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Address Protected Neighbor Discovery for Low-power and Lossy Networks draft-ietf-6lo-ap-nd-11

Abstract

This document specifies an extension to 6LoWPAN Neighbor Discovery (ND) protocol defined in RFC6775 and updated in RFC8505. The new extension is called Address Protected Neighbor Discovery (AP-ND) and it protects the owner of an address against address theft and impersonation attacks in a low-power and lossy network (LLN). Nodes supporting this extension compute a cryptographic identifier (Crypto-ID) and use it with one or more of their Registered Addresses. The Crypto-ID identifies the owner of the Registered Address and can be used to provide proof of ownership of the Registered Addresses. Once an address is registered with the Crypto-ID and a proof-of-ownership is provided, only the owner of that address can modify the registration information, thereby enforcing Source Address Validation.

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1. Introduction

Neighbor Discovery Optimizations for 6LoWPAN networks [RFC6775] (6LoWPAN ND) adapts the original IPv6 neighbor discovery (NDv6) protocols defined in [RFC4861] and [RFC4862] for constrained low-power and lossy network (LLN). In particular, 6LoWPAN ND introduces a unicast host address registration mechanism that reduces the use of multicast. 6LoWPAN ND defines a new Address Registration Option (ARO) that is carried in the unicast Neighbor Solicitation (NS) and Neighbor Advertisement (NA) messages exchanged between a 6LoWPAN Node (6LN) and a 6LoWPAN Router (6LR). It also defines the Duplicate Address Request (DAR) and Duplicate Address Confirmation (DAC) messages between the 6LR and the 6LoWPAN Border Router (6LBR). In LLN networks, the 6LBR is the central repository of all the registered addresses in its domain.

The registration mechanism in 6LoWPAN ND [RFC6775] prevents the use of an address if that address is already registered in the subnet (first come first serve). In order to validate address ownership, the registration mechanism enables the 6LR and 6LBR to validate the association between the registered address of a node, and its Registration Ownership Verifier (ROVR). ROVR is defined in [RFC8505] and it can be derived from the MAC address of the device (using the 64-bit Extended Unique Identifier EUI-64 address format specified by IEEE). However, the EUI-64 can be spoofed, and therefore, any node connected to the subnet and aware of a registered-address-to-ROVR mapping could effectively fake the ROVR. This would allow the an attacker to steal the address and redirect traffic for that address. [RFC8505] defines an Extended Address Registration Option (EARO) option that allows to transport alternate forms of ROVRs, and is a pre-requisite for this specification.

In this specification, a 6LN generates a cryptographic ID (Crypto-ID) and places it in the ROVR field during the registration of one (or more) of its addresses with the 6LR(s). Proof of ownership of the Crypto-ID is passed with the first registration exchange to a new 6LR, and enforced at the 6LR. The 6LR validates ownership of the cryptographic ID before it creates any new registration state, or changes existing information.

The protected address registration protocol proposed in this document enables Source Address Validation (SAVI) [RFC7039]. This ensures

that only the actual owner uses a registered address in the IPv6 source address field. A 6LN can only use a 6LR for forwarding packets only if it has previously registered the address used in the source field of the IPv6 packet.

The 6lo adaptation layer in [RFC4944] and [RFC6282] requires a device to form its IPv6 addresses based on its Layer-2 address to enable a better compression. This is incompatible with Secure Neighbor Discovery (SeND) [RFC3971] and Cryptographically Generated Addresses (CGAs) [RFC3972], since they derive the Interface ID (IID) in IPv6 addresses with cryptographic keys.

2. Terminology

2.1. BCP 14

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. References

Terms and concepts from the following documents are used in this specification:

- "Terms Used in Routing for Low-Power and Lossy Networks (LLNs)" [RFC7102],
- "SEcure Neighbor Discovery (SEND)" [RFC3971],
- "Cryptographically Generated Addresses (CGA)" [RFC3972],
- "Neighbor Discovery for IP version 6" [RFC4861] ,
- "IPv6 Stateless Address Autoconfiguration" [RFC4862],
- "IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs): Overview, Assumptions, Problem Statement, and Goals " [RFC4919],
- "Neighbor Discovery Optimization for Low-power and Lossy Networks" [RFC6775], and
- "Registration Extensions for 6LoWPAN Neighbor Discovery" [RFC8505].

2.3. Abbreviations

This document uses the following abbreviations:

6BBR: 6LoWPAN Backbone Router

6LBR: 6LoWPAN Border Router

6LN: 6LoWPAN Node

6LR: 6LoWPAN Router

6CIO: Capability Indication Option

ARO: Address Registration Option

CIPO: Crypto-ID Parameters Option

LLN: Low-Power and Lossy Network

NA: Neighbor Advertisement

NCE: Neighbor Cache Entry

ND: Neighbor Discovery

NDP: Neighbor Discovery Protocol

NDPSO: NDP Signature Option

NS: Neighbor Solicitation

ROVR: Registration Ownership Verifier

RPL: IPv6 Routing Protocol for LLNs

RA: Router Advertisement

RS: Router Solicitation

RSAO: RSA Signature Option

TID: Transaction ID

3. Updating RFC 8505

This specification introduces a new token called a cryptographic identifier (Crypto-ID) that is used to prove indirectly the ownership of an address that is being registered by means of [RFC8505].

In order to prove its ownership of a Crypto-ID, the registering node needs to supply certain parameters including a nonce and a signature that will prove that the node has the private-key corresponding to the public-key used to build the Crypto-ID. This specification adds the capability to carry new options in the NS(EARO) and the NA(EARO). The NS(EARO) carries a variation of the CGA Option (Section 4.3), a Nonce option and a variation of the RSA Signature option (Section 4.5) in the NS(EARO). The NA(EARO) carries a Nonce option.

4. New Fields and Options

In order to avoid the need for new ND option types, this specification reuses and extends options defined in SEND [RFC3971] and 6LoWPAN ND [RFC6775] [RFC8505]. This applies in particular to the CGA option and the RSA Signature Option. This specification provides aliases for the specific variations of those options as used in this document. The presence of the EARO option in the NS/NA messages indicates that the options are to be processed as specified in this document, and not as defined in SEND [RFC3971].

4.1. New Crypto-ID

The Crypto-ID can be used as a replacement to the MAC address in the ROVR field of the EARO option and the EDAR message, and is associated with the Registered Address. The ownership of a Crypto-ID can be demonstrated by cryptographic mechanisms, and by association, the ownership of the Registered Address can be acertained. A node in possession of the necessary cryptographic primitives SHOULD use Crypto-ID by default as ROVR in its registrations. Whether a ROVR is a Crypto-ID is indicated by a new "C" flag in the NS(EARO) message.

The computation of the Crypto-ID requires the support of Elliptic Curve Cryptography (ECC) and that of a hash function as detailed in Section 6.2. The elliptic curves and the hash functions that can be used with this specification are listed in Table 1 in Section 8.2. The signature scheme that specifies which combination is used is signaled by a Crypto-Type in a new Crypto-ID Parameters Option (see Section 4.3).

4.2. Updated EARO

This specification updates the EARO option as follows:

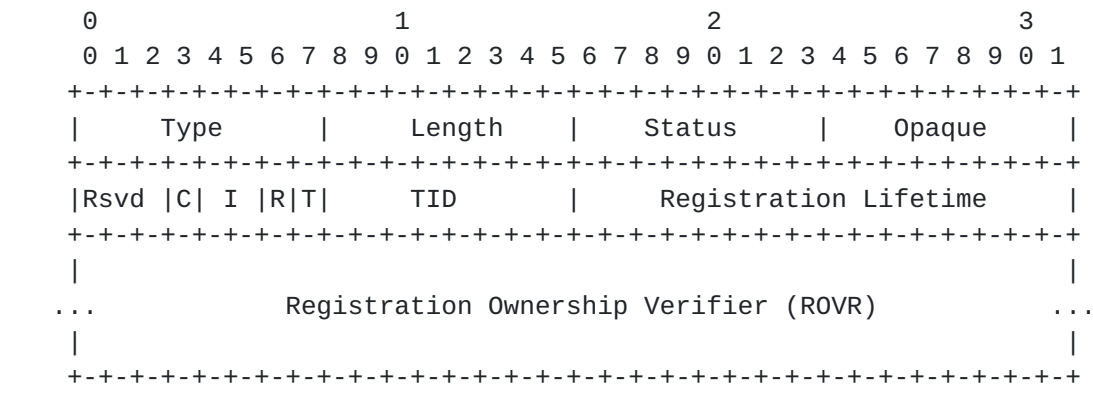

Figure 1: Enhanced Address Registration Option

Type: 33

Length: 8-bit unsigned integer. The length of the option (including the type and length fields) in units of 8 bytes.

Status: 8-bit unsigned integer. Indicates the status of a registration in the NA response. MUST be set to 0 in NS messages.

Opaque: Defined in [RFC8505].

Rsvd (Reserved): This field is unused. It MUST be initialized to zero by the sender and MUST be ignored by the receiver.

C: This "C" flag is set to indicate that the ROVR field contains a Crypto-ID and that the 6LN MAY be challenged for ownership as specified in this document.

I, R, T, and TID: Defined in [RFC8505].

Registration Ownership Verifier (ROVR): When the "C" flag is set, this field contains a Crypto-ID.

This specification uses Status values "Validation Requested" and "Validation Failed", which are defined in [RFC8505]. No other new Status values are defined.

4.3. Crypto-ID Parameters Option

This specification defines the Crypto-ID Parameters Option (CIPO), as a variation of the CGA Option that carries the parameters used to form a Crypto-ID. In order to provide cryptographic agility [RFC7696], this specification supports different elliptic curves, indicated by a Crypto-Type field. NIST P-256 [FIPS186-4] MUST be supported by all implementations. The Edwards-Curve Digital Signature Algorithm (EdDSA) curve Ed25519 (PureEdDSA) [RFC8032] MAY be supported as an alternate.

The type of cryptographic algorithm used in the calculation of the Crypto-ID is signaled by the Crypto-Type field of the CIPO as specified in Table 1 in Section 8.2. Although the different signature schemes target similar cryptographic strength, they rely on different curves, hash functions, signature algorithms, and/or representation conventions.

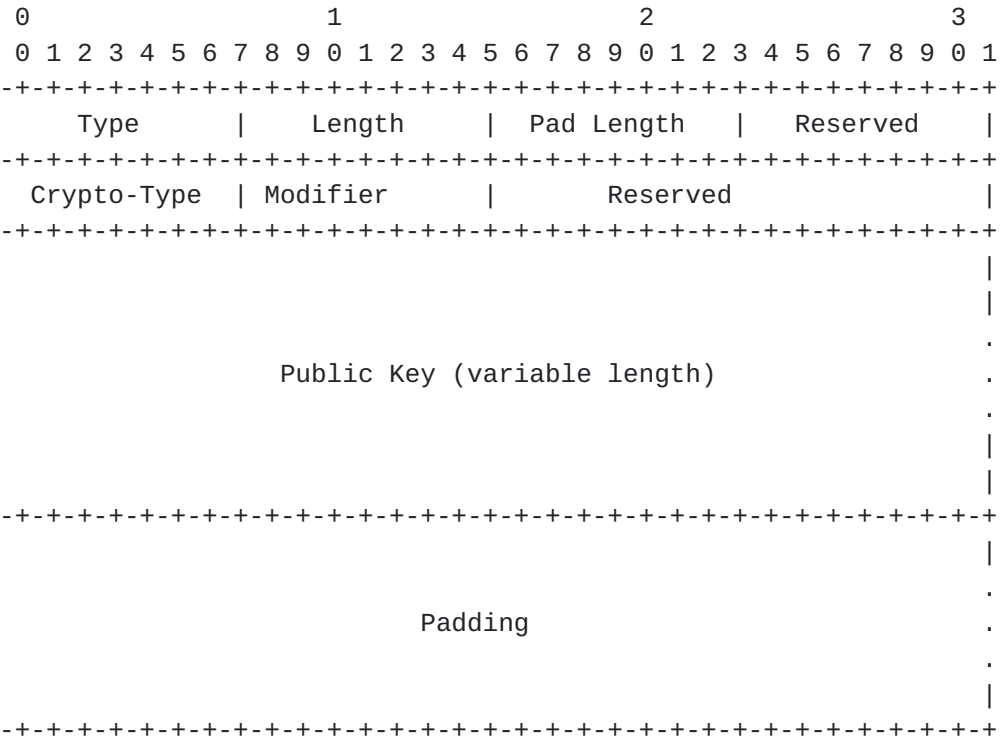

Figure 2: Crypto-ID Parameters Option

Type: 11. This is the same value as the CGA Option, CIPO is a particular case of the CGA option

Length: 8-bit unsigned integer. The length of the option in units of 8 octets.

Modifier: 8-bit unsigned integer.

Pad Length: 8-bit unsigned integer. The length of the Padding field.

Crypto-Type: The type of cryptographic algorithm used in calculation Crypto-ID (see Table 1 in Section 8.2).

Public Key: JWK-Encoded Public Key [RFC7517].

Padding: A variable-length field making the option length a multiple of 8, containing as many octets as specified in the Pad Length field.

The implementation of multiple hash functions in a constrained devices may consume excessive amounts of program memory. [I-D.ietf-lwig-curve-representations] provides information on how to represent Montgomery curves and (twisted) Edwards curves as curves in short-Weierstrass form and illustrates how this can be used to implement elliptic curve computations using existing implementations that already provide, e.g., ECDSA and ECDH using NIST [FIPS186-4] prime curves.

For more details on representation conventions, we refer to Appendix B.

4.4. Nonce Option

This document reuses the Nonce Option defined in section 5.3.2. of SEND [RFC3971] without a change.

4.5. NDP Signature Option

This document reuses the RSA Signature Option (RSAO) defined in section 5.2. of SEND [RFC3971]. Admittedly, the name is ill-chosen since the option is extended for non-RSA Signatures and this specification defines an alias to avoid the confusion.

The description of the operation on the option detailed in section 5.2. of SEND [RFC3971] apply, but for the following changes:

- The 128-bit CGA Message Type tag [RFC3972] for AP-ND is 0x8701 55c8 0cca dd32 6ab7 e415 f148 84d0. (The tag value has been generated by the editor of this specification on random.org).

- The signature is computed using the hash algorithm and the digital signature indicated in the Crypto-Type field of the CIPO option

using the private-key corresponding the public-key passed in the CIPO.

- The alias NDP Signature Option (NDPSO) can be used to refer to the RSAO when used as described in this specification.

5. Protocol Scope

The scope of the protocol specified here is a 6LoWPAN Low Power Lossy Network (LLN), typically a stub network connected to a larger IP network via a Border Router called a 6LBR per [RFC6775]. A 6LBR has sufficient capability to satisfy the needs of duplicate address detection.

The 6LBR maintains registration state for all devices in its attached LLN. Together with the first-hop router (the 6LR), the 6LBR assures uniqueness and grants ownership of an IPv6 address before it can be used in the LLN. This is in contrast to a traditional network that relies on IPv6 address auto-configuration [RFC4862], where there is no guarantee of ownership from the network, and each IPv6 Neighbor Discovery packet must be individually secured [RFC3971].

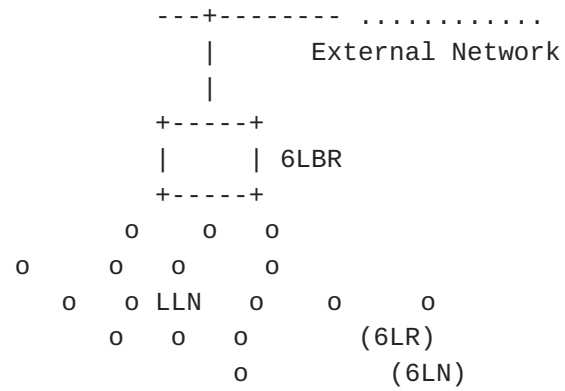

Figure 3: Basic Configuration

In a mesh network, the 6LR is directly connected to the host device. This specification mandates that the peer-wise layer-2 security is deployed so that all the packets from a particular host are securely identifiable by the 6LR. The 6LR may be multiple hops away from the 6LBR. Packets are routed between the 6LR and the 6LBR via other 6LRs. This specification mandates that a chain of trust is established so that a packet that was validated by the first 6LR can be safely routed by other on-path 6LRs to the 6LBR.

6. Protocol Flows

The 6LR/6LBR ensures first-come/first-serve by storing the EARO information including the Crypto-ID associated to the node being registered. The node can claim any address as long as it is the first to make such a claim. After a successful registration, the node becomes the owner of the registered address and the address is bound to the Crypto-ID in the 6LR/6LBR registry.

This specification enables the 6LR to verify the ownership of the binding at any time assuming that the "C" flag is set. The verification prevents other nodes from stealing the address and trying to attract traffic for that address or use it as their source address.

A node may use multiple IPv6 addresses at the same time. The node may use a same Crypto-ID, to prove the ownership of multiple IPv6 addresses. The separation of the address and the cryptographic material avoids the constrained device to compute multiple keys for multiple addresses. The registration process allows the node to use the same Crypto-ID for all of its addresses.

6.1. First Exchange with a 6LR

A 6LN registers to a 6LR that is one hop away from it with the "C" flag set in the EARO, indicating that the ROVR field contains a Crypto-ID. The Target Address in the NS message indicates the IPv6 address that the 6LN is trying to register. The on-link (local) protocol interactions are shown in Figure 4. If the 6LR does not have a state with the 6LN that is consistent with the NS(EARO), then it replies with a challenge NA (EARO, status=Validation Requested) that contains a Nonce Option (shown as NonceLR in Figure 4). The Nonce option MUST contain a random Nonce value that was never used with this device.

The 6LN replies to the challenge with an NS(EARO) that includes a new Nonce option (shown as NonceLN in Figure 4), the CIPO (Section 4.3), and the NDPSO containing the signature. The information associated to a Crypto-ID stored by the 6LR on the first NS exchange where it appears. The 6LR MUST store the CIPO parameters associated with the Crypto-ID so it can be used for more than one address.

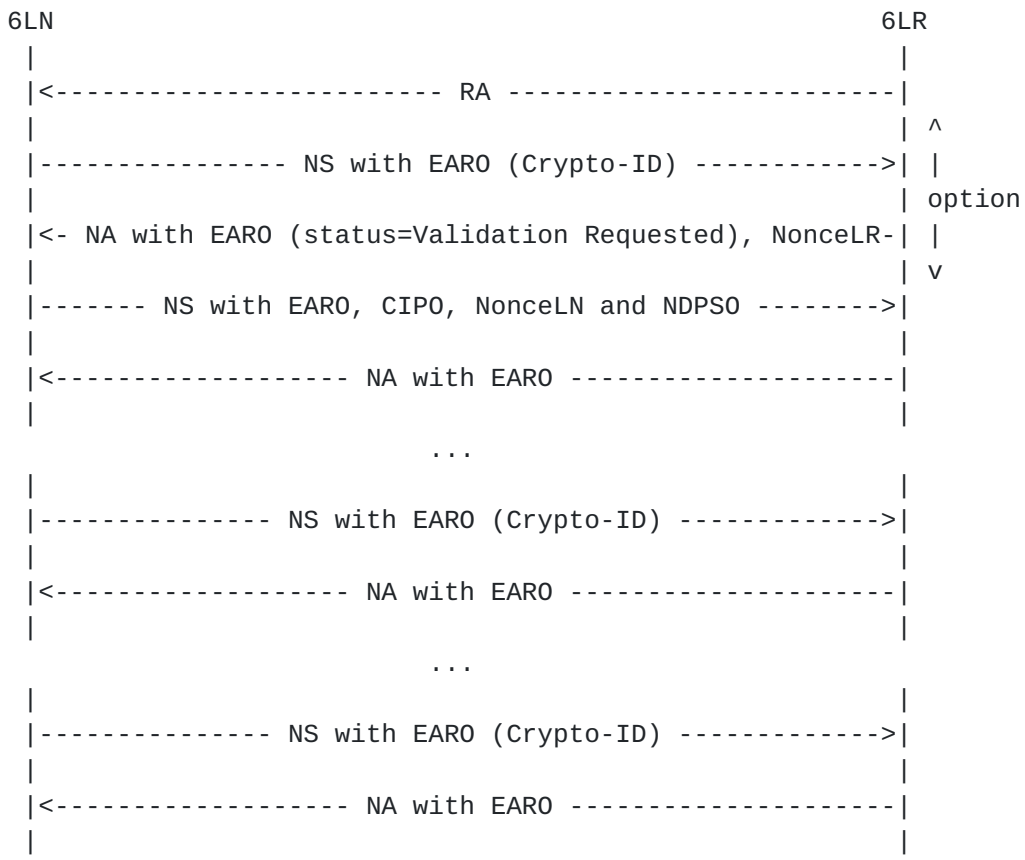

Figure 4: On-link Protocol Operation

The steps for the registration to the 6LR are as follows:

- Upon the first exchange with a 6LR, a 6LN will be challenged to prove ownership of the Crypto-ID and the Target Address being registered in the Neighbor Solicitation message. When a 6LR receives a NS(EARO) registration with a new Crypto-ID as a ROVR, it SHOULD challenge by responding with a NA(EARO) with a status of "Validation Requested".

- The challenge is triggered when the registration for a Source Link-Layer Address is not verifiable either at the 6LR or the 6LBR. In the latter case, the 6LBR returns a status of "Validation Requested" in the DAR/DAC exchange, which is echoed by the 6LR in the NA (EARO) back to the registering node. The challenge MUST NOT alter a valid registration in the 6LR or the 6LBR.

- Upon receiving a NA(EARO) with a status of "Validation Requested", the registering node SHOULD retry its registration with a Crypto-ID Parameters Option (CIPO) (Section 4.3) that contains all the necessary material for building the Crypto-ID, the NonceLN that it

generated, and the NDP signature (Section 4.5) option that proves its ownership of the Crypto-ID and intent of registering the Target Address.

- In order to validate the ownership, the 6LR performs the same steps as the 6LN and rebuilds the Crypto-ID based on the parameters in the CIPO. It also verifies the signature contained in the NDPSO option. If the Crypto-ID does not match with the public-key in the CIPO option, or if the signature in the NDPSO option cannot be verified, the validation fails.

- If the 6LR fails to validate the signed NS(EARO), it responds with a status of "Validation Failed". After receiving a NA(EARO) with a status of "Validation Failed", the registering node SHOULD try to register an alternate target address in the NS message.

6.2. NDPSO generation and verification

The signature generated by the 6LN to provide proof-of-ownership of the private-key is carried in the NDP Signature Option (NDPSO). It is generated by the 6LN in a fashion that depends on the Crypto-Type (see Table 1 in Section 8.2) chosen by the 6LN as follows:

- Concatenate the following in the order listed:

  1. 128-bit type tag (in network byte order)

  2. JWK-encoded public key

  3. the 16-byte Target Address (in network byte order) sent in the Neighbor Solicitation (NS) message. It is the address which the 6LN is registering with the 6LR and 6LBR.

  4. NonceLR received from the 6LR (in network byte order) in the Neighbor Advertisement (NA) message. The random nonce is at least 6 bytes long as defined in [RFC3971].

  5. NonceLN sent from the 6LN (in network byte order). The random nonce is at least 6 bytes long as defined in [RFC3971].

  6. The length of the ROVR field in the NS message containing the Crypto-ID that was sent.

  7. 1-byte (in network byte order) Crypto-Type value sent in the CIPO option.

- Depending on the Crypto-Type, apply the hash function on this concatenation.

- Depending on the Crypto-Type, sign the hash output with ECDSA (if curve P-256 is used) or sign the hash with EdDSA (if curve Ed25519 (PureEdDSA)).

The 6LR on receiving the NDPSO and CIPO options first hashes the JWK encoded public-key in the CIPO option to make sure that the leftmost bits up to the size of the ROVR match. Only if the check is successful, it tries to verify the signature in the NDPSO option using the following.

- Concatenate the following in the order listed:

  1. 128-bit type tag (in network byte order)

  2. JWK-encoded public key received in the CIPO option

  3. the 16-byte Target Address (in network byte order) received in the Neighbor Solicitation (NS) message. It is the address which the 6LN is registering with the 6LR and 6LBR.

  4. NonceLR sent in the Neighbor Advertisement (NA) message. The random nonce is at least 6 bytes long as defined in [RFC3971].

  5. NonceLN received from the 6LN (in network byte order) in the NS message. The random nonce is at least 6 bytes long as defined in [RFC3971].

  6. The length of the ROVR field in the NS message containing the Crypto-ID that was received.

  7. 1-byte (in network byte order) Crypto-Type value received in the CIPO option.

- Depending on the Crypto-Type indicated by the (6LN) in the CIPO, apply the hash function on this concatenation.

- Verify the signature with the public-key received and the locally computed values. If the verification succeeds, the 6LR and 6LBR add the state information about the Crypto-ID, public-key and Target Address being registered to their database.

6.3. Multihop Operation

In a multihop 6LoWPAN, the registration with Crypto-ID is propagated to 6LBR as described in this section. If the 6LR and the 6LBR maintain a security association, then there is no need to propagate the proof of ownership to the 6LBR.

A new device that joins the network auto-configures an address and performs an initial registration to a neighboring 6LR with an NS message that carries an Address Registration Option (EARO) [RFC8505]. The 6LR validates the address with an 6LBR using a DAR/DAC exchange, and the 6LR confirms (or denies) the address ownership with an NA message that also carries an Address Registration Option.

Figure 5 illustrates a registration flow all the way to a 6LowPAN Backbone Router (6BBR) [I-D.ietf-6lo-backbone-router].

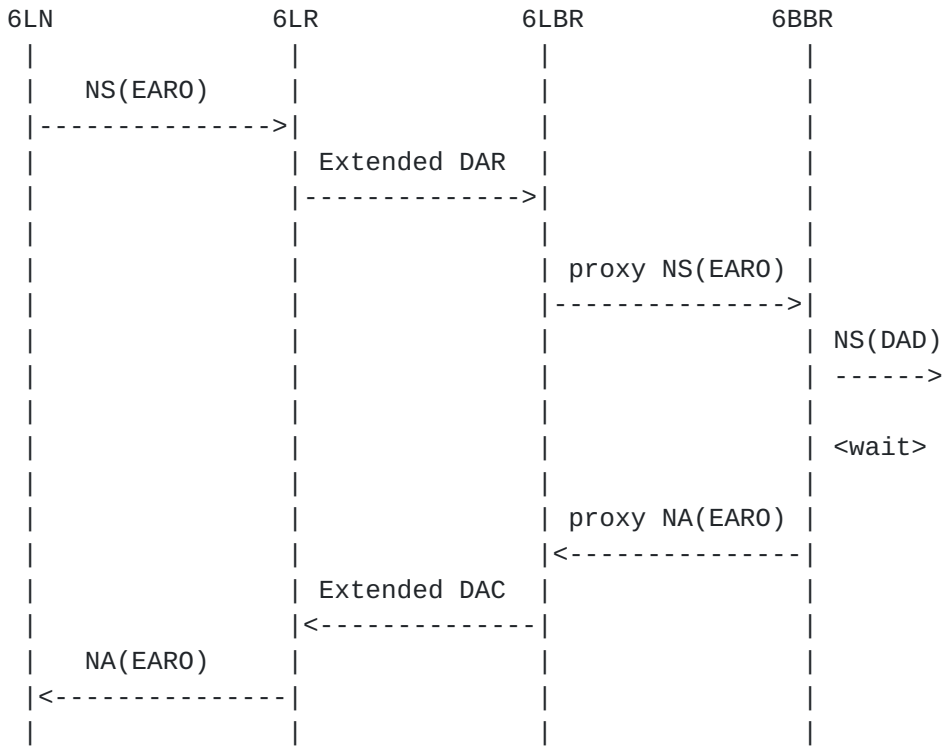

Figure 5: (Re-)Registration Flow

In a multihop 6LoWPAN, a 6LBR sends RAs with prefixes downstream and the 6LR receives and relays them to the nodes. 6LR and 6LBR communicate using ICMPv6 Duplicate Address Request (DAR) and Duplicate Address Confirmation (DAC) messages. The DAR and DAC use the same message format as NS and NA, but have different ICMPv6 type values.

In AP-ND we extend DAR/DAC messages to carry cryptographically generated ROVR. In a multihop 6LoWPAN, the node exchanges the messages shown in Figure 5. The 6LBR must identify who owns an address (EUI-64) to defend it, if there is an attacker on another 6LR.

7. Security Considerations

7.1. Inheriting from RFC 3971

Observations regarding the following threats to the local network in [RFC3971] also apply to this specification.

Neighbor Solicitation/Advertisement Spoofing

Threats in section 9.2.1 of RFC3971 apply. AP-ND counters the threats on NS(EARO) messages by requiring that the NDP Signature and CIPO options be present in these solicitations.

Duplicate Address Detection DoS Attack

Inside the LLN, Duplicate Addresses are sorted out using the ROVR, which differentiates it from a movement. DAD coming from the backbone are not forwarded over the LLN, which provides some protection against DoS attacks inside the resource-constrained part of the network. Over the backbone, the EARO option is present in NS/NA messages. This protects against misinterpreting a movement for a duplication, and enables the backbone routers to determine which one has the freshest registration and is thus the best candidate to validate the registration for the device attached to it. But this specification does not guarantee that the backbone router claiming an address over the backbone is not an attacker.

Router Solicitation and Advertisement Attacks

This specification does not change the protection of RS and RA which can still be protected by SEND.

Replay Attacks

Nonces (NonceLR and NonceLN) generated by the 6LR and 6LN guarantees against replay attacks of the NS(EARO).

Neighbor Discovery DoS Attack

A rogue node that managed to access the L2 network may form many addresses and register them using AP-ND. The perimeter of the attack is all the 6LRs in range of the attacker. The 6LR must protect itself against overflows and reject excessive registration with a status 2 "Neighbor Cache Full". This effectively blocks another (honest) 6LN from registering to the same 6LR, but the 6LN may register to other 6LRs that are in its range but not in that of the rogue.

7.2. Related to 6LoWPAN ND

The threats discussed in 6LoWPAN ND [RFC6775][RFC8505] also apply here. Compared with SeND, this specification saves about 1Kbyte in every NS/NA message. Also, this specification separates the cryptographic identifier from the registered IPv6 address so that a node can have more than one IPv6 address protected by the same cryptographic identifier. SeND forces the IPv6 address to be cryptographic since it integrates the CGA as the IID in the IPv6 address. This specification frees the device to form its addresses in any fashion, thereby enabling not only 6LoWPAN compression which derives IPv6 addresses from Layer-2 addresses but also privacy addresses.

7.3. ROVR Collisions

A collision of Registration Ownership Verifiers (ROVR) (i.e., the Crypto-ID in this specification) is possible, but it is a rare event. The formula for calculating the probability of a collision is 1 - e^{-k^2/(2n)} where n is the maximum population size (2^64 here, 1.84E19) and K is the actual population (number of nodes). If the Crypto-ID is 64-bits (the least possible size allowed), the chance of a collision is 0.01% when the network contains 66 million nodes. Moreover, the collision is only relevant when this happens within one stub network (6LBR). In the case of such a collision, an attacker may be able to claim the registered address of an another legitimate node. However for this to happen, the attacker would also need to know the address which was registered by the legitimate node. This registered address is never broadcasted on the network and therefore providing an additional 64-bits that an attacker must correctly guess. To prevent address disclosure, it is RECOMMENDED that nodes derive the address being registered independently of the ROVR.

7.4. Implementation Attacks

The signature schemes referenced in this specification comply with NIST [FIPS186-4] or Crypto Forum Research Group (CFRG) standards [RFC8032] and offer strong algorithmic security at roughly 128-bit security level. These signature schemes use elliptic curves that were either specifically designed with exception-free and constant-time arithmetic in mind [RFC7748] or where one has extensive implementation experience of resistance to timing attacks [FIPS186-4]. However, careless implementations of the signing operations could nevertheless leak information on private keys. For example, there are micro-architectural side channel attacks that implementors should be aware of [breaking-ed25519]. Implementors should be particularly aware that a secure implementation of Ed25519 requires a protected implementation of the hash function SHA-512,

whereas this is not required with implementations of SHA-256 used with ECDSA.

7.5. Cross-Protocol Attacks

The same private key MUST NOT be reused with more than one signature scheme in this specification.

8. IANA considerations

8.1. CGA Message Type

This document defines a new 128-bit value under the CGA Message Type [RFC3972] name space: 0x8701 55c8 0cca dd32 6ab7 e415 f148 84d0.

8.2. Crypto-Type Subregistry

IANA is requested to create a new subregistry "Crypto-Type Subregistry" in the "Internet Control Message Protocol version 6 (ICMPv6) Parameters". The registry is indexed by an integer in the interval 0..255 and contains an Elliptic Curve, a Hash Function, a Signature Algorithm, and Representation Conventions, as shown in Table 1, which together specify a signature scheme. The following Crypto-Type values are defined in this document:

Crypto-Type value	0 (ECDSA256)	1 (Ed25519)	2 (ECDSA25519)
Elliptic curve	NIST P-256 [FIPS186-4]	Curve25519 [RFC7748]	Curve25519 [RFC7748]
Hash function	SHA-256 [RFC6234]	SHA-512 [RFC6234]	SHA-256 [RFC6234]
Signature algorithm	ECDSA [FIPS186-4]	Ed25519 [RFC8032]	ECDSA [FIPS186-4]
Representation conventions	Weierstrass, (un)compressed, MSB/msb first	Edwards, compressed, LSB/lsb first	Weierstrass, (un)compressed, MSB/msb first
Defining specification	RFC THIS	RFC THIS	RFC THIS

Table 1: Crypto-Types

New Crypto-Type values providing similar or better security (with less code) may be defined in the future.

Assignment of new values for new Crypto-Type MUST be done through IANA with "Specification Required" and "IESG Approval" as defined in [RFC8126].

9. Acknowledgments

Many thanks to Charlie Perkins for his in-depth review and constructive suggestions. We are also especially grateful to Robert Moskowitz for his comments that led to many improvements.

10. References

10.1. Normative References

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Appendix A. Requirements Addressed in this Document

In this section we state requirements of a secure neighbor discovery protocol for low-power and lossy networks.

- The protocol MUST be based on the Neighbor Discovery Optimization for Low-power and Lossy Networks protocol defined in [RFC6775]. RFC6775 utilizes optimizations such as host-initiated interactions for sleeping resource-constrained hosts and elimination of multicast address resolution.

- New options to be added to Neighbor Solicitation messages MUST lead to small packet sizes, especially compared with existing protocols such as SEcure Neighbor Discovery (SEND). Smaller packet sizes facilitate low-power transmission by resource-constrained nodes on lossy links.

- The support for this registration mechanism SHOULD be extensible to more LLN links than IEEE 802.15.4 only. Support for at least the LLN links for which a 6lo "IPv6 over foo" specification exists, as well as Low-Power Wi-Fi SHOULD be possible.

- As part of this extension, a mechanism to compute a unique Identifier should be provided with the capability to form a Link Local Address that SHOULD be unique at least within the LLN connected to a 6LBR.

- The Address Registration Option used in the ND registration SHOULD be extended to carry the relevant forms of Unique Interface Identifier.

- The Neighbor Discovery should specify the formation of a site-local address that follows the security recommendations from [RFC7217].

Appendix B. Representation Conventions

B.1. Signature Schemes

The signature scheme ECDSA256 corresponding to Crypto-Type 0 is ECDSA, as specified in [FIPS186-4], instantiated with the NIST prime curve P-256, as specified in Appendix B of [FIPS186-4], and the hash function SHA-256, as specified in [RFC6234], where points of this NIST curve are represented as points of a short-Weierstrass curve (see [FIPS186-4]) and are encoded as octet strings in most-significant-bit first (msb) and most-significant-byte first (MSB) order. The signature itself consists of two integers (r and s), which are each encoded as fixed-size octet strings in most-

significant-bit first and most-significant-byte first order. For details on ECDSA, see [FIPS186-4]; for details on the integer encoding, see Appendix B.2.

The signature scheme Ed25519 corresponding to Crypto-Type 1 is EdDSA, as specified in [RFC8032], instantiated with the Montgomery curve Curve25519, as specified in [RFC7748], and the hash function SHA-512, as specified in [RFC6234], where points of this Montgomery curve are represented as points of the corresponding twisted Edwards curve (see Appendix B.3) and are encoded as octet strings in least-significant-bit first (lsb) and least-significant-byte first (LSB) order. The signature itself consists of a bit string that encodes a point of this twisted Edwards curve, in compressed format, and an integer encoded in least-significant-bit first and least-significant-byte first order. For details on EdDSA and on the encoding conversions, see the specification of pure Ed25519 in . [RFC8032]

The signature scheme ECDSA25519 corresponding to Crypto-Type 2 is ECDSA, as specified in [FIPS186-4], instantiated with the Montgomery curve Curve25519, as specified in [RFC7748], and the hash function SHA-256, as specified in [RFC6234], where points of this Montgomery curve are represented as points of a corresponding curve in short-Weierstrass form (see Appendix B.3) and are encoded as octet strings in most-significant-bit first and most-significant-byte first order. The signature itself consists of a bit string that encodes two integers, each encoded as fixed-size octet strings in most-significant-bit first and most-significant-byte first order. For details on ECDSA, see [FIPS186-4]; for details on the integer encoding, see Appendix B.2

B.2. Integer Representation for ECDSA signatures

With ECDSA, each signature is a pair (r, s) of integers [FIPS186-4]. Each integer is encoded as a fixed-size 256-bit bit string, where each integer is represented according to the Field Element to Octet String and Octet String to Bit String conversion rules in [SEC1] and where the ordered pair of integers is represented as the rightconcatenation of the resulting representation values. The inverse operation follows the corresponding Bit String to Octet String and Octet String to Field Element conversion rules of [SEC1].

B.3. Alternative Representations of Curve25519

The elliptic curve Curve25519, as specified in [RFC7748], is a so-called Montgomery curve. Each point of this curve can also be represented as a point of a twisted Edwards curve or as a point of an elliptic curve in short-Weierstrass form, via a coordinate transformation (a so-called isomorphic mapping). The parameters of

the Montgomery curve and the corresponding isomorphic curves in twisted Edwards curve and short-Weierstrass form are as indicated below. Here, the domain parameters of the Montgomery curve Curve25519 and of the twisted Edwards curve Edwards25519 are as specified in [RFC7748]; the domain parameters of the elliptic curve Wei25519 in short-Weierstrass curve comply with Section 6.1.1 of [FIPS186-4]. For details of the coordinate transformation referenced above, see [RFC7748] and [I-D.ietf-lwig-curve-representations].

General parameters (for all curve models):

p 2^{255}-19

(=0x7fffffff ffffffff ffffffff ffffffff ffffffff ffffffff ffffffff ffffffed)

h 8

n 7237005577332262213973186563042994240857116359379907606001950938285454250989

(=2^{252} + 0x14def9de a2f79cd6 5812631a 5cf5d3ed)

Montgomery curve-specific parameters (for Curve25519):

A 486662

B 1

Gu 9 (=0x9)

Gv 14781619447589544791020593568409986887264606134616475288964881837755586237401

(=0x20ae19a1 b8a086b4 e01edd2c 7748d14c 923d4d7e 6d7c61b2 29e9c5a2 7eced3d9)

Twisted Edwards curve-specific parameters (for Edwards25519):

a -1 (-0x01)

d -121665/121666

(=37095705934669439343138083508754565189542113879843219016388785533085940283555)

(=0x52036cee 2b6ffe73 8cc74079 7779e898 00700a4d 4141d8ab 75eb4dca 135978a3)

Gx 15112221349535400772501151409588531511454012693041857206046113283
949847762202

(=0x216936d3 cd6e53fe c0a4e231 fdd6dc5c 692cc760 9525a7b2
c9562d60 8f25d51a)

Gy 4/5

(=463168356949264781694283940034751631413079938662562256157830336
03165251855960)

(=0x66666666 66666666 66666666 66666666 66666666 66666666
66666666 66666658)

Weierstrass curve-specific parameters (for Wei25519):

a 19298681539552699237261830834781317975544997444273427339909597334
573241639236

(=0x2aaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa
aaaaaa98 4914a144)

b 55751746669818908907645289078257140818241103727901012315294400837
956729358436

(=0x7b425ed0 97b425ed 097b425e d097b425 ed097b42 5ed097b4
260b5e9c 7710c864)

GX 19298681539552699237261830834781317975544997444273427339909597334
652188435546

(=0x2aaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa aaaaaaaa
aaaaaaaa aaad245a)

GY 14781619447589544791020593568409986887264606134616475288964881837
755586237401

(=0x20ae19a1 b8a086b4 e01edd2c 7748d14c 923d4d7e 6d7c61b2
29e9c5a2 7eced3d9)

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