LIST

The DH_GROUP_LIST parameter contains the list of supported DH Group IDs of a host. It is defined in Section 5.2.6 of [RFC7401]. With HIP DEX, the DH Group IDs are restricted to:

Group	KDF	Value
NIST P-256 [RFC5903]	CKDF	7
NIST P-384 [RFC5903]	CKDF	8
NIST P-521 [RFC5903]	CKDF	9
Curve25519 [RFC7748]	CKDF	TBD7 (suggested value 12)
Curve448 [RFC7748]	CKDF	TBD8 (suggested value 13)

The ECDH groups with values 7 - 9 are defined in [RFC5903] and [RFC6090]. ECDH group 10 is covered in [SECG] and Appendix D of [RFC7401]. These curves, when used with HIP MUST have a co-factor of 1.

The ECDH groups with values TBD7 and TBD8 are defined in [RFC7748]. These curves have cofactors of 8 and 4 (respectively).

5.2.2. HIP_CIPHER

The HIP_CIPHER parameter contains the list of supported cipher algorithms to be used for encrypting the contents of the ENCRYPTED and ENCRYPTED_KEY parameters. The HIP_CIPHER parameter is defined in Section 5.2.8 of [RFC7401]. With HIP DEX, the Suite IDs are limited to:

Suite ID	Value	
RESERVED	0	
NULL-ENCRYPT	1	([RFC2410])
AES-128-CTR	TBD4 (suggested: 5)	([RFC3686])

Mandatory implementation: AES-128-CTR. Implementors SHOULD support NULL-ENCRYPT ([RFC2410]) for testing/debugging purposes but MUST NOT offer or accept this value unless explicitly configured for testing/debugging of HIP.

5.2.3. HOST_ID

The HOST_ID parameter conveys the Host Identity (HI) along with optional information about a host. The HOST_ID parameter is defined in Section 5.2.9 of [RFC7401].

HIP DEX uses the public portion of a host's static ECDH key-pair as the HI. Correspondingly, HIP DEX limits the HI algorithms to the following new profile:

Algorithm profiles	Value		
ECDH	TBD5 (suggested: 11)	[RFC6090]	(REQUIRED)

For hosts that implement ECDH as the algorithm, the following curves are required:

Group	Value
NIST P-256	1 [RFC5903]
NIST P-384	2 [RFC5903]
NIST P-521	3 [RFC5903]
Curve25519	5 [RFC7748]
Curve448	6 [RFC7748]

HIP DEX HIs are serialized equally to the ECC-based HIs in HIPv2 (see Section 5.2.9. of [RFC7401]). The Group ID of the HIP DEX HI is encoded in the "ECC curve" field of the HOST_ID parameter. The supported DH Group IDs are defined in Section 5.2.1.

5.2.4. HIT_SUITE_LIST

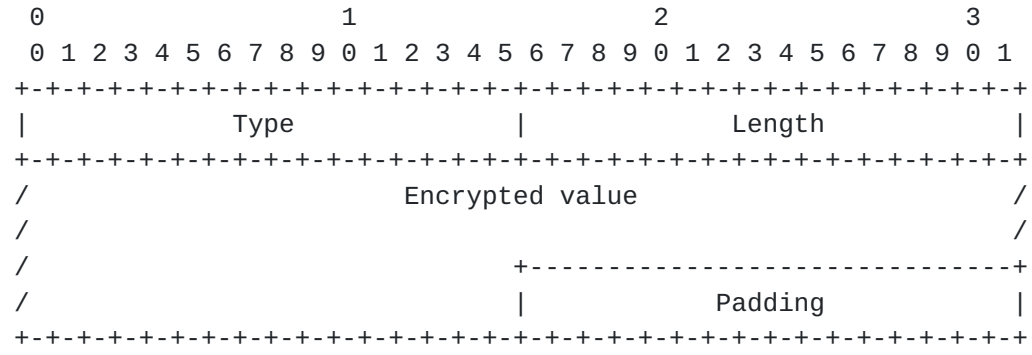
The HIT_SUITE_LIST parameter contains a list of the supported HIT suite IDs of the Responder. Based on the HIT_SUITE_LIST, the Initiator can determine which source HIT Suite IDs are supported by the Responder. The HIT_SUITE_LIST parameter is defined in Section 5.2.10 of [RFC7401].

The following new HIT Suite ID is defined for HIP DEX, and the relationship between the four-bit ID value used in the OGA ID field and the eight-bit encoding within the HIT_SUITE_LIST ID field is clarified:

HIT Suite	Four-bit ID	Eight-bit encoding
ECDH/FOLD	TBD2 (suggestion: 4)	TBD3 (suggestion: 0x40)

Note that the dedicated HIP DEX HIT Suite ID in the OGA ID field allows the peers to distinguish a HIP DEX handshake from a HIPv2 handshake. The Responder MUST respond with a HIP DEX HIT suite ID when the HIT of the Initiator is a HIP DEX HIT.

5.2.5. ENCRYPTED_KEY

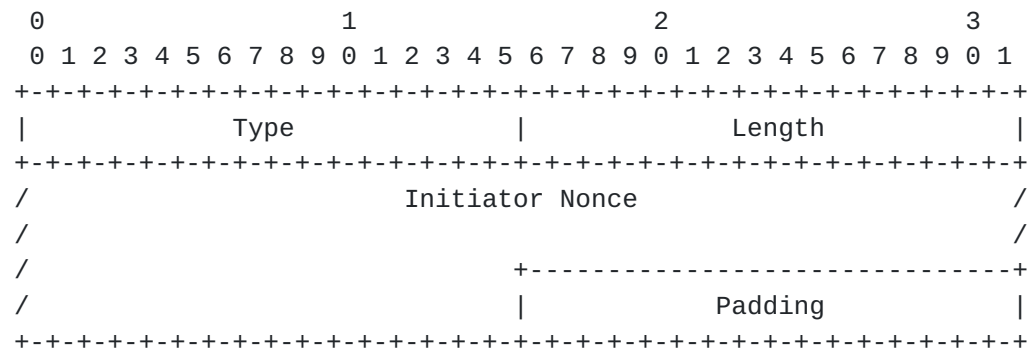


Type	TBD1 (suggested value 643)
Length	length in octets, excluding Type, Length, and Padding
Encrypted value	The value is encrypted using an encryption algorithm as defined in the HIP_CIPHER parameter.

The ENCRYPTED_KEY parameter encapsulates a random value that is later used in the session key creation process (see Section 6.3). This random value MUST have a length of at least 64 bits. The puzzle value #I and the puzzle solution #J (see Section 4.1.2 in [RFC7401]) are used as the initialization vector (IV) for the encryption process. To this end, the IV is computed as FOLD(I | J, 128). Moreover, a 16 bit counter value, which is initialized to zero on first use, is appended to the IV value in order to guarantee that a non-repeating nonce is fed to the encryption algorithm defined by the HIP_CIPHER.

Once this encryption process is completed, the "encrypted value" data field is ready for inclusion in the Parameter. If necessary, additional Padding for 8-byte alignment is then added according to the rules of TLV Format in [RFC7401].

5.2.6. I_NONCE



Type	TBD6 (suggested value 644)
Length	length in octets, excluding Type, Length, and Padding
Initiator Nonce	Nonce provided by the Initiator for use in the Master Key

The I_NONCE parameter encapsulates a random value that is later used in the Master key creation process (see Section 6.3). This random value MUST have a length of 2 x RHASH_len. This parameter is sent to the Responder in I2 which echos it back to the Initiator in R2.

If necessary, additional Padding for 8-byte alignment is added according to the rules of TLV Format in [RFC7401].

5.3. HIP Packets

HIP DEX uses the same eight basic HIP packets as HIPv2 (see Section 5.3 of [RFC7401]). Four of them are for the HIP handshake (I1, R1, I2, and R2), one is for updating an association (UPDATE), one is for sending notifications (NOTIFY), and two are for closing the association (CLOSE and CLOSE_ACK). There are some differences regarding the HIP parameters that are included in the handshake packets concerning HIP BEX and HIP DEX. This section covers these differences for the DEX packets. Packets not discussed here, follow the structure defined in [RFC7401].

An important difference between packets in HIP BEX and HIP DEX is that the DIFFIE_HELLMAN and the HIP_SIGNATURE parameters are not included in HIP DEX. Thus, the R1 packet is completely unprotected and can be spoofed. As a result, negotiation parameters contained in the R1 packet have to be re-included in later, protected packets in order to detect and prevent potential downgrading attacks. Moreover, the I2, R2, UPDATE, NOTIFY, CLOSE, and CLOSE_ACK packets are not covered by a signature and purely rely on the HIP_MAC parameter for

packet authentication. The processing of these packets is changed accordingly.

In the future, an optional upper-layer payload MAY follow the HIP header. The Next Header field in the header indicates if there is additional data following the HIP header.

5.3.1. I1 - the HIP Initiator Packet

The HIP header values for the I1 packet:

```
  Header:
    Packet Type = 1
    SRC HIT = Initiator's HIT
    DST HIT = Responder's HIT, or NULL

  IP ( HIP ( DH_GROUP_LIST ) )
```

Valid control bits: none

The I1 packet contains the fixed HIP header and the Initiator's DH_GROUP_LIST. The Initiator's HIT Suite ID MUST be of a HIP DEX type as defined in Section 5.2.4.

Regarding the Responder's HIT, the Initiator may receive this HIT either from a DNS lookup of the Responder's FQDN, from some other repository, or from a local table. The Responder's HIT also MUST be of a HIP DEX type. If the Initiator does not know the Responder's HIT, it may attempt to use opportunistic mode by using NULL (all zeros) as the Responder's HIT. See Section 4.1.8 of [RFC7401] for detailed information about the "HIP Opportunistic Mode".

As the Initiator's and the Responder's HITs are compressions of the employed HIs, they determine the DH Group ID that must be used in order to successfully conclude the triggered handshake. HITs, however, only include the OGA ID identifying the HI algorithm. They do not include information about the specific group ID of the HI. To inform the Responder about its employed and its otherwise supported DH Group IDs, the Initiator therefore includes the DH_GROUP_LIST parameter in the I1 packet. This parameter MUST include the DH group ID that corresponds to the currently employed Initiator HIT as the first list element. With HIP DEX, the DH_GROUP_LIST parameter MUST only include ECDH groups defined in Section 5.2.1.

Since this packet is so easy to spoof even if it were protected, no attempt is made to add to its generation or processing cost. As a result, the DH_GROUP_LIST in the I1 packet is not protected.

Implementations MUST be able to handle a storm of received I1 packets, discarding those with common content that arrive within a small time delta.

5.3.2. R1 - the HIP Responder Packet

The HIP header values for the R1 packet:

```
  Header:
    Packet Type = 2
    SRC HIT = Responder's HIT
    DST HIT = Initiator's HIT

  IP ( HIP ( [ R1_COUNTER, ]
             PUZZLE,
             DH_GROUP_LIST,
             HIP_CIPHER,
             HOST_ID,
             HIT_SUITE_LIST,
             TRANSPORT_FORMAT_LIST,
             [ <, ECHO_REQUEST_UNSIGNED >i ])
```

Valid control bits: A

If the Responder's HI is an anonymous one, the A control bit MUST be set.

The Initiator's HIT MUST match the one received in the I1 packet if the R1 is a response to an I1. If the Responder has multiple HIs, the Responder's HIT MUST match the Initiator's request. If the Initiator used opportunistic mode, the Responder may select among its HIs as described below. See Section 4.1.8 of [RFC7401] for detailed information about the "HIP Opportunistic Mode".

The R1 packet generation counter is used to determine the currently valid generation of puzzles. The value is increased periodically, and it is RECOMMENDED that it is increased at least as often as solutions to old puzzles are no longer accepted.

The Puzzle contains a Random value #I and the puzzle difficulty K. The difficulty K indicates the number of lower-order bits, in the puzzle CMAC result, that MUST be zeros (see [RFC7401]). Responders SHOULD set K to zero by default and only increase the puzzle difficulty to protect against a DoS attack targeting the HIP DEX handshake. A puzzle difficulty of zero effectively turns the puzzle mechanism into a return-routability test and is strongly encouraged during normal operation in order to conserve energy resources as well as to prevent unnecessary handshake delay in case of a resource-

constrained Initiator. Please also refer to Section 7 for further recommendations on choosing puzzle difficulty.

The DH_GROUP_LIST parameter contains the Responder's order of preference based on the Responder's choice the ECDH key contained in the HOST_ID parameter (see below). This allows the Initiator to determine whether its own DH_GROUP_LIST in the I1 packet was manipulated by an attacker. There is a further risk that the Responder's DH_GROUP_LIST was manipulated by an attacker, as the R1 packet cannot be authenticated in HI DEX. Thus, this parameter is repeated in the R2 packet to allow for a final, cryptographically secured validation.

The HIP_CIPHER contains the encryption algorithms supported by the Responder to protect the key exchange, in the order of preference. All implementations MUST support the AES-CTR [RFC3686].

The HIT_SUITE_LIST parameter is an ordered list of the Responder's supported and preferred HIT Suites. It enables a Responder to notify the Initiator about other available HIT suites than the one used in the current handshake. Based on the received HIT_SUITE_LIST, the Initiator MAY decide to abort the current handshake and initiate a new handshake with a different mutually supported HIT suite. This mechanism can, e.g., be used to move from an initial HIP DEX handshake to a HIP BEX handshake for peers supporting both protocol variants.

The HOST_ID parameter depends on the received DH_GROUP_LIST parameter and the Responder HIT in the I1 packet. Specifically, if the I1 contains a Responder HIT, the Responder verifies that this HIT matches the required DH group based on the received DH_GROUP_LIST parameter included in the I1. In case of a positive result, the Responder selects the corresponding HOST_ID for inclusion in the R1 packet. Likewise, if the Responder HIT in the I1 packet is NULL (i.e., during an opportunistic handshake), the Responder chooses its HOST_ID according to the Initiator's employed DH group as indicated in the received DH_GROUP_LIST parameter and sets the source HIT in the R1 packet accordingly. If the Responder however does not support the DH group required by the Initiator or if the Responder HIT in the I1 packet does not match the required DH group, the Responder selects the mutually preferred and supported DH group based on the DH_GROUP_LIST parameter in the I1 packet. The Responder then includes the corresponding ECDH key in the HOST_ID parameter. This parameter also indicates the selected DH group. Moreover, the Responder sets the source HIT in the R1 packet based on the destination HIT from the I1 packet. Based on the deviating DH group ID in the HOST_ID parameter, the Initiator then SHOULD abort the

current handshake and initiate a new handshake with the mutually supported DH group as far as local policies (see Section 7) permit.

The TRANSPORT_FORMAT_LIST parameter is an ordered list of the Responder's supported and preferred transport format types. The list allows the Initiator and the Responder to agree on a common type for payload protection. The different format types are DEFAULT, ESP and ESP-TCP as explained in Section 3.1 in [RFC6261].

The ECHO_REQUEST_UNSIGNED parameters contain data that the sender wants to receive unmodified in the corresponding response packet in the ECHO_RESPONSE_UNSIGNED parameter. The R1 packet may contain zero or more ECHO_REQUEST_UNSIGNED parameters.

5.3.3. I2 - the Second HIP Initiator Packet

The HIP header values for the I2 packet:

```
  Header:
    Type = 3
    SRC HIT = Initiator's HIT
    DST HIT = Responder's HIT

  IP ( HIP ( [R1_COUNTER,]
             SOLUTION,
             HIP_CIPHER,
             ENCRYPTED_KEY,
             HOST_ID,
             TRANSPORT_FORMAT_LIST,
             I_NONCE,
             HIP_MAC
             [<, ECHO_RESPONSE_UNSIGNED>i )] )
```

Valid control bits: A

The HITs MUST match the ones used in the R1 packet.

If the Initiator's HI is an anonymous one, the A control bit MUST be set.

If present in the R1 packet, the Initiator MUST include an unmodified copy of the R1_COUNTER parameter into the I2 packet.

The Solution contains the Random #I from the R1 packet and the computed #J value. The low-order #K bits of the RHASH(I | ... | J) MUST be zero.

The HIP_CIPHER contains the single encryption transform selected by the Initiator that it uses to encrypt the ENCRYPTED and ENCRYPTED_KEY parameters. The chosen cipher MUST correspond to one of the ciphers offered by the Responder in the R1. All implementations MUST support the AES-CTR transform [RFC3686].

The HOST_ID parameter contains the Initiator HI corresponding to the Initiator HIT.

The ENCRYPTED_KEY parameter contains an Initiator generated random value that MUST be uniformly distributed. This random value is encrypted with the Master Key SA using the HIP_CIPHER encryption algorithm.

The ECHO_RESPONSE_UNSIGNED parameter(s) contain the unmodified Opaque data copied from the corresponding echo request parameter(s). This parameter can also be used for two-factor password authentication as shown in Appendix A.

The TRANSPORT_FORMAT_LIST parameter contains the single transport format type selected by the Initiator. The chosen type MUST correspond to one of the types offered by the Responder in the R1 packet. The different format types are DEFAULT, ESP and ESP-TCP as explained in Section 3.1 in [RFC6261].

The I_NONCE parameter contains the nonce, supplied by the Initiator for the Master Key generation as shown in Section 6.3. This is echoed back to the Initiator in the R2 packet.

The MAC is calculated over the whole HIP envelope, excluding any parameters after the HIP_MAC parameter as described in Section 6.2. The Responder MUST validate the HIP_MAC parameter.

5.3.4. R2 - the Second HIP Responder Packet

The HIP header values for the R2 packet:

```
  Header:
    Packet Type = 4
    SRC HIT = Responder's HIT
    DST HIT = Initiator's HIT

  IP ( HIP ( DH_GROUP_LIST,
             HIP_CIPHER,
             ENCRYPTED_KEY,
             HIT_SUITE_LIST,
             TRANSPORT_FORMAT_LIST,
             I_NONCE,
             HIP_MAC)
```

Valid control bits: none

The HITs used MUST match the ones used in the I2 packet.

The Responder repeats the DH_GROUP_LIST, HIP_CIPHER, HIT_SUITE_LIST, and TRANSPORT_FORMAT_LIST parameters in the R2 packet. These parameters MUST be the same as included in the R1 packet. The parameter are re-included here because the R2 packet is MACed and thus cannot be altered by an attacker. For verification purposes, the Initiator re-evaluates the selected suites and compares the results against the chosen ones. If the re-evaluated suites do not match the chosen ones, the Initiator acts based on its local policy.

The ENCRYPTED_KEY parameter contains an Responder generated random value that MUST be uniformly distributed. This random value is encrypted with the Master Key SA using the HIP_CIPHER encryption algorithm.

The I_NONCE parameter contains the nonce, supplied by the Initiator for the Master Key generation as shown in Section 6.3. The Responder is echoing the value back to the Initiator to show it used the Initiator provided nonce.

The MAC is calculated over the whole HIP envelope, excluding any parameters after the HIP_MAC, as described in Section 6.2. The Initiator MUST validate the HIP_MAC parameter.

5.4. ICMP Messages

When a HIP implementation detects a problem with an incoming packet, and it either cannot determine the identity of the sender of the packet or does not have any existing HIP association with the sender of the packet, it MAY respond with an ICMP packet. Any such reply MUST be rate-limited as described in [RFC4443]. In most cases, the ICMP packet has the Parameter Problem type (12 for ICMPv4, 4 for

ICMPv6) and Code of 0. The Pointer field pointing to the field that caused the ICMP message to be generated, for example to the first 8 bytes of a UDP payload for "SPI is Unknown". The problem cases specified in Section 5.4. of [RFC7401] also apply to HIP DEX.

6. Packet Processing

Due to the adopted protocol semantics and the inherited general packet structure, the packet processing in HIP DEX only differs from HIPv2 in very few places. Here, we focus on these differences and refer to Section 6 in [RFC7401] otherwise.

The processing of outgoing and incoming application data remains the same as in HIP BEX (see Sections 6.1 and 6.2 in [RFC7401]).

6.1. Solving the Puzzle

The procedures for solving and verifying a puzzle in HIP DEX are strongly based on the corresponding procedures in HIPv2. The only exceptions are that HIP DEX does not use pre-computation of R1 packets and that RHASH is set to CMAC. As a result, the pre-computation step in Section 6.3 of [RFC7401] is skipped in HIP DEX.

Moreover, the Initiator solves a puzzle by computing:

```
Ltrunc( CMAC( I, HIT-I | HIT-R | J ), K ) == 0
```

Similarly, the Responder verifies a puzzle by computing:

```
V := Ltrunc( CMAC( I, HIT-I | HIT-R | J ), K )
```

Apart from these modifications, the procedures defined in Section 6.3 of [RFC7401] also apply for HIP DEX.

6.2. HIP_MAC Calculation and Verification

The following subsections define the actions for processing the HIP_MAC parameter.

6.2.1. CMAC Calculation

The HIP_MAC calculation uses RHASH, i.e., CMAC, as the underlying cryptographic function. The scope of the calculation for HIP_MAC is:

CMAC: { HIP header | [Parameters] }

where Parameters include all HIP parameters of the packet that is being calculated with Type values ranging from 1 to (HIP_MAC's Type value - 1) and exclude parameters with Type values greater or equal to HIP_MAC's Type value.

During HIP_MAC calculation, the following applies:

- In the HIP header, the Checksum field is set to zero.
- In the HIP header, the Header Length field value is calculated to the beginning of the HIP_MAC parameter.

The parameter order is described in Section 5.2.1 of [RFC7401].

The CMAC calculation and verification process is as follows:

Packet sender:

1. Create the HIP packet, without the HIP_MAC or any other parameter with greater Type value than the HIP_MAC parameter has.
2. Calculate the Header Length field in the HIP header.
3. Compute the CMAC using either HIP-gl or HIP-lg integrity key retrieved from KEYMAT as defined in Section 6.3. HIP-gl refers to host with greater HIT value and HIP-lg refers to the host with smaller HIT value.
4. Add the HIP_MAC parameter to the packet and any parameter with greater Type value than the HIP_MAC's that may follow.
5. Recalculate the Length field in the HIP header.

Packet receiver:

1. Verify the HIP header Length field.
2. Remove the HIP_MAC parameter, as well as all other parameters that follow it with greater Type value, saving the contents if they will be needed later.
3. Recalculate the HIP packet length in the HIP header and clear the Checksum field (set it to all zeros).
4. Compute the CMAC using either HIP-gl or HIP-lg integrity key as defined in Section 6.3 and verify it against the received CMAC.
5. Set Checksum and Header Length fields in the HIP header to original values. Note that the Checksum and Length fields contain incorrect values after this step.

6.3. HIP DEX KEYMAT Generation

The HIP DEX KEYMAT process is used to derive the keys for the Master Key SA as well as for the Pair-wise Key SA. The keys for the Master Key SA are based on the Diffie-Hellman derived key, Kij, which is produced during the HIP DEX handshake. The Initiator generates Kij during the creation of the I2 packet and the Responder generates Kij once it receives the I2 packet. This is why the I2 packet can already contain authenticated and/or encrypted information.

The keys derived for the Pair-wise Key SA are not used during the HIP DEX handshake. Instead, these keys are made available as payload protection keys (e.g., for IPsec).

The HIP DEX KEYMAT process is based on the Hash-based Key Derivation Function (HKDF) defined in [RFC5869] and consists of two components, CKDF-Extract and CKDF-Expand. The CKDF-Extract function compresses a non-uniformly distributed key, such as the output of a Diffie-Hellman key derivation, to extract the key entropy into a fixed length output. The CKDF-Expand function takes either the output of the Extract function or directly uses a uniformly distributed key and expands the length of the key, repeatedly distributing the key entropy, to produce the keys needed.

The key derivation for the Master Key SA employs always both the Extract and Expand phases. The Pair-wise Key SA needs only the Extract phase when the key is smaller or equal to 128 bits, but otherwise requires also the Expand phase.

The CKDF-Extract function is the following operation:

```
CKDF-Extract(I, IKM, info) -> PRK

Inputs:
  I         Random #I, provided by the Responder, from the PUZZLE
            parameter
  IKM       Input keying material
              the Diffie-Hellman derived key, concatenated with the
                random I_NONCE value for the Master Key SA
              the Diffie-Hellman derived key, concatenated with the
                random values of the ENCRYPTED_KEY parameters in
                the same order as the HITs with sort(HIT-I | HIT-R)
                for the Pair-wise Key SA

  info      sort(HIT-I | HIT-R) | "CKDF-Extract"
            where "CKDF-Extract" is an octet string

Output:
  PRK       a pseudorandom key (of RHASH_len/8 octets)
```

The pseudorandom key PRK is calculated as follows:

```
PRK     = CMAC(I, IKM | info)
```

The CKDF-Expand function is the following operation:

```
  CKDF-Expand(PRK, info, L) -> OKM

  Inputs:
    PRK       a pseudorandom key of at least RHASH_len/8 octets
              (either the output from the extract step or the
              concatenation of the random values of the
              ENCRYPTED_KEY parameters in the same order as the
              HITs with sort(HIT-I | HIT-R) in case of no extract)
    info      sort(HIT-I | HIT-R) | "CKDF-Expand"
              where "CKDF-Expand" is an octet string
    L         length of output keying material in octets
              (<= 255*RHASH_len/8)

  Output:
    OKM        output keying material (of L octets)
```

The output keying material OKM is calculated as follows:

```
    N       =  ceil(L/(RHASH_len/8))
    T       =  T(1) | T(2) | T(3) | ... | T(N)
    OKM     =  first L octets of T
```

where

```
    T(0) = empty string (zero length)
    T(1) = CMAC(PRK, T(0) | info | 0x01)
    T(2) = CMAC(PRK, T(1) | info | 0x02)
    T(3) = CMAC(PRK, T(2) | info | 0x03)
    ...
```

(where the constant concatenated to the end of each T(n) is a single octet.)

sort(HIT-I | HIT-R) is defined as the network byte order concatenation of the two HITs, with the smaller HIT preceding the larger HIT, resulting from the numeric comparison of the two HITs interpreted as positive (unsigned) 128-bit integers in network byte order.

The initial keys for the Master Key SA are drawn sequentially in the order that is determined by the numeric comparison of the two HITs, with the comparison method described in the previous paragraph. HOST_g denotes the host with the greater HIT value, and HOST_l the host with the lower HIT value.

The drawing order for initial keys:

1. HIP-gl encryption key for HOST_g's outgoing HIP packets

2. HIP-gl integrity (CMAC) key for HOST_g's outgoing HIP packets

3. HIP-lg encryption key for HOST_l's outgoing HIP packets

4. HIP-lg integrity (CMAC) key for HOST_l's outgoing HIP packets

The number of bits drawn for a given algorithm is the "natural" size of the keys regarding the algorithm defined in the HIP_CIPHER. For the mandatory algorithms, the following size applies:

AES 128 bits

If other key sizes are used, they must be treated as different encryption algorithms and defined separately.

6.4. Initiation of a HIP Diet EXchange

The initiation of a HIP DEX handshake proceeds as described in Section 6.6 of [RFC7401]. The I1 packet contents are specified in Section 5.3.1.

6.5. Processing Incoming I1 Packets

I1 packets in HIP DEX are handled almost identical to HIPv2 (see Section 6.7 of [RFC7401]). The main differences are that the Responder SHOULD select a HIP DEX HIT Suite in the R1 response. Moreover, as R1 packets are neither covered by a signature nor incur the overhead of generating an ephemeral Diffie-Hellman key-pair, pre-computation of an R1 is only marginally beneficial, but would incur additional memory resources at the Responder. Hence, the R1 pre-computation SHOULD be omitted in HIP DEX.

Correspondingly, the modified conceptual processing rules for responding to an I1 packet are as follows:

1. The Responder MUST check that the Responder's HIT in the received I1 packet is either one of its own HITs or NULL. Otherwise, it MUST drop the packet.

2. If the Responder is in ESTABLISHED state, the Responder MAY respond to this with an R1 packet, prepare to drop an existing HIP security association with the peer, and stay at ESTABLISHED state.

3. If the Responder is in I1-SENT state, it MUST make a comparison between the sender's HIT and its own (i.e., the receiver's) HIT. If the sender's HIT is greater than its own HIT, it should drop the I1 packet and stay at I1-SENT. If the sender's HIT is

smaller than its own HIT, it SHOULD send the R1 packet and stay at I1-SENT. The HIT comparison is performed as defined in Section 6.3.

4. If the implementation chooses to respond to the I1 packet with an R1 packet, it creates a new R1 according to the format described in Section 5.3.2. It chooses the HI based on the destination HIT and the DH_GROUP_LIST in the I1 packet. If the implementation does not support the DH group required by the Initiator or if the destination HIT in the I1 packet does not match the required DH group, it selects the mutually preferred and supported DH group based on the DH_GROUP_LIST parameter in the I1 packet. The implementation includes the corresponding ECDH public key in the HOST_ID parameter. If no suitable DH Group ID was contained in the DH_GROUP_LIST in the I1 packet, it sends an R1 packet with any suitable ECDH public key.

5. If the received Responder's HIT in the I1 packet is not NULL, the Responder's HIT in the R1 packet MUST match the destination HIT in the I1 packet. Otherwise, the Responder MUST select a HIT with the same HIT Suite as the Initiator's HIT. If this HIT Suite is not supported by the Responder, it SHOULD select a REQUIRED HIT Suite from Section 5.2.10 of [RFC7401], which is currently RSA/DSA/SHA-256. Other than that, selecting the HIT is a local policy matter.

6. The Responder expresses its supported HIP transport formats in the TRANSPORT_FORMAT_LIST as described in Section 5.2.11 of [RFC7401]. The Responder MUST provide at least one payload transport format type.

7. The Responder sends the R1 packet to the source IP address of the I1 packet.

Note that only steps 4 and 5 have been changed with regard to the processing rules of HIPv2. The considerations about R1 management (except pre-computation) and malformed I1 packets in Sections 6.7.1 and 6.7.2 of [RFC7401] likewise apply to HIP DEX.

6.6. Processing Incoming R1 Packets

R1 packets in HIP DEX are handled identically to HIPv2 (see Section 6.8 in [RFC7401]) with the following exceptions: HIP DEX uses ECDH public keys as HIs and does not employ signatures.

The modified conceptual processing rules for responding to an R1 packet are as follows:

1. A system receiving an R1 MUST first check to see if it has sent an I1 packet to the originator of the R1 packet (i.e., it has a HIP association that is in state I1-SENT and that is associated with the HITs in the R1). Unless the I1 packet was sent in opportunistic mode (see Section 4.1.8 of [RFC7401]), the IP addresses in the received R1 packet SHOULD be ignored by the R1 processing and, when looking up the correct HIP association, the received R1 packet SHOULD be matched against the associations using only the HITs. If a match exists, the system processes the R1 packet as described below.

2. Otherwise, if the system is in any state other than I1-SENT or I2-SENT with respect to the HITs included in the R1 packet, it SHOULD silently drop the R1 packet and remain in the current state.

3. If the HIP association state is I1-SENT or I2-SENT, the received Initiator's HIT MUST correspond to the HIT used in the original I1 packet. Also, the Responder's HIT MUST correspond to the one used in the I1 packet, unless this packet contained a NULL HIT.

4. If the HIP association state is I1-SENT, and multiple valid R1 packets are present, the system MUST select from among the R1 packets with the largest R1 generation counter.

5. The system MUST check that the Initiator's HIT Suite is contained in the HIT_SUITE_LIST parameter in the R1 packet (i.e., the Initiator's HIT Suite is supported by the Responder). If the HIT Suite is supported by the Responder, the system proceeds normally. Otherwise, the system MAY stay in state I1-SENT and restart the HIP DEX handshake by sending a new I1 packet with an Initiator HIT that is supported by the Responder and hence is contained in the HIT_SUITE_LIST in the R1 packet. The system MAY abort the handshake if no suitable source HIT is available. The system SHOULD wait for an acceptable time span to allow further R1 packets with higher R1 generation counters or different HIT and HIT Suites to arrive before restarting or aborting the HIP DEX handshake.

6. The system MUST check that the DH Group ID in the HOST_ID parameter in the R1 matches the first DH Group ID in the Responder's DH_GROUP_LIST in the R1 packet, and also that this Group ID corresponds to a value that was included in the Initiator's DH_GROUP_LIST in the I1 packet. If the DH Group ID of the HOST_ID parameter does not express the Responder's best choice, the Initiator can conclude that the DH_GROUP_LIST in the I1 or R1 packet was adversely modified. In such a case, the Initiator MAY send a new I1 packet; however, it SHOULD NOT

change its preference in the DH_GROUP_LIST in the new I1 packet. Alternatively, the Initiator MAY abort the HIP DEX handshake. Moreover, if the DH Group ID indicated in the HOST_ID parameter does not match the DH Group ID of the HI employed by the Initiator, the system SHOULD wait for an acceptable time span to allow further R1 packets with different DH Group IDs to arrive before restarting or aborting the HIP DEX handshake. When restarting the handshake, the Initiator MUST consult local policies (see Section 7) regarding the use of another, mutually supported DH group for the subsequent handshake with the Responder.

7. If the HIP association state is I2-SENT, the system MAY re-enter state I1-SENT and process the received R1 packet if it has a larger R1 generation counter than the R1 packet responded to previously.

8. The R1 packet can have the A-bit set - in this case, the system MAY choose to refuse it by dropping the R1 packet and returning to state UNASSOCIATED. The system SHOULD consider dropping the R1 packet only if it used a NULL HIT in the I1 packet. If the A-bit is set, the Responder's HIT is anonymous and SHOULD NOT be stored permanently.

9. The system SHOULD attempt to validate the HIT against the received Host Identity by using the received Host Identity to construct a HIT and verify that it matches the Sender's HIT.

10. The system MUST store the received R1 generation counter for future reference.

11. The system attempts to solve the puzzle in the R1 packet. The system MUST terminate the search after exceeding the remaining lifetime of the puzzle. If the puzzle is not successfully solved, the implementation MAY either resend the I1 packet within the retry bounds or abandon the HIP base exchange.

12. The system computes standard Diffie-Hellman keying material according to the public value and Group ID provided in the HOST_ID parameter. The Diffie-Hellman keying material Kij is used for key extraction as specified in Section 6.3.

13. The system selects the HIP_CIPHER ID from the choices presented in the R1 packet and uses the selected values subsequently when generating and using encryption keys, and when sending the I2 packet. If the proposed alternatives are not acceptable to the system, it MAY either resend an I1 packet within the retry bounds or abandon the HIP base exchange.

14. The system chooses one suitable transport format from the TRANSPORT_FORMAT_LIST and includes the respective transport format parameter in the subsequent I2 packet.

15. The system initializes the remaining variables in the associated state, including Update ID counters.

16. The system prepares and sends an I2 packet as described in Section 5.3.3.

17. The system SHOULD start a timer whose timeout value SHOULD be larger than the worst-case anticipated RTT, and MUST increment a trial counter associated with the I2 packet. The sender SHOULD retransmit the I2 packet upon a timeout and restart the timer, up to a maximum of I2_RETRIES_MAX tries.

18. If the system is in state I1-SENT, it SHALL transition to state I2-SENT. If the system is in any other state, it remains in the current state.

Note that step 4 from the original processing rules of HIPv2 (signature verification) has been removed in the above processing rules for HIP DEX. Moreover, step 7 of the original processing rules has been adapted in step 6 above to account for the fact that HIP DEX uses ECDH public keys as HIs. The considerations about malformed R1 packets in Sections 6.8.1 of [RFC7401] also apply to HIP DEX.

6.7. Processing Incoming I2 Packets

The processing of I2 packets follows similar rules as HIPv2 (see Section 6.9 of [RFC7401]). The main differences to HIPv2 are that HIP DEX introduces a new session key exchange via the ENCRYPTED_KEY parameter as well as an I2 reception acknowledgement for retransmission purposes. Moreover, with HIP DEX the Initiator is responsible for triggering retransmissions, whereas the Responder merely replies to received I2 packets.

The modified HIP DEX conceptual processing rules for responding to an I2 packet are:

1. The system MAY perform checks to verify that the I2 packet corresponds to a recently sent R1 packet. Such checks are implementation dependent. See Appendix A in [RFC7401] for a description of an example implementation.

2. The system MUST check that the Responder's HIT corresponds to one of its own HITs and MUST drop the packet otherwise.

3. The system MUST further check that the Initiator's HIT Suite is supported. The Responder SHOULD silently drop I2 packets with unsupported Initiator HITs.

4. The system MUST validate the Initiator's HI per Section 9.1.

5. If the system's state machine is in the R2-SENT state, the system MUST check to see if the newly received I2 packet is similar to the one that triggered moving to R2-SENT. If so, it MUST retransmit a previously sent R2 packet and reset the R2-SENT timer. The system SHOULD re-use the previously established state to re-create the corresponding R2 packet in order to prevent unnecessary computation overhead.

6. If the system's state machine is in the I2-SENT state, the system MUST make a comparison between its local and sender's HITs (similarly as in Section 6.3). If the local HIT is smaller than the sender's HIT, it should drop the I2 packet, use the peer Diffie-Hellman key, ENCRYPTED_KEY keying material and nonce #I from the R1 packet received earlier, and get the local Diffie-Hellman key, ENCRYPTED_KEY keying material, and nonce #J from the I2 packet sent to the peer earlier. Otherwise, the system processes the received I2 packet and drops any previously derived Diffie-Hellman keying material Kij and ENCRYPTED_KEY keying material it might have generated upon sending the I2 packet previously. The peer Diffie-Hellman key, ENCRYPTED_KEY, and the nonce #J are taken from the just arrived I2 packet. The local Diffie-Hellman key, ENCRYPTED_KEY keying material, and the nonce #I are the ones that were sent earlier in the R1 packet.

7. If the system's state machine is in the I1-SENT state, and the HITs in the I2 packet match those used in the previously sent I1 packet, the system uses this received I2 packet as the basis for the HIP association it was trying to form, and stops retransmitting I1 packets (provided that the I2 packet passes the additional checks below).

8. If the system's state machine is in any state other than R2-SENT, the system SHOULD check that the echoed R1 generation counter in the I2 packet is within the acceptable range if the counter is included. Implementations MUST accept puzzles from the current generation and MAY accept puzzles from earlier generations. If the generation counter in the newly received I2 packet is outside the accepted range, the I2 packet is stale (and perhaps replayed) and SHOULD be dropped.

9. The system MUST validate the solution to the puzzle as described in Section 6.1.

10. The I2 packet MUST have a single value in the HIP_CIPHER parameter, which MUST match one of the values offered to the Initiator in the R1 packet.

11. The system MUST derive Diffie-Hellman keying material Kij based on the public value and Group ID in the HOST_ID parameter. This keying material is used to derive the keys of the Master Key SA as described in Section 6.3. If the Diffie-Hellman Group ID is unsupported, the I2 packet is silently dropped. If the processing time for the derivation of the Diffie-Hellman keying material Kij is likely to cause premature I2 retransmissions by the Initiator, the system MAY send a NOTIFY packet before starting the key derivation process. The NOTIFY packet contains a NOTIFICATION parameter with Notify Message Type I2_ACKNOWLEDGEMENT. The NOTIFICATION parameter indicates the anticipated remaining processing time for the I2 packet in milliseconds as two-octet Notification Data.

12. The implementation SHOULD also verify that the Initiator's HIT in the I2 packet corresponds to the Host Identity sent in the I2 packet. (Note: some middleboxes may not be able to make this verification.)

13. The system MUST process the TRANSPORT_FORMAT_LIST parameter. Other documents specifying transport formats (e.g., [RFC7402]) contain specifications for handling any specific transport selected.

14. The system MUST verify the HIP_MAC according to the procedures in Section 6.2.

15. If the checks above are valid, then the system proceeds with further I2 processing; otherwise, it discards the I2 and its state machine remains in the same state.

16. The I2 packet may have the A-bit set - in this case, the system MAY choose to refuse it by dropping the I2 and the state machine returns to state UNASSOCIATED. If the A-bit is set, the Initiator's HIT is anonymous and MUST NOT be stored permanently.

17. The system MUST decrypt the keying material from the ENCRYPTED_KEY parameter. This keying material is a partial input to the key derivation process for the Pair-wise Key SA (see Section 6.3).

18. The system initializes the remaining variables in the associated state, including Update ID counters.

19. Upon successful processing of an I2 packet when the system's state machine is in state UNASSOCIATED, I1-SENT, I2-SENT, or R2-SENT, an R2 packet is sent as described in Section 5.3.4 and the system's state machine transitions to state R2-SENT.

20. Upon successful processing of an I2 packet when the system's state machine is in state ESTABLISHED, the old HIP association is dropped and a new one is installed, an R2 packet is sent as described in Section 5.3.4, and the system's state machine transitions to R2-SENT.

21. Upon the system's state machine transitioning to R2-SENT, the system starts a timer. The state machine transitions to ESTABLISHED if some data has been received on the incoming HIP association, or an UPDATE packet has been received (or some other packet that indicates that the peer system's state machine has moved to ESTABLISHED). If the timer expires (allowing for a maximal amount of retransmissions of I2 packets), the state machine transitions to ESTABLISHED.

Note that steps 11 (encrypted HOST_ID) and 15 (signature verification) from the original processing rules of HIPv2 have been removed in the above processing rules for HIP DEX. Moreover, step 10 of the HIPv2 processing rules has been adapted to account for optional extension of the retransmission mechanism. Step 16 has been added to the processing rules in this document. The considerations about malformed I2 packets in Sections 6.9.1 of [RFC7401] also apply to HIP DEX.

6.8. Processing Incoming R2 Packets

R2 packets in HIP DEX are handled identically to HIPv2 (see Section 6.10 of [RFC7401]) with the following exceptions: HIP DEX introduces a new session key exchange via the ENCRYPTED_KEY parameter and does not employ signatures.

The modified conceptual processing rules for responding to an R2 packet are as follows:

1. If the system is in any other state than I2-SENT, the R2 packet is silently dropped.

2. The system MUST verify that the HITs in use correspond to the HITs that were received in the R1 packet that caused the transition to the I2-SENT state.

3. The system MUST verify the HIP_MAC according to the procedures in Section 6.2.

4. The system MUST re-evaluate the DH_GROUP_LIST, HIP_CIPHER, HIT_SUITE_LIST, and TRANSPORT_FORMAT_LIST parameters in the R2 packet and compare the results against the chosen suites.

5. The system MUST validate the Responder's HI per Section 9.1.

6. If any of the checks above fail, there is a high probability of an ongoing man-in-the-middle or other security attack. The system SHOULD act accordingly, based on its local policy.

7. The system MUST decrypt the keying material from the ENCRYPTED_KEY parameter. This keying material is a partial input to the key derivation process for the Pair-wise Key SA (see Section 6.3).

8. Upon successful processing of the R2 packet, the state machine transitions to state ESTABLISHED.

Note that step 4 (signature verification) from the original processing rules of HIPv2 has been replaced with a negotiation re-evaluation in the above processing rules for HIP DEX. Moreover, step 6 has been added to the processing rules.

6.9. Processing Incoming NOTIFY Packets

Processing of NOTIFY packets is OPTIONAL. If processed, any errors in a received NOTIFICATION parameter SHOULD be logged. Received errors MUST be considered only as informational, and the receiver SHOULD NOT change its HIP state purely based on the received NOTIFY packet.

If a NOTIFY packet is received in state I2-SENT, this packet is an I2 reception acknowledgement of the optional retransmission mechanism extension and SHOULD be processed. The following steps define the conceptual processing rules for such incoming NOTIFY packets in state I2-SENT:

1. The system MUST verify that the HITs in use correspond to the HITs that were received in the R1 packet that caused the transition to the I2-SENT state. If this check fails, the NOTIFY packet MUST be dropped silently.

2. If the NOTIFY packet contains a NOTIFICATION parameter with Notify Message Type I2_ACKNOWLEDGEMENT, the system SHOULD set the I2 retransmission timer to the I2 processing time indicated in the NOTIFICATION parameter plus half the RTT-based timeout value. The system MUST NOT set the retransmission timeout to a higher value than allowed by a local policy. Moreover, the system

SHOULD reset the I2 retransmission timer to the RTT-based timeout value after the next I2 retransmission.

6.10. Processing UPDATE, CLOSE, and CLOSE_ACK Packets

UPDATE, CLOSE, and CLOSE_ACK packets are handled similarly in HIP DEX as in HIPv2 (see Sections 6.11, 6.12, 6.14, and 6.15 of [RFC7401]). The only difference is the that the HIP_SIGNATURE is never present and, therefore, is not required to be processed by the receiving party.

[RFC7402] specifies the rekeying of an existing HIP SA using the UPDATE message. This rekeying procedure can also be used with HIP DEX. However, where rekeying involves a new Diffie-Hellman key exchange, HIP DEX peers MUST establish a new HIP association in order to create a new Pair-wise Key SA due to the use of static ECDH key-pairs with HIP DEX.

6.11. Handling State Loss

Implementors MAY choose to use non-volatile, secure storage for HIP states in order for them to survive a system reboot. If no secure storage capabilities are available, the system SHOULD delete the corresponding HIP state, including the keying material. If the implementation does drop the state (as RECOMMENDED), it MUST also drop the peer's R1 generation counter value, unless a local policy explicitly defines that the value of that particular host is stored. Such storing of the R1 generation counter values MUST be configured by explicit HITs.

7. HIP Policies

There are a number of variables that will influence the HIP exchanges that each host must support. The value of puzzle difficulty K used in the HIP R1 must be chosen with care. Values for the K that are too high will exclude clients with weak CPUs because these devices cannot solve the puzzle within a reasonable amount of time. The K value should only be raised if a Responder is under high load, i.e., it cannot process all incoming HIP handshakes any more.

If a Responder is not under high load, K SHOULD be 0.

All HIP DEX implementations SHOULD provide for an Access Control List (ACL), representing for which hosts they accept HIP diet exchanges, and the preferred transport format and local lifetimes. Wildcarding SHOULD be supported for such ACLs.

7.1. HIT/HI ACL

Both the Initiator and Responder SHOULD implement an ACL. Minimally, these ACLs will be a list of trusted HIT/HIs. They may also contain the password used in the password-based two-factor authentication (Appendix A) and preferred HIT Suite.

ACL processing is applied to all HIP packets. A HIP peer MAY reject any packet where the Receiver's HIT is not in the ACL. The HI (in the R1, I2, and optionally NOTIFY packets) MUST be validated as well, when present in the ACL. This is the defense against collision and second-image attacks on the HIT generation.

Devices with no input mechanism (e.g. sensors) SHOULD accept R1 packets from unknown HITs. These R1 packets SHOULD contain the start of the password-based two-factor authentication . If the R2 for this HIT indicates success, then the device may add this HIT to its ACL for future use.

Devices unable to manage an ACL (e.g. sensors) are subject to MITM attacks, even with the use of the password authentication (password theft by attacker). As long as the other peer (e.g. sensor controller) does use an ACL, the attack can be recognized there and addressed. This is often seen where the sensor does not appear as properly operating with the controller, as the attacker cannot impersonate information in the ACL.

8. Interoperability between HIP DEX and HIPv2

HIP DEX and HIPv2 both use the same protocol number and packet formats. Hence, an implementation that either supports HIP DEX or HIPv2 has to be able to detect the dialect that the peer is speaking. This section outlines how a HIP DEX implementation can achieve such detection for the two relevant cases where:

1. the Initiator supports HIP DEX and the Responder supports HIP BEX,

2. the Initiator supports HIP BEX and the Responder supports HIP DEX.

In the first case, the HIP DEX implementation (Initiator) inspects the Responder's HIT prior to sending the I1 packet. If the OGA ID field of this HIT does not indicate the HIP DEX HIT Suite ID, the HIP DEX implementation cancels the handshake. If the Responder is unknown prior to sending the I1 packet (i.e., opportunistic mode), the HIP DEX implementation performs the above check on reception of the R1 packet and cancels the handshake in case of a negative result.

In both failure scenarios, the implementation should report an error to the user via appropriate means.

In the second case, the HIP DEX implementation (Responder) inspects the Initiator's HIT on reception of an I1 packet. If the OGA ID field of this HIT does not indicate the HIP DEX HIT Suite ID, the HIP DEX implementation cancels the handshake and sends an ICMP packet with type Parameter Problem, with the Pointer pointing to the source HIT, to the Initiator. As an off-path adversary could also send such an ICMP packet with the aim to prevent the HIP DEX handshake from completing, the Initiator SHOULD NOT react to an ICMP message before retransmission counter reaches I1_RETRIES_MAX in its state machine (see Table 3 in [RFC7401]).

9. Security Considerations

HIP DEX closely resembles HIPv2. As such, the security considerations discussed in Section 8 of [RFC7401] similarly apply to HIP DEX. HIP DEX, however, replaces the SIGMA-based authenticated Diffie-Hellman key exchange of HIPv2 with an exchange of random keying material that is encrypted with a Diffie-Hellman derived key. Both the Initiator and Responder contribute to this keying material. As a result, the following additional security considerations apply to HIP DEX:

- The strength of the keys for both the Master and Pair-wise Key SAs is based on the quality of the random keying material generated by the Initiator and the Responder. As either peer may be a sensor or an actuator device, there is a natural concern about the quality of its random number generator. Thus at least a CSPRNG SHOULD be used.

- HIP DEX lacks the Perfect Forward Secrecy (PFS) property of HIPv2. Consequently, if an HI is compromised, all previous HIP connections protected with that HI are compromised as explained in Section 1.

- The HIP DEX HIT generation may present new attack opportunities. Hence, HIP DEX HITs MUST NOT be used as the only means to identify a peer in an ACL. Instead, the use of the peer's HI is recommended as explained in Section 3.

- The R1 packet is unauthenticated and offers an adversary a new attack vector against the Initiator. This is mitigated by only processing a received R1 packet when the Initiator has previously sent a corresponding I1 packet. Moreover, the Responder repeats the DH_GROUP_LIST, HIP_CIPHER, HIT_SUITE_LIST, and TRANSPORT_FORMAT_LIST parameters in the R2 packet in order to

enable the Initiator to verify that these parameters have not been modified by an attacker in the unprotected R1 packet as explained in Section 6.8.

- Contrary to HIPv2, HIP DEX does not provide for end-point anonymity for the Initiator or Responder. Thus, any signaling that indicates such anonymity should be ignored as explained in Section 1.1.

The optional retransmission extension of HIP DEX is based on a NOTIFY packet that the Responder can use to inform the Initiator about the reception of an I2 packet. The Responder, however, cannot protect the authenticity of this packet as it did not yet set up the Master Key SA. Hence, an eavesdropping adversary may send spoofed reception acknowledgements for an overheard I2 packet and signal an arbitrary I2 processing time to the Initiator. The adversary can, e.g., indicate a lower I2 processing time than actually required by the Responder in order to cause premature retransmissions. To protect against this attack, the Initiator SHOULD set the NOTIFY-based timeout value to the maximum indicated packet processing time in case of conflicting NOTIFY packets. This allows the legitimate Responder to extend the retransmission timeout to the intended length. The adversary, however, can still arbitrarily delay the protocol handshake beyond the Responder's actual I2 processing time. To limit the extend of such a maliciously induced handshake delay, this specification additionally requires the Initiator not to set the NOTIFY-based timeout value higher than allowed by a local policy.

Section 5.3.1 mentions that implementations need to be able to handle storms of I1 packets. Contrary to HIPv2, R1 packets cannot be pre-computed in HIP DEX and also the state machine does not include an "R1_SENT" state (that would enable caching of R1 packets). Therefore, an implementation has to cache information (e.g., at least the HITs) from incoming I1 packets and rate control the incoming I1 packets to avoid unnecessary packet processing during I1 packet storms.

9.1. Need to Validate Public Keys

With the curves specified here, there is a straightforward key extraction attack, which is a very serious problem with the use of static keys by HIP-DEX. Thus it is MANDATORY to validate the peer's Public Key.

With the NIST curves, there are no internal length markers, so each number representation occupies as many octets as implied by the curve parameters. For P-256, this means that each of X and Y use 32

octets, padded on the left by zeros if necessary. For P-384, they take 48 octets each. For P-521, they take 66 octets each.

For Curve25519 and Curve448, the contents of the public value are the byte string inputs and outputs of the corresponding functions defined in [RFC7748]: 32 bytes for EC25519 and 56 bytes for EC448.

The validation is done in Section 6.7, step 4 and Section 6.8, step 5.

9.2. NULL-ENCRYPT ONLY for Testing/Debugging

Production deployments of this specification MUST NOT use the NULL-ENCRYPT HIP_CIPHER. Per Section 5.2.2, the NULL-ENCRYPT MUST NOT be offered or accepted unless explicitly configured for testing/debugging of HIP.

10. IANA Considerations

The following changes to the "Host Identity Protocol (HIP) Parameters" registries have been made:

ENCRYPTED_KEY "ENCRYPTED_KEY" with type number TBD1 (suggested: 643) (see Section 5.2.5) in the "Parameter Types" subregistry of the "Host Identity Protocol (HIP) Parameters" registry.

DH_GROUP_LIST This document defines the new DH_GROUPS Curve25519 with value TBD7 (suggested: 12) and Curve448 with value TBD8 (suggested: 13) (see Section 5.2.1) in the "Group IDs" subregistry of the "Host Identity Protocol (HIP) Parameters" registry.

HIT Suite ID This document defines the new HIT Suite "ECDH/FOLD" without four-bit ID of TBD2 (suggested: 4) and eight-bit encoding of TBD3 (suggested: 0x40) (see Section 5.2.4) in the "HIT Suite ID" subregistry of the "Host Identity Protocol (HIP) Parameters" registry.

HIP Cipher ID This document defines the new HIP Cipher ID "AES-128-CTR" with type number TBD4 (suggested: 5) (see Section 5.2.2) in the "HIP Cipher ID" subregistry of the "Host Identity Protocol (HIP) Parameters" registry.

HI Algorithm This document defines the new HI Algorithm "ECDH" with type number TBD5 (suggested: 11) (see Section 5.2.3) in the "HI Algorithm" subregistry of the "Host Identity Protocol (HIP) Parameters" registry.

I_NONCE "I_NONCE" with type number TBD6 (suggested: 644) (see Section 5.2.6) in the "Parameter Types" subregistry of the "Host Identity Protocol (HIP) Parameters" registry.

ECC Curve Label This document specifies a new algorithm-specific subregistry named "ECDH Curve Label". The values for this subregistry are defined in Section 5.2.1. The complete list of algorithms for the DH_GROUP_LIST parameter are listed in the "Group IDs" subregistry of the "Host Identity Protocol (HIP) Parameters" registry.

11. Acknowledgements

The drive to put HIP on a cryptographic 'Diet' came out of a number of discussions with sensor vendors at IEEE 802.15 meetings. David McGrew was very helpful in crafting this document. Special thanks to Mohit Sethi in helping with the draft during IESG process.

12. Changelog

This section summarizes the changes made from draft-moskowitz-hip-rg-dex-05, which was the first stable version of the draft. Note that the draft was renamed after draft-moskowitz-hip-rg-dex-06.

The draft was then renamed from draft-moskowitz-hip-dex to draft-ietf-hip-dex.

12.1. Changes in draft-ietf-hip-dex-16

- Remove old placeholder text.
- Remove SECP160R1. Experience has shown EC25519 performance equal enough to not need it.

12.2. Changes in draft-ietf-hip-dex-15

- Added Public Key validation in I2 and R2 processing.
- Added ACL processing (Section 7.1).
- Added IANA instructions for DH_GROUP_LIST.

12.3. Changes in draft-ietf-hip-dex-14

- Changes to (Section 5.4) per Jeff Ahrenholz for Suresh Krishnan comment

12.4. Changes in draft-ietf-hip-dex-12 and 13

- Nits from Jeff Ahrenholz (including some formatting issues)

12.5. Changes in draft-ietf-hip-dex-11 and 12

- Included more precise references to the IANA subregistries
- Addressed GEN-ART feedback from Francis Dupont
- Added reasoning for PFS in a separate section, and it is mentioned also in the abstract and intro.
- Donald Eastlake's (secdir) nits addressed
- Resolved IANA nits from Amanda Baber.
- New sections: "Why introduce folding" (Section 3.2.1), "SECP160R1 Considered Unsafe" (removed in ver 16), "Need to Validate Public Keys" (Section 9.1), and "I_NONCE" (Section 5.2.6) to address Eric Rescorla's concerns.

12.6. Changes in draft-ietf-hip-dex-11

- Update IANA considerations as requested by Eric Envyncke

12.7. Changes in draft-ietf-hip-dex-10

- Explanations on why the document includes so many SHOULDs

12.8. Changes in draft-ietf-hip-dex-09

- Fixed values for
  - DH_GROUP_LIST
  - HIT_SUITE_LIST

  to match [RFC7401].

12.9. Changes in draft-ietf-hip-dex-05

- Clarified main differences between HIP BEX and HIP DEX in Section 1.
- Addressed MitM attack in Section 8.
- Minor editorial changes.

12.10. Changes in draft-ietf-hip-dex-04

- Added new paragraph on rekeying procedure with HIP DEX.
- Updated references.
- Editorial changes.

12.11. Changes in draft-ietf-hip-dex-03

- Added new section on HIP DEX/HIPv2 interoperability
- Added reference to RFC4493 for CMAC.
- Added reference to RFC5869 for CKDF.
- Added processing of NOTIFY message in I2-SENT of state diagram.
- Editorial changes.

12.12. Changes in draft-ietf-hip-dex-02

- Author address change.

12.13. Changes in draft-ietf-hip-dex-01

- Added the new ECDH groups of Curve25519 and Curve448 from RFC 7748.

12.14. Changes in draft-ietf-hip-dex-00

- The Internet Draft was adopted by the HIP WG.

12.15. Changes in draft-moskowitz-hip-rg-dex-06

- A major change in the ENCRYPT parameter to use AES-CTR rather than AES-CBC.

12.16. Changes in draft-moskowitz-hip-dex-00

- Draft name change. HIPRG ended in IRTF, HIP DEX is now individual submission.
- Added the change section.
- Added a Definitions section.

- Changed I2 and R2 packets to reflect use of AES-CTR for ENCRYPTED_KEY parameter.
- Cleaned up KEYMAT Generation text.
- Added Appendix with C code for the ECDH shared secret generation on an 8 bit processor.

12.17. Changes in draft-moskowitz-hip-dex-01

- Numerous editorial changes.
- New retransmission strategy.
- New HIT generation mechanism.
- Modified layout of ENCRYPTED_KEY parameter.
- Clarify use puzzle difficulty of zero under normal network conditions.
- Align inclusion directive of R1_COUNTER with HIPv2 (from SHOULD to MUST).
- Align inclusion of TRANSPORT_FORMAT_LIST with HIPv2 (added to R1 and I2).
- HIP_CIPHER, HIT_SUITE_LIST, and TRANSPORT_FORMAT_LIST must now be echoed in R2 packet.
- Added new author.

12.18. Changes in draft-moskowitz-hip-dex-02

- Introduced formal definition of FOLD function.
- Clarified use of CMAC for puzzle computation in section "Solving the Puzzle".
- Several editorial changes.

12.19. Changes in draft-moskowitz-hip-dex-03

- Addressed HI crypto agility.
- Clarified purpose of secret exchanged via ENCRYPTED_KEY parameter.
- Extended the IV in the ENCRYPTED_KEY parameter.

- Introduced forward-references to HIP DEX KEYMAT process and improved KEYMAT section.
- Replaced Appendix A on "C code for ECC point multiplication" with short discussion in introduction.
- Updated references.
- Further editorial changes.

12.20. Changes in draft-moskowitz-hip-dex-04

- Improved retransmission extension.
- Updated and strongly revised packet processing rules.
- Updated security considerations.
- Updated IANA considerations.
- Move the HI Algorithm for ECDH to a value of 11.
- Many editorial changes.

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Appendix A. Password-based two-factor authentication during the HIP DEX handshake

HIP DEX allows identifying authorized connections based on a two-factor authentication mechanism. With two-factor authentication, devices that are authorized to communicate with each other are required to be pre-provisioned with a shared (group) key. The Initiator uses this pre-provisioned key to encrypt the ECHO_RESPONSE_UNSIGNED in the I2 packet. Upon reception of the I2, the Responder verifies that its challenge in the ECHO_REQUEST_UNSIGNED parameter in the R1 packet has been encrypted with the correct key. If verified successfully, the Responder proceeds with the handshake. Otherwise, it silently drops the I2 packet.

Note that there is no explicit signaling in the HIP DEX handshake for this behavior. Thus, knowledge of two-factor authentication must be configured externally prior to the handshake.

Appendix B. IESG Considerations

During IESG review, a concern was raised on the number of SHOULDS in this document. Here is an analysis of the 57 SHOULDS in HIP DEX.

46 of SHOULDS are also in [RFC7401]. Here are the sections with SHOULDS that match up with [RFC7401]:

5.2.2. HIP_CIPHER (same as 7401)

6.5. Processing Incoming I1 Packets
3. (same as 7401)
5. (same as 7401)

6.6. Processing Incoming R1 Packets (same as 7401)

6.7. Processing Incoming I2 Packets
3. (same as 7401)
7. (same as 7401)
11. (same as 7401)

6.8. Processing Incoming R2 Packets
5. (same as 7401)

6.9. Processing Incoming NOTIFY Packets
1st para (same as 7401)

6.11. Handling State Loss (same as 7401)

7. HIP Policies (1st and 3rd same as 7401)

Many of the other 11 SHOULDS are due to the nature of constrained devices and in most cases the text points this out:

In Section 4.1.1, this is clearly adjusting for how the puzzle could actually be an attack against a constrained device. Same situation in Section 5.3.2.

Section 6, clearly states that:

> it should be noted that many of the packet processing rules are denoted here with "SHOULD" but may be updated to "MUST" when further implementation experience provides better guidance.

thus the SHOULD here is informative of future guidance.

The SHOULD in Section 6.3, clearly reflects new work with the new Sponge Function KDFs:

The keys derived for the Pair-wise Key SA are not used during the HIP DEX handshake. Instead, these keys are made available as payload protection keys (e.g., for IPsec). Some payload protection mechanisms have their own Key Derivation Function, and if so this mechanism SHOULD be used. Otherwise, the HIP DEX KEYMAT process MUST be used to derive the keys of the Pair-wise Key SA based on the

concatenation of the random values that are contained in the exchanged ENCRYPTED_KEY parameters.

In Section 6.5, the reason why this is a SHOULD should be clear to any implementer. That is the HIT Suite list in I1 is a desire on what suite to use. The Responder may have 'different ideas' about the Suite to use (like what it supports). Thus it is best that the Responder selects a DEX HIT, but there are good reasons, in an implementation not to do so. The implementer should know this and will deal with it appropriately.

The SHOULDs in Section 6.7 and Section 6.9 are there for considerations for constrained systems. Some constrained systems need this approach, others may not.

The 2nd SHOULD in Section 7 follows the same as above. ACLs and constrained systems tend to go together.

Similarly in Section 8 the SHOULD is again is highlighting constrained system processing considerations.

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