

Network Working Group
Internet-Draft
Obsoletes: [4423](#) (if approved)
Intended status: Informational
Expires: May 27, 2018

R. Moskowitz, Ed.
HTT Consulting
M. Komu
Ericsson
November 23, 2017

Host Identity Protocol Architecture draft-ietf-hip-rfc4423-bis-18

Abstract

This memo describes a new namespace, the Host Identity namespace, and a new protocol layer, the Host Identity Protocol, between the internetworking and transport layers. Herein are presented the basics of the current namespaces, their strengths and weaknesses, and how a new namespace will add completeness to them. The roles of this new namespace in the protocols are defined.

This document obsoletes [RFC 4423](#) and addresses the concerns raised by the IESG, particularly that of crypto agility. It incorporates lessons learned from the implementations of [RFC 5201](#) and goes further to explain how HIP works as a secure signaling channel.

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Table of Contents

| | | |
|----------------------|--|--------------------|
| 1. | Introduction | 3 |
| 2. | Terminology | 4 |
| 2.1. | Terms common to other documents | 4 |
| 2.2. | Terms specific to this and other HIP documents | 5 |
| 3. | Background | 6 |
| 3.1. | A desire for a namespace for computing platforms | 7 |
| 4. | Host Identity namespace | 9 |
| 4.1. | Host Identifiers | 10 |
| 4.2. | Host Identity Hash (HIH) | 10 |
| 4.3. | Host Identity Tag (HIT) | 11 |
| 4.4. | Local Scope Identifier (LSI) | 11 |
| 4.5. | Storing Host Identifiers in directories | 12 |
| 5. | New stack architecture | 13 |
| 5.1. | On the multiplicity of identities | 14 |
| 6. | Control plane | 15 |
| 6.1. | Base exchange | 15 |
| 6.2. | End-host mobility and multi-homing | 16 |
| 6.3. | Rendezvous mechanism | 16 |
| 6.4. | Relay mechanism | 17 |
| 6.5. | Termination of the control plane | 17 |
| 7. | Data plane | 17 |
| 8. | HIP and NATs | 18 |
| 8.1. | HIP and Upper-layer checksums | 19 |
| 9. | Multicast | 19 |
| 10. | HIP policies | 19 |
| 11. | Design considerations | 20 |

| | | |
|-------------------------|--|--------------------|
| 11.1. | Benefits of HIP | 20 |
| 11.2. | Drawbacks of HIP | 23 |
| 11.3. | Deployment and adoption considerations | 24 |
| 11.3.1. | Deployment analysis | 24 |
| 11.3.2. | HIP in 802.15.4 networks | 25 |
| 11.3.3. | HIP and Internet of Things | 26 |
| 11.4. | Answers to NSRG questions | 27 |
| 12. | Security considerations | 29 |
| 12.1. | MiTM Attacks | 29 |
| 12.2. | Protection against flooding attacks | 30 |
| 12.3. | HITs used in ACLs | 31 |
| 12.4. | Alternative HI considerations | 32 |
| 13. | IANA considerations | 33 |
| 14. | Acknowledgments | 33 |
| 15. | Changes from RFC 4423 | 33 |
| 16. | References | 34 |
| 16.1. | Normative References | 34 |
| 16.2. | Informative references | 35 |
| | Authors' Addresses | 42 |

[1.](#) Introduction

The Internet has two important global namespaces: Internet Protocol (IP) addresses and Domain Name Service (DNS) names. These two namespaces have a set of features and abstractions that have powered the Internet to what it is today. They also have a number of weaknesses. Basically, since they are all we have, we try and do too much with them. Semantic overloading and functionality extensions have greatly complicated these namespaces.

The proposed Host Identity namespace fills an important gap between the IP and DNS namespaces. A Host Identity conceptually refers to a computing platform, and there may be multiple such Host Identities per computing platform (because the platform may wish to present a different identity to different communicating peers). The Host Identity namespace consists of Host Identifiers (HI). There is exactly one Host Identifier for each Host Identity (although there may be transient periods of time such as key replacement when more than one identifier may be active). While this text later talks about non-cryptographic Host Identifiers, the architecture focuses on the case in which Host Identifiers are cryptographic in nature. Specifically, the Host Identifier is the public key of an asymmetric key-pair. Each Host Identity uniquely identifies a single host, i.e., no two hosts have the same Host Identity. If two or more computing platforms have the same Host Identifier, then they are instantiating a distributed host. The Host Identifier can either be public (e.g. published in the DNS), or unpublished. Client systems will tend to have both public and unpublished Host Identifiers.

There is a subtle but important difference between Host Identities and Host Identifiers. An Identity refers to the abstract entity that is identified. An Identifier, on the other hand, refers to the concrete bit pattern that is used in the identification process.

Although the Host Identifiers could be used in many authentication systems, such as IKEv2 [[RFC4306](#)], the presented architecture introduces a new protocol, called the Host Identity Protocol (HIP), and a cryptographic exchange, called the HIP base exchange; see also [Section 6](#). HIP provides for limited forms of trust between systems, enhance mobility, multi-homing and dynamic IP renumbering, aid in protocol translation / transition, and reduce certain types of denial-of-service (DoS) attacks.

When HIP is used, the actual payload traffic between two HIP hosts is typically, but not necessarily, protected with ESP [[RFC7402](#)]. The Host Identities are used to create the needed ESP Security Associations (SAs) and to authenticate the hosts. When ESP is used, the actual payload IP packets do not differ in any way from standard ESP protected IP packets.

Much has been learned about HIP [[RFC6538](#)] since [[RFC4423](#)] was published. This document expands Host Identities beyond use to enable IP connectivity and security to general interhost secure signalling at any protocol layer. The signal may establish a security association between the hosts, or simply pass information within the channel.

[2.](#) Terminology

[2.1.](#) Terms common to other documents

| Term | Explanation |
|-----------------|--|
| Public key | The public key of an asymmetric cryptographic key pair. Used as a publicly known identifier for cryptographic identity authentication. Public is a relative term here, ranging from "known to peers only" to "known to the world." |
| Private key | The private or secret key of an asymmetric cryptographic key pair. Assumed to be known only to the party identified by the corresponding public key. Used by the identified party to authenticate its identity to other parties. |
| Public key pair | An asymmetric cryptographic key pair consisting of public and private keys. For example, Rivest-Shamir-Adleman (RSA), Digital Signature Algorithm (DSA) and Elliptic Curve DSA (ECDSA) key pairs are such key pairs. |
| End-point | A communicating entity. For historical reasons, the term 'computing platform' is used in this document as a (rough) synonym for end-point. |

2.2. Terms specific to this and other HIP documents

It should be noted that many of the terms defined herein are tautologous, self-referential or defined through circular reference to other terms. This is due to the succinct nature of the definitions. See the text elsewhere in this document and the base specification [[RFC7401](#)] for more elaborate explanations.

| Term | Explanation |
|--|---|
| Computing platform | An entity capable of communicating and computing, for example, a computer. See the definition of 'End-point', above. |
| HIP base exchange | A cryptographic protocol; see also Section 6 . |
| HIP packet | An IP packet that carries a 'Host Identity Protocol' message. |
| Host Identity | An abstract concept assigned to a 'computing platform'. See 'Host Identifier', below. |
| Host Identity namespace | A name space formed by all possible Host Identifiers. |
| Host Identity Protocol | A protocol used to carry and authenticate Host Identifiers and other information. |
| Host Identity Hash | The cryptographic hash used in creating the Host Identity Tag from the Host Identity. |
| Host Identity Tag | A 128-bit datum created by taking a cryptographic hash over a Host Identifier plus bits to identify which hash used. |
| Host Identifier | A public key used as a name for a Host Identity. |
| Local Scope Identifier | A 32-bit datum denoting a Host Identity. |
| Public Host Identifier and Identity | A published or publicly known Host Identifier used as a public name for a Host Identity, and the corresponding Identity. |
| Unpublished Host Identifier and Identity | A Host Identifier that is not placed in any public directory, and the corresponding Host Identity. Unpublished Host Identities are typically short lived in nature, being often replaced and possibly used just once. |
| Rendezvous Mechanism | A mechanism used to locate mobile hosts based on their HIT. |

3. Background

The Internet is built from three principal components: computing platforms (end-points), packet transport (i.e., internetworking) infrastructure, and services (applications). The Internet exists to service two principal components: people and robotic services (silicon-based people, if you will). All these components need to be named in order to interact in a scalable manner. Here we concentrate on naming computing platforms and packet transport elements.

There are two principal namespaces in use in the Internet for these components: IP addresses, and Domain Names. Domain Names provide hierarchically assigned names for some computing platforms and some services. Each hierarchy is delegated from the level above; there is no anonymity in Domain Names. Email, HTTP, and SIP addresses all reference Domain Names.

The IP addressing namespace has been overloaded to name both interfaces (at layer-3) and endpoints (for the endpoint-specific part of layer-3, and for layer-4). In their role as interface names, IP addresses are sometimes called "locators" and serve as an endpoint within a routing topology.

IP addresses are numbers that name networking interfaces, and typically only when the interface is connected to the network. Originally, IP addresses had long-term significance. Today, the vast number of interfaces use ephemeral and/or non-unique IP addresses. That is, every time an interface is connected to the network, it is assigned an IP address.

In the current Internet, the transport layers are coupled to the IP addresses. Neither can evolve separately from the other. IPng deliberations were strongly shaped by the decision that a corresponding TCPng would not be created.

There are three critical deficiencies with the current namespaces. Firstly, dynamic readdressing cannot be directly managed. Secondly, confidentiality is not provided in a consistent, trustable manner. Finally, authentication for systems and datagrams is not provided. All of these deficiencies arise because computing platforms are not well named with the current namespaces.

3.1. A desire for a namespace for computing platforms

An independent namespace for computing platforms could be used in end-to-end operations independent of the evolution of the internetworking layer and across the many internetworking layers. This could support rapid readdressing of the internetworking layer because of mobility, rehomeing, or renumbering.

If the namespace for computing platforms is based on public-key cryptography, it can also provide authentication services. If this namespace is locally created without requiring registration, it can provide anonymity.

Such a namespace (for computing platforms) and the names in it should have the following characteristics:

- o The namespace should be applied to the IP 'kernel' or stack. The IP stack is the 'component' between applications and the packet transport infrastructure.
- o The namespace should fully decouple the internetworking layer from the higher layers. The names should replace all occurrences of IP addresses within applications (like in the Transport Control Block, TCB). This replacement can be handled transparently for legacy applications as the LSIs and HITs are compatible with IPv4 and IPv6 addresses [[RFC5338](#)]. However, HIP-aware applications require some modifications from the developers, who may employ networking API extensions for HIP [[RFC6317](#)].
- o The introduction of the namespace should not mandate any administrative infrastructure. Deployment must come from the bottom up, in a pairwise deployment.
- o The names should have a fixed length representation, for easy inclusion in datagram headers and existing programming interfaces (e.g the TCB).
- o Using the namespace should be affordable when used in protocols. This is primarily a packet size issue. There is also a computational concern in affordability.
- o Name collisions should be avoided as much as possible. The mathematics of the birthday paradox can be used to estimate the chance of a collision in a given population and hash space. In general, for a random hash space of size n bits, we would expect to obtain a collision after approximately $1.2 \cdot \sqrt{2^n}$ hashes were obtained. For 64 bits, this number is roughly 4 billion. A hash size of 64 bits may be too small to avoid collisions in a large population; for example, there is a 1% chance of collision in a population of 640M. For 100 bits (or more), we would not expect a collision until approximately 2^{50} (1 quadrillion) hashes were generated.
- o The names should have a localized abstraction so that they can be used in existing protocols and APIs.
- o It must be possible to create names locally. When such names are not published, this can provide anonymity at the cost of making resolvability very difficult.
- o The namespace should provide authentication services.
- o The names should be long lived, but replaceable at any time. This impacts access control lists; short lifetimes will tend to result

in tedious list maintenance or require a namespace infrastructure for central control of access lists.

In this document, a new namespace approaching these ideas is called the Host Identity namespace. Using Host Identities requires its own protocol layer, the Host Identity Protocol, between the internetworking and transport layers. The names are based on public-key cryptography to supply authentication services. Properly designed, it can deliver all of the above stated requirements.

4. Host Identity namespace

A name in the Host Identity namespace, a Host Identifier (HI), represents a statistically globally unique name for naming any system with an IP stack. This identity is normally associated with, but not limited to, an IP stack. A system can have multiple identities, some 'well known', some unpublished or 'anonymous'. A system may self-assert its own identity, or may use a third-party authenticator like DNSSEC [[RFC2535](#)], PGP, or X.509 to 'notarize' the identity assertion to another namespace. It is expected that the Host Identifiers will initially be authenticated with DNSSEC and that all implementations will support DNSSEC as a minimal baseline.

In theory, any name that can claim to be 'statistically globally unique' may serve as a Host Identifier. In the HIP architecture, the public key of a private-public key pair has been chosen as the Host Identifier because it can be self managed and it is computationally difficult to forge. As specified in the Host Identity Protocol [[RFC7401](#)] specification, a public-key-based HI can authenticate the HIP packets and protect them from man-in-the-middle attacks. Since authenticated datagrams are mandatory to provide much of HIP's denial-of-service protection, the Diffie-Hellman exchange in HIP base exchange has to be authenticated. Thus, only public-key HI and authenticated HIP messages are supported in practice.

In this document, the non-cryptographic forms of HI and HIP are presented to complete the theory of HI, but they should not be implemented as they could produce worse denial-of-service attacks than the Internet has without Host Identity. There has been past research in challenge puzzles to use non-cryptographic HI, for Radio Frequency IDentification (RFID), in an HIP exchange tailored to the workings of such challenges (as described further in [[urien-rfid](#)] and [[urien-rfid-draft](#)]).

4.1. Host Identifiers

Host Identity adds two main features to Internet protocols. The first is a decoupling of the internetworking and transport layers; see [Section 5](#). This decoupling will allow for independent evolution of the two layers. Additionally, it can provide end-to-end services over multiple internetworking realms. The second feature is host authentication. Because the Host Identifier is a public key, this key can be used for authentication in security protocols like ESP.

The only completely defined structure of the Host Identity is that of a public/private key pair. In this case, the Host Identity is referred to by its public component, the public key. Thus, the name representing a Host Identity in the Host Identity namespace, i.e., the Host Identifier, is the public key. In a way, the possession of the private key defines the Identity itself. If the private key is possessed by more than one node, the Identity can be considered to be a distributed one.

Architecturally, any other Internet naming convention might form a usable base for Host Identifiers. However, non-cryptographic names should only be used in situations of high trust - low risk. That is any place where host authentication is not needed (no risk of host spoofing) and no use of ESP. However, at least for interconnected networks spanning several operational domains, the set of environments where the risk of host spoofing allowed by non-cryptographic Host Identifiers is acceptable is the null set. Hence, the current HIP documents do not specify how to use any other types of Host Identifiers but public keys. For instance, Back-to-My-Mac [[RFC6281](#)] from Apple comes pretty close to the functionality of HIP, but unlike HIP, it is based on non-cryptographic identifiers.

The actual Host Identifiers are never directly used at the transport or network layers. The corresponding Host Identifiers (public keys) may be stored in various DNS or other directories as identified elsewhere in this document, and they are passed in the HIP base exchange. A Host Identity Tag (HIT) is used in other protocols to represent the Host Identity. Another representation of the Host Identities, the Local Scope Identifier (LSI), can also be used in protocols and APIs.

4.2. Host Identity Hash (HIH)

The Host Identity Hash is the cryptographic hash algorithm used in producing the HIT from the HI. It is also the hash used throughout the HIP protocol for consistency and simplicity. It is possible to for the two hosts in the HIP exchange to use different hash algorithms.

Multiple HIHs within HIP are needed to address the moving target of creation and eventual compromise of cryptographic hashes. This significantly complicates HIP and offers an attacker an additional downgrade attack that is mitigated in the HIP protocol [[RFC7401](#)].

4.3. Host Identity Tag (HIT)

A Host Identity Tag is a 128-bit representation for a Host Identity. It is created from an HIH, an IPv6 prefix [[RFC7343](#)] and a hash identifier. There are two advantages of using the HIT over using the Host Identifier in protocols. Firstly, its fixed length makes for easier protocol coding and also better manages the packet size cost of this technology. Secondly, it presents the identity in a consistent format to the protocol independent of the cryptographic algorithms used.

In essence, the HIT is a hash over the public key. As such, two algorithms affect the generation of a HIT: the public-key algorithm of the HI and the used HIH. The two algorithms are encoded in the bit presentation of the HIT. As the two communicating parties may support different algorithms, [[RFC7401](#)] defines the minimum set for interoperability. For further interoperability, the responder may store its keys in DNS records, and thus the initiator may have to couple destination HITs with appropriate source HITs according to matching HIH.

In the HIP packets, the HITs identify the sender and recipient of a packet. Consequently, a HIT should be unique in the whole IP universe as long as it is being used. In the extremely rare case of a single HIT mapping to more than one Host Identity, the Host Identifiers (public keys) will make the final difference. If there is more than one public key for a given node, the HIT acts as a hint for the correct public key to use.

4.4. Local Scope Identifier (LSI)

An LSI is a 32-bit localized representation for a Host Identity. The purpose of an LSI is to facilitate using Host Identities in existing APIs for IPv4-based applications. Besides facilitating HIP-based connectivity for legacy IPv4 applications, the LSIs are beneficial in two other scenarios [[RFC6538](#)].

In the first scenario, two IPv4-only applications are residing on two separate hosts connected by IPv6-only network. With HIP-based connectivity, the two applications are able to communicate despite of the mismatch in the protocol families of the applications and the underlying network. The reason is that the HIP layer translates the

LSIs originating from the upper layers into routable IPv6 locators before delivering the packets on the wire.

The second scenario is the same as the first one, but with the difference that one of the applications supports only IPv6. Now two obstacles hinder the communication between the application: the addressing families of the two applications differ, and the application residing at the IPv4-only side is again unable to communicate because of the mismatch between addressing families of the application (IPv4) and network (IPv6). With HIP-based connectivity for applications, this scenario works; the HIP layer can choose whether to translate the locator of an incoming packet into an LSI or HIT.

Effectively, LSIs improve IPv6 interoperability at the network layer as described in the first scenario and at the application layer as depicted in the second example. The interoperability mechanism should not be used to avoid transition to IPv6; the authors firmly believe in IPv6 adoption and encourage developers to port existing IPv4-only applications to use IPv6. However, some proprietary, closed-source, IPv4-only applications may never see the daylight of IPv6, and the LSI mechanism is suitable for extending the lifetime of such applications even in IPv6-only networks.

The main disadvantage of an LSI is its local scope. Applications may violate layering principles and pass LSIs to each other in application-layer protocols. As the LSIs are valid only in the context of the local host, they may represent an entirely different host when passed to another host. However, it should be emphasized here that the LSI concept is effectively a host-based NAT and does not introduce any more issues than the prevalent middlebox based NATs for IPv4. In other words, the applications violating layering principles are already broken by the NAT boxes that are ubiquitously deployed.

4.5. Storing Host Identifiers in directories

The public Host Identifiers should be stored in DNS; the unpublished Host Identifiers should not be stored anywhere (besides the communicating hosts themselves). The (public) HI along with the supported HIHs are stored in a new RR type. This RR type is defined in HIP DNS Extension [[RFC8005](#)].

Alternatively, or in addition to storing Host Identifiers in the DNS, they may be stored in various other directories. For instance, a directory based on the Lightweight Directory Access Protocol (LDAP) or a Public Key Infrastructure (PKI) [[RFC8002](#)] may be used. Alternatively, Distributed Hash Tables (DHTs) [[RFC6537](#)] have

successfully been utilized [[RFC6538](#)]. Such a practice may allow them to be used for purposes other than pure host identification.

Some types of applications may cache and use Host Identifiers directly, while others may indirectly discover them through symbolic host name (such as FQDN) look up from a directory. Even though Host Identities can have a substantially longer lifetime associated with them than routable IP addresses, directories may be a better approach to manage the lifespan of Host Identities. For example, an LDAP-based directory or DHT can be used for locally published identities whereas DNS can be more suitable for public advertisement.

5. New stack architecture

One way to characterize Host Identity is to compare the proposed new architecture with the current one. Using the terminology from the IRTF Name Space Research Group Report [[nsrg-report](#)] and, e.g., the unpublished Internet-Draft Endpoints and Endpoint Names [[chiappa-endpoints](#)], the IP addresses currently embody the dual role of locators and end-point identifiers. That is, each IP address names a topological location in the Internet, thereby acting as a routing direction vector, or locator. At the same time, the IP address names the physical network interface currently located at the point-of-attachment, thereby acting as a end-point name.

In the HIP architecture, the end-point names and locators are separated from each other. IP addresses continue to act as locators. The Host Identifiers take the role of end-point identifiers. It is important to understand that the end-point names based on Host Identities are slightly different from interface names; a Host Identity can be simultaneously reachable through several interfaces.

The difference between the bindings of the logical entities are illustrated in Figure 1. Left side illustrates the current TCP/IP architecture and right side the HIP-based architecture.

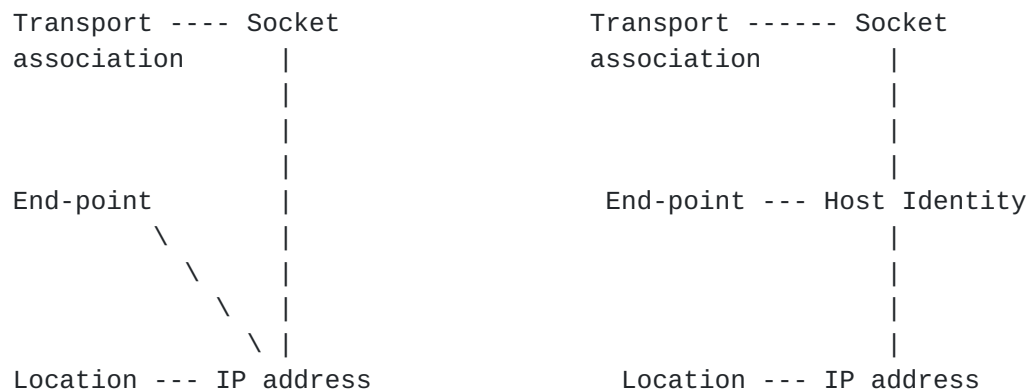


Figure 1

Architecturally, HIP provides for a different binding of transport-layer protocols. That is, the transport-layer associations, i.e., TCP connections and UDP associations, are no longer bound to IP addresses but rather to Host Identities. In practice, the Host Identities are exposed as LSIs and HITs for legacy applications and the transport layer to facilitate backward compatibility with existing networking APIs and stacks.

5.1. On the multiplicity of identities

A host may have multiple identities both at the client and server side. This raises some additional concerns that are addressed in this section.

For security reasons, it may be a bad idea to duplicate the same Host Identity on multiple hosts because the compromise of a single host taints the identities of the other hosts. Management of machines with identical Host Identities may also present other challenges and, therefore, it is advisable to have a unique identity for each host.

Instead of duplicating identities, HIP opportunistic mode can be employed, where the initiator leaves out the identifier of the responder when initiating the key exchange and learns it upon the completion of the exchange. The tradeoffs are related to lowered security guarantees, but a benefit of the approach is to avoid publishing of Host Identifiers in any directories [[komu-leap](#)]. The approach could also be used for load balancing purposes at the HIP layer because the identity of the responder can be decided dynamically during the key exchange. Thus, the approach has the potential to be used as a HIP-layer "anycast", either directly between two hosts or indirectly through the rendezvous service [[komu-diss](#)].

At the client side, a host may have multiple Host Identities, for instance, for privacy purposes. Another reason can be that the person utilizing the host employs different identities for different administrative domains as an extra security measure. If a HIP-aware middlebox, such as a HIP-based firewall, is on the path between the client and server, the user or the underlying system should carefully choose the correct identity to avoid the firewall to unnecessarily drop HIP-base connectivity [[komu-diss](#)].

Similarly, a server may have multiple Host Identities. For instance, a single web server may serve multiple different administrative domains. Typically, the distinction is accomplished based on the DNS name, but also the Host Identity could be used for this purpose. However, a more compelling reason to employ multiple identities are HIP-aware firewalls that are unable see the HTTP traffic inside the encrypted IPsec tunnel. In such a case, each service could be configured with a separate identity, thus allowing the firewall to segregate the different services of the single web server from each other [[lindqvist-enterprise](#)].

6. Control plane

HIP decouples control and data plane from each other. Two end-hosts initialize the control plane using a key exchange procedure called the base exchange. The procedure can be assisted by new infrastructural intermediaries called rendezvous or relay servers. In the event of IP address changes, the end-hosts sustain control plane connectivity with mobility and multihoming extensions. Eventually, the end-hosts terminate the control plane and remove the associated state.

6.1. Base exchange

The base exchange is a key exchange procedure that authenticates the initiator and responder to each other using their public keys. Typically, the initiator is the client-side host and the responder is the server-side host. The roles are used by the state machine of a HIP implementation, but discarded upon successful completion.

The exchange consists of four messages during which the hosts also create symmetric keys to protect the control plane with Hash-based message authentication codes (HMACs). The keys can be also used to protect the data plane, and IPsec ESP [[RFC7402](#)] is typically used as the data-plane protocol, albeit HIP can also accommodate others. Both the control and data plane are terminated using a closing procedure consisting of two messages.

In addition, the base exchange also includes a computational puzzle [[RFC7401](#)] that the initiator must solve. The responder chooses the difficulty of the puzzle which permits the responder to delay new incoming initiators according to local policies, for instance, when the responder is under heavy load. The puzzle can offer some resiliency against DoS attacks because the design of the puzzle mechanism allows the responder to remain stateless until the very end of the base exchange [[aura-dos](#)]. HIP puzzles have also been studied under steady-state DDoS attacks [[beal-dos](#)], on multiple adversary models with varying puzzle difficulties [[tritanunt-dos](#)] and with ephemeral Host Identities [[komu-mitigation](#)].

6.2. End-host mobility and multi-homing

HIP decouples the transport from the internetworking layer, and binds the transport associations to the Host Identities (actually through either the HIT or LSI). After the initial key exchange, the HIP layer maintains transport-layer connectivity and data flows using its mobility [[RFC8046](#)] and multihoming [[RFC8047](#)] extensions. Consequently, HIP can provide for a degree of internetworking mobility and multi-homing at a low infrastructure cost. HIP mobility includes IP address changes (via any method) to either party. Thus, a system is considered mobile if its IP address can change dynamically for any reason like PPP, DHCP, IPv6 prefix reassignments, or a NAT device remapping its translation. Likewise, a system is considered multi-homed if it has more than one globally routable IP address at the same time. HIP links IP addresses together, when multiple IP addresses correspond to the same Host Identity. If one address becomes unusable, or a more preferred address becomes available, existing transport associations can easily be moved to another address.

When a node moves while communication is already on-going, address changes are rather straightforward. The peer of the mobile node can just accept a HIP or an integrity protected ESP packet from any address and ignore the source address. However, as discussed in [Section 12.2](#) below, a mobile node must send a HIP UPDATE packet to inform the peer of the new address(es), and the peer must verify that the mobile node is reachable through these addresses. This is especially helpful for those situations where the peer node is sending data periodically to the mobile node (that is, re-starting a connection after the initial connection).

6.3. Rendezvous mechanism

Establishing a contact to a mobile, moving node is slightly more involved. In order to start the HIP exchange, the initiator node has to know how to reach the mobile node. For instance, the mobile node

can employ Dynamic DNS [[RFC2136](#)] to update its reachability information in the DNS. To avoid the dependency to DNS, HIP provides its own HIP-specific alternative: the HIP rendezvous mechanism as defined in HIP Rendezvous specifications [[RFC8004](#)].

Using the HIP rendezvous extensions, the mobile node keeps the rendezvous infrastructure continuously updated with its current IP address(es). The mobile nodes trusts the rendezvous mechanism in order to properly maintain their HIT and IP address mappings.

The rendezvous mechanism is especially useful in scenarios where both of the nodes are expected to change their address at the same time. In such a case, the HIP UPDATE packets will cross each other in the network and never reach the peer node.

6.4. Relay mechanism

The HIP relay mechanism [[I-D.ietf-hip-native-nat-traversal](#)] is an alternative to the HIP rendezvous mechanism. The HIP relay mechanism is more suitable for IPv4 networks with NATs because a HIP relay can forward all control and data plane communications in order to guarantee successful NAT traversal.

6.5. Termination of the control plane

The control plane between two hosts is terminated using a secure two message exchange as specified in base exchange specification [[RFC7401](#)]. The related state (i.e. host associations) should be removed upon successful termination.

7. Data plane

The encapsulation format for the data plane used for carrying the application-layer traffic can be dynamically negotiated during the key exchange. For instance, HICCUPS extensions [[RFC6078](#)] define one way to transport application-layer datagrams directly over the HIP control plane, protected by asymmetric key cryptography. Also, S-RTP has been considered as the data encapsulation protocol [[hip-srtp](#)]. However, the most widely implemented method is the Encapsulated Security Payload (ESP) [[RFC7402](#)] that is protected by symmetric keys derived during the key exchange. ESP Security Associations (SAs) offer both confidentiality and integrity protection, of which the former can be disabled during the key exchange. In the future, other ways of transporting application-layer data may be defined.

The ESP SAs are established and terminated between the initiator and the responder hosts. Usually, the hosts create at least two SAs, one in each direction (initiator-to-responder SA and responder-to-

initiator SA). If the IP addresses of either host changes, the HIP mobility extensions can be used to re-negotiate the corresponding SAs.

On the wire, the difference in the use of identifiers between the HIP control and data plane is that the HITs are included in all control packets, but not in the data plane when ESP is employed. Instead, the ESP employs SPI numbers that act as compressed HITs. Any HIP-aware middlebox (for instance, a HIP-aware firewall) interested in the ESP based data plane should keep track between the control and data plane identifiers in order to associate them with each other.

Since HIP does not negotiate any SA lifetimes, all lifetimes are subject to local policy. The only lifetimes a HIP implementation must support are sequence number rollover (for replay protection), and SA timeout. An SA times out if no packets are received using that SA. Implementations may support lifetimes for the various ESP transforms and other data-plane protocols.

8. HIP and NATs

Passing packets between different IP addressing realms requires changing IP addresses in the packet header. This may occur, for example, when a packet is passed between the public Internet and a private address space, or between IPv4 and IPv6 networks. The address translation is usually implemented as Network Address Translation (NAT) [[RFC3022](#)] or NAT Protocol translation (NAT-PT) [[RFC2766](#)].

In a network environment where identification is based on the IP addresses, identifying the communicating nodes is difficult when NATs are employed because private address spaces are overlapping. In other words, two hosts cannot be distinguished from each other solely based on their IP address. With HIP, the transport-layer end-points (i.e. applications) are bound to unique Host Identities rather than overlapping private addresses. This allows two end-points to distinguish one other even when they are located in different private address realms. Thus, the IP addresses are used only for routing purposes and can be changed freely by NATs when a packet between two HIP capable hosts traverses through multiple private address realms.

NAT traversal extensions for HIP [[I-D.ietf-hip-native-nat-traversal](#)] can be used to realize the actual end-to-end connectivity through NAT devices. To support basic backward compatibility with legacy NATs, the extensions encapsulate both HIP control and data plane in UDP. The extensions define mechanisms for forwarding the two planes through an intermediary host called HIP relay and procedures to establish direct end-to-end connectivity by penetrating NATs.

Besides this "native" NAT traversal mode for HIP, other NAT traversal mechanisms have been successfully utilized, such as Teredo [[varjonen-split](#)].

Besides legacy NATs, a HIP-aware NAT has been designed and implemented [[ylitalo-spinat](#)]. For a HIP-based flow, a HIP-aware NAT or NAT-PT system tracks the mapping of HITs, and the corresponding ESP SPIs, to an IP address. The NAT system has to learn mappings both from HITs and from SPIs to IP addresses. Many HITs (and SPIs) can map to a single IP address on a NAT, simplifying connections on address poor NAT interfaces. The NAT can gain much of its knowledge from the HIP packets themselves; however, some NAT configuration may be necessary.

8.1. HIP and Upper-layer checksums

There is no way for a host to know if any of the IP addresses in an IP header are the addresses used to calculate the TCP checksum. That is, it is not feasible to calculate the TCP checksum using the actual IP addresses in the pseudo header; the addresses received in the incoming packet are not necessarily the same as they were on the sending host. Furthermore, it is not possible to recompute the upper-layer checksums in the NAT/NAT-PT system, since the traffic is ESP protected. Consequently, the TCP and UDP checksums are calculated using the HITs in the place of the IP addresses in the pseudo header. Furthermore, only the IPv6 pseudo header format is used. This provides for IPv4 / IPv6 protocol translation.

9. Multicast

A number of studies investigating HIP-based multicast have been published (including [[shields-hip](#)], [[xueyong-hip](#)], [[xueyong-hip](#)], [[amir-hip](#)], [[kovacshazi-host](#)] and [[xueyong-secure](#)]). In particular, so-called Bloom filters, that allow compressing of multiple labels into small data structures, may be a promising way forward [[sarela-bloom](#)]. However, the different schemes have not been adopted by the HIP working group (nor the HIP research group in IRTF), so the details are not further elaborated here.

10. HIP policies

There are a number of variables that influence the HIP exchange that each host must support. All HIP implementations should support at least 2 HIs, one to publish in DNS or similar directory service and an unpublished one for anonymous usage. Although unpublished HIs will be rarely used as responder HIs, they are likely to be common for initiators. Support for multiple HIs is recommended. This

provides new challenges for systems or users to decide which type of HI to expose when they start a new session.

Opportunistic mode (where the initiator starts a HIP exchange without prior knowledge of the responder's HI) presents a security tradeoff. At the expense of being subject to MITM attacks, the opportunistic mode allows the initiator to learn the identity of the responder during communication rather than from an external directory. Opportunistic mode can be used for registration to HIP-based services [[RFC8003](#)] (i.e. utilized by HIP for its own internal purposes) or by the application layer [[komu-leap](#)]. For security reasons, especially the latter requires some involvement from the user to accept the identity of the responder similar to how SSH prompts the user when connecting to a server for the first time [[pham-leap](#)]. In practice, this can be realized in end-host based firewalls in the case of legacy applications [[karvonen-usable](#)] or with native APIs for HIP APIs [[RFC6317](#)] in the case of HIP-aware applications.

Many initiators would want to use a different HI for different responders. The implementations should provide for a policy mapping of initiator HITs to responder HITs. This policy should also include preferred transforms and local lifetimes.

Responders would need a similar policy, describing the hosts allowed to participate in HIP exchanges, and the preferred transforms and local lifetimes.

[11.](#) Design considerations

[11.1.](#) Benefits of HIP

In the beginning, the network layer protocol (i.e., IP) had the following four "classic" invariants:

1. Non-mutable: The address sent is the address received.
2. Non-mobile: The address doesn't change during the course of an "association".
3. Reversible: A return header can always be formed by reversing the source and destination addresses.
4. Omniscient: Each host knows what address a partner host can use to send packets to it.

Actually, the fourth can be inferred from 1 and 3, but it is worth mentioning explicitly for reasons that will be obvious soon if not already.

In the current "post-classic" world, we are intentionally trying to get rid of the second invariant (both for mobility and for multi-homing), and we have been forced to give up the first and the fourth. Realm Specific IP [[RFC3102](#)] is an attempt to reinstate the fourth invariant without the first invariant. IPv6 is an attempt to reinstate the first invariant.

Few client-side systems on the Internet have DNS names that are meaningful. That is, if they have a Fully Qualified Domain Name (FQDN), that name typically belongs to a NAT device or a dial-up server, and does not really identify the system itself but its current connectivity. FQDNs (and their extensions as email names) are application-layer names; more frequently naming services than particular systems. This is why many systems on the Internet are not registered in the DNS; they do not have services of interest to other Internet hosts.

DNS names are references to IP addresses. This only demonstrates the interrelationship of the networking and application layers. DNS, as the Internet's only deployed and distributed database, is also the repository of other namespaces, due in part to DNSSEC and application specific key records. Although each namespace can be stretched (IP with v6, DNS with KEY records), neither can adequately provide for host authentication or act as a separation between internetworking and transport layers.

The Host Identity (HI) namespace fills an important gap between the IP and DNS namespaces. An interesting thing about the HI is that it actually allows a host to give up all but the 3rd network-layer invariant. That is to say, as long as the source and destination addresses in the network-layer protocol are reversible, HIP takes care of host identification, and reversibility allows a local host to receive a packet back from a remote host. The address changes occurring during NAT transit (non-mutable) or host movement (non-omniscient or non-mobile) can be managed by the HIP layer.

With the exception of High-Performance Computing applications, the Sockets API is the most common way to develop network applications. Applications use the Sockets API either directly or indirectly through some libraries or frameworks. However, the Sockets API is based on the assumption of static IP addresses, and DNS with its lifetime values was invented at later stages during the evolution of the Internet. Hence, the Sockets API does not deal with the lifetime of addresses [[RFC6250](#)]. As the majority of the end-user equipment is mobile today, their addresses are effectively ephemeral, but the Sockets API still gives a fallacious illusion of persistent IP addresses to the unwary developer. HIP can be used to solidify this

illusion because HIP provides persistent surrogate addresses to the application layer in the form of LSIs and HITs.

The persistent identifiers as provided by HIP are useful in multiple scenarios (see, e.g., [[ylitalo-diss](#)] or [[komu-diss](#)], for a more elaborate discussion):

- o When a mobile host moves physically between two different WLAN networks and obtains a new address, an application using the identifiers remains isolated regardless of the topology changes while the underlying HIP layer re-establishes connectivity (i.e. a horizontal handoff).
- o Similarly, the application utilizing the identifiers remains again unaware of the topological changes when the underlying host equipped with WLAN and cellular network interfaces switches between the two different access technologies (i.e. a vertical handoff).
- o Even when hosts are located in private address realms, applications can uniquely distinguish different hosts from each other based on their identifiers. In other words, it can be stated that HIP improves Internet transparency for the application layer [[komu-diss](#)].
- o Site renumbering events for services can occur due to corporate mergers or acquisitions, or by changes in Internet Service Provider. They can involve changing the entire network prefix of an organization, which is problematic due to hard-coded addresses in service configuration files or cached IP addresses at the client side [[RFC5887](#)]. Considering such human errors, a site employing location-independent identifiers as promoted by HIP may experience less problems while renumbering their network.
- o More agile IPv6 interoperability can be achieved, as discussed in [Section 4.4](#). IPv6-based applications can communicate using HITs with IPv4-based applications that are using LSIs. Additionally, the underlying network type (IPv4 or IPv6) becomes independent of the addressing family of the application.
- o HITs (or LSIs) can be used in IP-based access control lists as a more secure replacement for IPv6 addresses. Besides security, HIT based access control has two other benefits. First, the use of HITs can potentially halve the size of access control lists because separate rules for IPv4 are not needed [[komu-diss](#)]. Second, HIT-based configuration rules in HIP-aware middleboxes remain static and independent of topology changes, thus simplifying administrative efforts particularly for mobile

environments. For instance, the benefits of HIT based access control have been harnessed in the case of HIP-aware firewalls, but can be utilized directly at the end-hosts as well [[RFC6538](#)].

While some of these benefits could be and have been redundantly implemented by individual applications, providing such generic functionality at the lower layers is useful because it reduces software development effort and networking software bugs (as the layer is tested with multiple applications). It also allows the developer to focus on building the application itself rather than delving into the intricacies of mobile networking, thus facilitating separation of concerns.

HIP could also be realized by combining a number of different protocols, but the complexity of the resulting software may become substantially larger, and the interaction between multiple possibly layered protocols may have adverse effects on latency and throughput. It is also worth noting that virtually nothing prevents realizing the HIP architecture, for instance, as an application-layer library, which has been actually implemented in the past [[xin-hip-lib](#)]. However, the tradeoff in moving the HIP layer to the application layer is that legacy applications may not be supported.

11.2. Drawbacks of HIP

In computer science, many problems can be solved with an extra layer of indirection. However, the indirection always involves some costs as there is no such a thing as "free lunch". In the case of HIP, the main costs could be stated as follows:

- o In general, a new layer and a new namespace always involve some initial effort in terms of implementation, deployment and maintenance. Some education of developers and administrators may also be needed. However, the HIP community at the IETF has spent years in experimenting, exploring, testing, documenting and implementing HIP to ease the adoption costs.
- o HIP decouples identifier and locator roles of IP addresses. Consequently, a mapping mechanism is needed to associate them together. A failure to map a HIT to its corresponding locator may result in failed connectivity because a HIT is "flat" by its nature and cannot be looked up from the hierarchically organized DNS. HITs are flat by design due to a security tradeoff. The more bits are allocated for the hash in the HIT, the less likely there will be (malicious) collisions.

- o From performance viewpoint, HIP control and data plane processing introduces some overhead in terms of throughput and latency as elaborated below.

The key exchange introduces some extra latency (two round trips) in the initial transport layer connection establishment between two hosts. With TCP, additional delay occurs if the underlying network stack implementation drops the triggering SYN packet during the key exchange. The same cost may also occur during HIP handoff procedures. However, subsequent TCP sessions using the same HIP association will not bear this cost (within the key lifetime). Both the key exchange and handoff penalties can be minimized by caching TCP packets. The latter case can further be optimized with TCP user timeout extensions [[RFC5482](#)] as described in further detail by Schuetz et al [[schuetz-intermittent](#)].

The most CPU-intensive operations involve the use of the asymmetric keys and Diffie-Hellman key derivation at the control plane, but this occurs only during the key exchange, its maintenance (handoffs, refreshing of key material) and tear down procedures of HIP associations. The data plane is typically implemented with ESP because it has a smaller overhead due to symmetric key encryption. Naturally, even ESP involves some overhead in terms of latency (processing costs) and throughput (tunneling) (see e.g. [[ylitalo-diss](#)] for a performance evaluation).

[11.3.](#) Deployment and adoption considerations

This section describes some deployment and adoption considerations related to HIP from a technical perspective.

[11.3.1.](#) Deployment analysis

HIP has commercially been utilized at Boeing airplane factory for their internal purposes [[paine-hip](#)]. It has been included in a security product called Tofino to support layer-two Virtual Private Networks [[henderson-vpls](#)] to facilitate, e.g, supervisory control and data acquisition (SCADA) security. However, HIP has not been a "wild success" [[RFC5218](#)] in the Internet as argued by Levae et al [[leva-barriers](#)]. Here, we briefly highlight some of their findings based on interviews with 19 experts from the industry and academia.

From a marketing perspective, the demand for HIP has been low and substitute technologies have been favored. Another identified reason has been that some technical misconceptions related to the early stages of HIP specifications still persist. Two identified misconceptions are that HIP does not support NAT traversal, and that HIP must be implemented in the OS kernel. Both of these claims are

untrue; HIP does have NAT traversal extensions [[I-D.ietf-hip-native-nat-traversal](#)], and kernel modifications can be avoided with modern operating systems by diverting packets for userspace processing.

The analysis by Levae et al clarifies infrastructural requirements for HIP. In a minimal set up, a client and server machine have to run HIP software. However, to avoid manual configurations, usually DNS records for HIP are set up. For instance, the popular DNS server software Bind9 does not require any changes to accommodate DNS records for HIP because they can be supported in binary format in its configuration files [[RFC6538](#)]. HIP rendezvous servers and firewalls are optional. No changes are required to network address points, NATs, edge routers or core networks. HIP may require holes in legacy firewalls.

The analysis also clarifies the requirements for the host components that consist of three parts. First, a HIP control plane component is required, typically implemented as a userspace daemon. Second, a data plane component is needed. Most HIP implementations utilize the so called BEET mode of ESP that has been available since Linux kernel 2.6.27, but is included also as a userspace component in a few of the implementations. Third, HIP systems usually provide a DNS proxy for the local host that translates HIP DNS records to LSIs and HITs, and communicates the corresponding locators to HIP userspace daemon. While the third component is not mandatory, it is very useful for avoiding manual configurations. The three components are further described in the HIP experiment report [[RFC6538](#)].

Based on the interviews, Levae et al suggest further directions to facilitate HIP deployment. Transitioning the HIP specifications to the standards track may help, but other measures could be taken. As a more radical measure, the authors suggest to implement HIP as a purely application-layer library [[xin-hip-lib](#)] or other kind of middleware. On the other hand, more conservative measures include focusing on private deployments controlled by a single stakeholder. As a more concrete example of such a scenario, HIP could be used by a single service provider to facilitate secure connectivity between its servers [[komu-cloud](#)].

[11.3.2.](#) HIP in 802.15.4 networks

The IEEE 802 standards have been defining MAC layered security. Many of these standards use EAP [[RFC3748](#)] as a Key Management System (KMS) transport, but some like IEEE 802.15.4 [[IEEE.802-15-4.2011](#)] leave the KMS and its transport as "Out of Scope".

HIP is well suited as a KMS in these environments:

- o HIP is independent of IP addressing and can be directly transported over any network protocol.
- o Master Keys in 802 protocols are commonly pair-based with group keys transported from the group controller using pair-wise keys.
- o AdHoc 802 networks can be better served by a peer-to-peer KMS than the EAP client/server model.
- o Some devices are very memory constrained and a common KMS for both MAC and IP security represents a considerable code savings.

11.3.3. HIP and Internet of Things

HIP requires certain amount computational resources from a device due to cryptographic processing. HIP scales down to phones and small system-on-chip devices (such as Raspberry Pis, Intel Edison), but small sensors operating with small batteries have remained problematic. Different extensions to the HIP have been developed to scale HIP down to smaller devices, typically with different security tradeoffs. For example, the non-cryptographic identifiers have been proposed in RFID scenarios. The slimfit approach [[hummen](#)] proposes a compression layer for HIP to make it more suitable for constrained networks. The approach is applied to a light-weight version of HIP (i.e. "Diet HIP") in order to scale down to small sensors.

The HIP Diet Exchange [[I-D.ietf-hip-dex](#)] design aims at reducing the overhead of the employed cryptographic primitives by omitting public-key signatures and hash functions. In doing so, the main goal is to still deliver similar security properties to the Base Exchange (BEX).

DEX is primarily designed for computation or memory- constrained sensor/actuator devices. Like BEX, 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. In addition, DEX can also be used as a keying mechanism for security primitives at the MAC layer, e.g., for IEEE 802.15.9 networks ([[IEEE.802-15-9](#)]).

The main differences between HIP BEX and DEX are:

1. Minimum collection of cryptographic primitives to reduce the protocol overhead.
 - * Static Elliptic Curve Diffie-Hellman key pairs for peer authentication and encryption of the session key.

- * AES-CTR for symmetric encryption and AES-CMAC for MACing function.
 - * A simple fold function for HIT generation.
2. Forfeit of Perfect Forward Secrecy with the dropping of an ephemeral Diffie-Hellman key agreement.
 3. Forfeit of digital signatures with the removal of a hash function. Reliance on ECDH derived key used in HIP_MAC to prove ownership of the private key.
 4. Diffie-Hellman derived key ONLY used to protect the HIP packets. A separate secret exchange within the HIP packets creates the session key(s).
 5. Optional retransmission strategy tailored to handle the potentially extensive processing time of the employed cryptographic operations on computationally constrained devices.

11.4. Answers to NSRG questions

The IRTF Name Space Research Group has posed a number of evaluating questions in their report [[nsrg-report](#)]. In this section, we provide answers to these questions.

1. How would a stack name improve the overall functionality of the Internet?

HIP decouples the internetworking layer from the transport layer, allowing each to evolve separately. The decoupling makes end-host mobility and multi-homing easier, also across IPv4 and IPv6 networks. HIs make network renumbering easier, and they also make process migration and clustered servers easier to implement. Furthermore, being cryptographic in nature, they provide the basis for solving the security problems related to end-host mobility and multi-homing.

2. What does a stack name look like?

A HI is a cryptographic public key. However, instead of using the keys directly, most protocols use a fixed size hash of the public key.

3. What is its lifetime?

HIP provides both stable and temporary Host Identifiers. Stable HIs are typically long lived, with a lifetime of years

or more. The lifetime of temporary HIs depends on how long the upper-layer connections and applications need them, and can range from a few seconds to years.

4. Where does it live in the stack?

The HIs live between the transport and internetworking layers.

5. How is it used on the end points?

The Host Identifiers may be used directly or indirectly (in the form of HITs or LSIs) by applications when they access network services. Additionally, the Host Identifiers, as public keys, are used in the built in key agreement protocol, called the HIP base exchange, to authenticate the hosts to each other.

6. What administrative infrastructure is needed to support it?

In some environments, it is possible to use HIP opportunistically, without any infrastructure. However, to gain full benefit from HIP, the HIs must be stored in the DNS or a PKI, and a new rendezvous mechanism is needed [[RFC8005](#)].

7. If we add an additional layer would it make the address list in SCTP unnecessary?

Yes

8. What additional security benefits would a new naming scheme offer?

HIP reduces dependency on IP addresses, making the so called address ownership [[Nik2001](#)] problems easier to solve. In practice, HIP provides security for end-host mobility and multi-homing. Furthermore, since HIP Host Identifiers are public keys, standard public key certificate infrastructures can be applied on the top of HIP.

9. What would the resolution mechanisms be, or what characteristics of a resolution mechanisms would be required?

For most purposes, an approach where DNS names are resolved simultaneously to HIs and IP addresses is sufficient. However, if it becomes necessary to resolve HIs into IP addresses or back to DNS names, a flat resolution infrastructure is needed. Such an infrastructure could be

based on the ideas of Distributed Hash Tables, but would require significant new development and deployment.

12. Security considerations

This section includes discussion on some issues and solutions related to security in the HIP architecture.

12.1. MiTM Attacks

HIP takes advantage of the new Host Identity paradigm to provide secure authentication of hosts and to provide a fast key exchange for ESP. HIP also attempts to limit the exposure of the host to various denial-of-service (DoS) and man-in-the-middle (MitM) attacks. In so doing, HIP itself is subject to its own DoS and MitM attacks that potentially could be more damaging to a host's ability to conduct business as usual.

Resource exhausting denial-of-service attacks take advantage of the cost of setting up a state for a protocol on the responder compared to the 'cheapness' on the initiator. HIP allows a responder to increase the cost of the start of state on the initiator and makes an effort to reduce the cost to the responder. This is done by having the responder start the authenticated Diffie-Hellman exchange instead of the initiator, making the HIP base exchange 4 packets long. The first packet sent by the responder can be prebuilt to further mitigate the costs. This packet also includes a computational puzzle that can optionally be used to further delay the initiator, for instance, when the responder is overloaded. The details are explained in the base exchange specification [[RFC7401](#)].

Man-in-the-middle (MitM) attacks are difficult to defend against, without third-party authentication. A skillful MitM could easily handle all parts of the HIP base exchange, but HIP indirectly provides the following protection from a MitM attack. If the responder's HI is retrieved from a signed DNS zone or securely obtained by some other means, the initiator can use this to authenticate the signed HIP packets. Likewise, if the initiator's HI is in a secure DNS zone, the responder can retrieve it and validate the signed HIP packets. However, since an initiator may choose to use an unpublished HI, it knowingly risks a MitM attack. The responder may choose not to accept a HIP exchange with an initiator using an unknown HI.

Other types of MitM attacks against HIP can be mounted using ICMP messages that can be used to signal about problems. As a overall guideline, the ICMP messages should be considered as unreliable "hints" and should be acted upon only after timeouts. The exact

attack scenarios and countermeasures are described in full detail the base exchange specification [[RFC7401](#)].

The need to support multiple hashes for generating the HIT from the HI affords the MitM to mount a potentially powerful downgrade attack due to the a-priori need of the HIT in the HIP base exchange. The base exchange has been augmented to deal with such an attack by restarting on detecting the attack. At worst this would only lead to a situation in which the base exchange would never finish (or would be aborted after some retries). As a drawback, this leads to an 6-way base exchange which may seem bad at first. However, since this only occurs in an attack scenario and since the attack can be handled (so it is not interesting to mount anymore), we assume the subsequent messages do not represent a security threat. Since the MitM cannot be successful with a downgrade attack, these sorts of attacks will only occur as 'nuisance' attacks. So, the base exchange would still be usually just four packets even though implementations must be prepared to protect themselves against the downgrade attack.

In HIP, the Security Association for ESP is indexed by the SPI; the source address is always ignored, and the destination address may be ignored as well. Therefore, HIP-enabled Encapsulated Security Payload (ESP) is IP address independent. This might seem to make attacking easier, but ESP with replay protection is already as well protected as possible, and the removal of the IP address as a check should not increase the exposure of ESP to DoS attacks.

12.2. Protection against flooding attacks

Although the idea of informing about address changes by simply sending packets with a new source address appears appealing, it is not secure enough. That is, even if HIP does not rely on the source address for anything (once the base exchange has been completed), it appears to be necessary to check a mobile node's reachability at the new address before actually sending any larger amounts of traffic to the new address.

Blindly accepting new addresses would potentially lead to flooding Denial-of-Service attacks against third parties [[RFC4225](#)]. In a distributed flooding attack an attacker opens high volume HIP connections with a large number of hosts (using unpublished HIs), and then claims to all of these hosts that it has moved to a target node's IP address. If the peer hosts were to simply accept the move, the result would be a packet flood to the target node's address. To prevent this type of attack, HIP mobility extensions include a return routability check procedure where the reachability of a node is separately checked at each address before using the address for larger amounts of traffic.

A credit-based authorization approach for host mobility with the Host Identity Protocol [[RFC8046](#)] can be used between hosts for sending data prior to completing the address tests. Otherwise, if HIP is used between two hosts that fully trust each other, the hosts may optionally decide to skip the address tests. However, such performance optimization must be restricted to peers that are known to be trustworthy and capable of protecting themselves from malicious software.

12.3. HITs used in ACLs

At end-hosts, HITs can be used in IP-based access control lists at the application and network layers. At middleboxes, HIP-aware firewalls [[lindqvist-enterprise](#)] can use HITs or public keys to control both ingress and egress access to networks or individual hosts, even in the presence of mobile devices because the HITs and public keys are topologically independent. As discussed earlier in [Section 7](#), once a HIP session has been established, the SPI value in an ESP packet may be used as an index, indicating the HITs. In practice, firewalls can inspect HIP packets to learn of the bindings between HITs, SPI values, and IP addresses. They can even explicitly control ESP usage, dynamically opening ESP only for specific SPI values and IP addresses. The signatures in HIP packets allow a capable firewall to ensure that the HIP exchange is indeed occurring between two known hosts. This may increase firewall security.

A potential drawback of HITs in ACLs is their 'flatness' means they cannot be aggregated, and this could potentially result in larger table searches in HIP-aware firewalls. A way to optimize this could be to utilize Bloom filters for grouping of HITs [[sarela-bloom](#)]. However, it should be noted that it is also easier to exclude individual, misbehaving hosts out when the firewall rules concern individual HITs rather than groups.

There has been considerable bad experience with distributed ACLs that contain public key related material, for example, with SSH. If the owner of a key needs to revoke it for any reason, the task of finding all locations where the key is held in an ACL may be impossible. If the reason for the revocation is due to private key theft, this could be a serious issue.

A host can keep track of all of its partners that might use its HIT in an ACL by logging all remote HITs. It should only be necessary to log responder hosts. With this information, the host can notify the various hosts about the change to the HIT. There have been attempts to develop a secure method to issue the HIT revocation notice [[zhang-revocation](#)].

Some of the HIP-aware middleboxes, such as firewalls [[lindqvist-enterprise](#)] or NATs [[ylitalo-spinat](#)], may observe the on-path traffic passively. Such middleboxes are transparent by their nature and may not get a notification when a host moves to a different network. Thus, such middleboxes should maintain soft state and timeout when the control and data plane between two HIP end-hosts has been idle too long. Correspondingly, the two end-hosts may send periodically keepalives, such as UPDATE packets or ICMP messages inside the ESP tunnel, to sustain state at the on-path middleboxes.

One general limitation related to end-to-end encryption is that middleboxes may not be able to participate to the protection of data flows. While the issue may affect also other protocols, Heer et al [[heer-end-host](#)] have analyzed the problem in the context of HIP. More specifically, when ESP is used as the data-plane protocol for HIP, the association between the control and data plane is weak and can be exploited under certain assumptions. In the scenario, the attacker has already gained access to the target network protected by a HIP-aware firewall, but wants to circumvent the HIP-based firewall. To achieve this, the attacker passively observes a base exchange between two HIP hosts and later replays it. This way, the attacker manages to penetrate the firewall and can use a fake ESP tunnel to transport its own data. This is possible because the firewall cannot distinguish when the ESP tunnel is valid. As a solution, HIP-aware middleboxes may participate to the control plane interaction by adding random nonce parameters to the control traffic, which the end-hosts have to sign to guarantee the freshness of the control traffic [[heer-midauth](#)]. As an alternative, extensions for transporting data plane directly over the control plane can be used [[RFC6078](#)].

12.4. Alternative HI considerations

The definition of the Host Identifier states that the HI need not be a public key. It implies that the HI could be any value; for example a FQDN. This document does not describe how to support such a non-cryptographic HI, but examples of such protocol variants do exist ([[urien-rfid](#)], [[urien-rfid-draft](#)]). A non-cryptographic HI would still offer the services of the HIT or LSI for NAT traversal. It would be possible to carry HITs in HIP packets that had neither privacy nor authentication. Such schemes may be employed for resource constrained devices, such as small sensors operating on battery power, but are not further analyzed here.

If it is desirable to use HIP in a low security situation where public key computations are considered expensive, HIP can be used with very short Diffie-Hellman and Host Identity keys. Such use makes the participating hosts vulnerable to MitM and connection hijacking attacks. However, it does not cause flooding dangers,

since the address check mechanism relies on the routing system and not on cryptographic strength.

13. IANA considerations

This document has no actions for IANA.

14. Acknowledgments

For the people historically involved in the early stages of HIP, see the Acknowledgments section in the Host Identity Protocol specification.

During the later stages of this document, when the editing baton was transferred to Pekka Nikander, the comments from the early implementers and others, including Jari Arkko, Tom Henderson, Petri Jokela, Miika Komu, Mika Kousa, Andrew McGregor, Jan Melen, Tim Shepard, Jukka Ylitalo, Sasu Tarkoma, and Jorma Wall, were invaluable. Also, the comments from Lars Eggert, Spencer Dawkins and Dave Crocker were also useful.

The authors want to express their special thanks to Tom Henderson, who took the burden of editing the document in response to IESG comments at the time when both of the authors were busy doing other things. Without his perseverance original document might have never made it as [RFC4423](#).

This main effort to update and move HIP forward within the IETF process owes its impetus to a number of HIP development teams. The authors are grateful for Boeing, Helsinki Institute for Information Technology (HIIT), NomadicLab of Ericsson, and the three universities: RWTH Aachen, Aalto and University of Helsinki, for their efforts. Without their collective efforts HIP would have withered as on the IETF vine as a nice concept.

Thanks also for Suvi Koskinen for her help with proofreading and with the reference jungle.

15. Changes from [RFC 4423](#)

In a nutshell, the changes from [RFC 4423](#) [[RFC4423](#)] are mostly editorial, including clarifications on topics described in a difficult way and omitting some of the non-architectural (implementation) details that are already described in other documents. A number of missing references to the literature were also added. New topics include the drawbacks of HIP, discussion on 802.15.4 and MAC security, HIP for IoT scenarios, deployment considerations and description of the base exchange.

16. References

16.1. Normative References

- [I-D.ietf-hip-dex] Moskowitz, R. and R. Hummen, "HIP Diet EXchange (DEX)", [draft-ietf-hip-dex-05](#) (work in progress), February 2017.
- [I-D.ietf-hip-native-nat-traversal] Keranen, A., Melen, J., and M. Komu, "Native NAT Traversal Mode for the Host Identity Protocol", [draft-ietf-hip-native-nat-traversal-23](#) (work in progress), November 2017.
- [RFC5482] Eggert, L. and F. Gont, "TCP User Timeout Option", [RFC 5482](#), DOI 10.17487/RFC5482, March 2009, <<https://www.rfc-editor.org/info/rfc5482>>.
- [RFC7343] Laganier, J. and F. Dupont, "An IPv6 Prefix for Overlay Routable Cryptographic Hash Identifiers Version 2 (ORCHIDv2)", [RFC 7343](#), DOI 10.17487/RFC7343, September 2014, <<https://www.rfc-editor.org/info/rfc7343>>.
- [RFC7401] Moskowitz, R., Ed., Heer, T., Jokela, P., and T. Henderson, "Host Identity Protocol Version 2 (HIPv2)", [RFC 7401](#), DOI 10.17487/RFC7401, April 2015, <<https://www.rfc-editor.org/info/rfc7401>>.
- [RFC7402] Jokela, P., Moskowitz, R., and J. Melen, "Using the Encapsulating Security Payload (ESP) Transport Format with the Host Identity Protocol (HIP)", [RFC 7402](#), DOI 10.17487/RFC7402, April 2015, <<https://www.rfc-editor.org/info/rfc7402>>.
- [RFC8002] Heer, T. and S. Varjonen, "Host Identity Protocol Certificates", [RFC 8002](#), DOI 10.17487/RFC8002, October 2016, <<https://www.rfc-editor.org/info/rfc8002>>.
- [RFC8003] Laganier, J. and L. Eggert, "Host Identity Protocol (HIP) Registration Extension", [RFC 8003](#), DOI 10.17487/RFC8003, October 2016, <<https://www.rfc-editor.org/info/rfc8003>>.
- [RFC8004] Laganier, J. and L. Eggert, "Host Identity Protocol (HIP) Rendezvous Extension", [RFC 8004](#), DOI 10.17487/RFC8004, October 2016, <<https://www.rfc-editor.org/info/rfc8004>>.
- [RFC8005] Laganier, J., "Host Identity Protocol (HIP) Domain Name System (DNS) Extension", [RFC 8005](#), DOI 10.17487/RFC8005, October 2016, <<https://www.rfc-editor.org/info/rfc8005>>.

[RFC8046] Henderson, T., Ed., Vogt, C., and J. Arkko, "Host Mobility with the Host Identity Protocol", [RFC 8046](#), DOI 10.17487/RFC8046, February 2017, <<https://www.rfc-editor.org/info/rfc8046>>.

[RFC8047] Henderson, T., Ed., Vogt, C., and J. Arkko, "Host Multihoming with the Host Identity Protocol", [RFC 8047](#), DOI 10.17487/RFC8047, February 2017, <<https://www.rfc-editor.org/info/rfc8047>>.

16.2. Informative references

[amir-hip]

Amir, K., Forsgren, H., Grahm, K., Karvi, T., and G. Pulkkis, "Security and Trust of Public Key Cryptography for HIP and HIP Multicast", International Journal of Dependable and Trustworthy Information Systems (IJDTIS), 2(3), 17-35, DOI: 10.4018/jdtis.2011070102, 2013.

[aura-dos]

Aura, T., Nikander, P., and J. Leiwo, "DOS-resistant Authentication with Client Puzzles", 8th International Workshop on Security Protocols, pages 170-177. Springer, , April 2001.

[beal-dos]

Beal, J. and T. Shephard, "Deamplification of DoS Attacks via Puzzles", , October 2004.

[chiappa-endpoints]

Chiappa, J., "Endpoints and Endpoint Names: A Proposed Enhancement to the Internet Architecture", URL <http://www.chiappa.net/~jnc/tech/endpoints.txt>, 1999.

[heer-end-host]

Heer, T., Hummen, R., Komu, M., Goetz, S., and K. Wehre, "End-host Authentication and Authorization for Middleboxes based on a Cryptographic Namespace", ICC2009 Communication and Information Systems Security Symposium, , 2009.

[heer-midauth]

Heer, T. and M. Komu, "End-Host Authentication for HIP Middleboxes", Working draft [draft-heer-hip-middle-auth-02](#), September 2009.

[henderson-vpls]

Henderson, T. and D. Mattes, "HIP-based Virtual Private LAN Service (HIPLS)", Working draft [draft-henderson-hip-vpls-07](#), Dec 2013.

[hip-srtp]

Tschofenig, H., Muenz, F., and M. Shanmugam, "Using SRTP transport format with HIP", Working draft [draft-tschofenig-hiprg-hip-srtp-01](#), October 2005.

[hummen]

Hummen, R., Hiller, J., Henze, M., and K. Wehrle, "Slimfit - A HIP DEX Compression Layer for the IP-based Internet of Things", Wireless and Mobile Computing, Networking and Communications (WiMob), 2013 IEEE 9th International Conference on , page 259-266. DOI: 10.1109/WiMOB.2013.6673370, October 2013.

[IEEE.802-15-4.2011]

"Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs)", IEEE Standard 802.15.4, September 2011, <<http://standards.ieee.org/getieee802/download/802.15.4-2011.pdf>>.

[IEEE.802-15-9]

"IEEE Draft Recommended Practice for Transport of Key Management Protocol (KMP) Datagrams", IEEE P802.15.9/D04, May 2015.

[karvonen-usable]

Karvonen, K., Komu, M., and A. Gurtov, "Usable Security Management with Host Identity Protocol", 7th ACS/IEEE International Conference on Computer Systems and Applications, (AICCSA-2009), 2009.

[komu-cloud]

Komu, M., Sethi, M., Mallavarapu, R., Oirola, H., Khan, R., and S. Tarkoma, "Secure Networking for Virtual Machines in the Cloud", International Workshop on Power and QoS Aware Computing (PQoSCom2012), IEEE, ISBN: 978-1-4244-8567-3, September 2012.

[komu-diss]

Komu, M., "A Consolidated Namespace for Network Applications, Developers, Administrators and Users", Dissertation, Aalto University, Espoo, Finland ISBN: 978-952-60-4904-5 (printed), ISBN: 978-952-60-4905-2 (electronic). , December 2012.

[komu-leap]

Komu, M. and J. Lindqvist, "Leap-of-Faith Security is Enough for IP Mobility", 6th Annual IEEE Consumer Communications and Networking Conference IEEE CCNC 2009, Las Vegas, Nevada, , January 2009.

[komu-mitigation]

Komu, M., Tarkoma, S., and A. Lukyanenko, "Mitigation of Unsolicited Traffic Across Domains with Host Identities and Puzzles", 15th Nordic Conference on Secure IT Systems (NordSec 2010), Springer Lecture Notes in Computer Science, Volume 7127, pp. 33-48, ISBN: 978-3-642-27936-2, October 2010.

[kovacshazi-host]

Kovacshazi, Z. and R. Vida, "Host Identity Specific Multicast", International conference on Networking and Services (ICNS'06), IEEE Computer Society, Los Alamitos, CA, USA, <http://doi.ieeecomputersociety.org/10.1109/ICNS.2007.66>, 2007.

[leva-barriers]

Levae, A., Komu, M., and S. Luukkainen, "Adoption Barriers of Network-layer Protocols: the Case of Host Identity Protocol", The International Journal of Computer and Telecommunications Networking, ISSN: 1389-1286, March 2013.

[lindqvist-enterprise]

Lindqvist, J., Vehmersalo, E., Manner, J., and M. Komu, "Enterprise Network Packet Filtering for Mobile Cryptographic Identities", International Journal of Handheld Computing Research, 1 (1), 79-94, , January-March 2010.

[Nik2001]

Nikander, P., "Denial-of-Service, Address Ownership, and Early Authentication in the IPv6 World", in Proceedings of Security Protocols, 9th International Workshop, Cambridge, UK, April 25-27 2001, LNCS 2467, pp. 12-26, Springer, 2002.

[nsrg-report]

Lear, E. and R. Droms, "What's In A Name: Thoughts from the NSRG", [draft-irtf-nsrg-report-10](#) (work in progress), September 2003.

[paine-hip]

Paine, R., "Beyond HIP: The End to Hacking As We Know It", BookSurge Publishing, ISBN: 1439256047, 9781439256046, 2009.

[pham-leap]

Pham, V. and T. Aura, "Security Analysis of Leap-of-Faith Protocols", Seventh ICST International Conference on Security and Privacy for Communication Networks, , September 2011.

[RFC2136] Vixie, P., Ed., Thomson, S., Rekhter, Y., and J. Bound, "Dynamic Updates in the Domain Name System (DNS UPDATE)", [RFC 2136](#), DOI 10.17487/RFC2136, April 1997, <<https://www.rfc-editor.org/info/rfc2136>>.

[RFC2535] Eastlake 3rd, D., "Domain Name System Security Extensions", [RFC 2535](#), DOI 10.17487/RFC2535, March 1999, <<https://www.rfc-editor.org/info/rfc2535>>.

[RFC2766] Tsirtsis, G. and P. Srisuresh, "Network Address Translation - Protocol Translation (NAT-PT)", [RFC 2766](#), DOI 10.17487/RFC2766, February 2000, <<https://www.rfc-editor.org/info/rfc2766>>.

[RFC3022] Srisuresh, P. and K. Egevang, "Traditional IP Network Address Translator (Traditional NAT)", [RFC 3022](#), DOI 10.17487/RFC3022, January 2001, <<https://www.rfc-editor.org/info/rfc3022>>.

[RFC3102] Borella, M., Lo, J., Grabelsky, D., and G. Montenegro, "Realm Specific IP: Framework", [RFC 3102](#), DOI 10.17487/RFC3102, October 2001, <<https://www.rfc-editor.org/info/rfc3102>>.

[RFC3748] Aboba, B., Blunk, L., Vollbrecht, J., Carlson, J., and H. Levkowetz, Ed., "Extensible Authentication Protocol (EAP)", [RFC 3748](#), DOI 10.17487/RFC3748, June 2004, <<https://www.rfc-editor.org/info/rfc3748>>.

- [RFC4225] Nikander, P., Arkko, J., Aura, T., Montenegro, G., and E. Nordmark, "Mobile IP Version 6 Route Optimization Security Design Background", [RFC 4225](#), DOI 10.17487/RFC4225, December 2005, <<https://www.rfc-editor.org/info/rfc4225>>.
- [RFC4306] Kaufman, C., Ed., "Internet Key Exchange (IKEv2) Protocol", [RFC 4306](#), DOI 10.17487/RFC4306, December 2005, <<https://www.rfc-editor.org/info/rfc4306>>.
- [RFC4423] Moskowitz, R. and P. Nikander, "Host Identity Protocol (HIP) Architecture", [RFC 4423](#), DOI 10.17487/RFC4423, May 2006, <<https://www.rfc-editor.org/info/rfc4423>>.
- [RFC5218] Thaler, D. and B. Aboba, "What Makes for a Successful Protocol?", [RFC 5218](#), DOI 10.17487/RFC5218, July 2008, <<https://www.rfc-editor.org/info/rfc5218>>.
- [RFC5338] Henderson, T., Nikander, P., and M. Komu, "Using the Host Identity Protocol with Legacy Applications", [RFC 5338](#), DOI 10.17487/RFC5338, September 2008, <<https://www.rfc-editor.org/info/rfc5338>>.
- [RFC5887] Carpenter, B., Atkinson, R., and H. Flinck, "Renumbering Still Needs Work", [RFC 5887](#), DOI 10.17487/RFC5887, May 2010, <<https://www.rfc-editor.org/info/rfc5887>>.
- [RFC6078] Camarillo, G. and J. Melen, "Host Identity Protocol (HIP) Immediate Carriage and Conveyance of Upper-Layer Protocol Signaling (HICCUPS)", [RFC 6078](#), DOI 10.17487/RFC6078, January 2011, <<https://www.rfc-editor.org/info/rfc6078>>.
- [RFC6250] Thaler, D., "Evolution of the IP Model", [RFC 6250](#), DOI 10.17487/RFC6250, May 2011, <<https://www.rfc-editor.org/info/rfc6250>>.
- [RFC6281] Cheshire, S., Zhu, Z., Wakikawa, R., and L. Zhang, "Understanding Apple's Back to My Mac (BTMM) Service", [RFC 6281](#), DOI 10.17487/RFC6281, June 2011, <<https://www.rfc-editor.org/info/rfc6281>>.
- [RFC6317] Komu, M. and T. Henderson, "Basic Socket Interface Extensions for the Host Identity Protocol (HIP)", [RFC 6317](#), DOI 10.17487/RFC6317, July 2011, <<https://www.rfc-editor.org/info/rfc6317>>.
- [RFC6537] Ahrenholz, J., "Host Identity Protocol Distributed Hash Table Interface", [RFC 6537](#), DOI 10.17487/RFC6537, February 2012, <<https://www.rfc-editor.org/info/rfc6537>>.

[RFC6538] Henderson, T. and A. Gurtov, "The Host Identity Protocol (HIP) Experiment Report", [RFC 6538](#), DOI 10.17487/RFC6538, March 2012, <<https://www.rfc-editor.org/info/rfc6538>>.

[sarela-bloom]

Saerelae, M., Esteve Rothenberg, C., Zahemszky, A., Nikander, P., and J. Ott, "BloomCasting: Security in Bloom filter based multicast", , Lecture Notes in Computer Science 2012, , pages 1-16, Springer Berlin Heidelberg, 2012.

[schuetz-intermittent]

Schuetz, S., Eggert, L., Schmid, S., and M. Brunner, "Protocol enhancements for intermittently connected hosts", SIGCOMM Comput. Commun. Rev., 35(3):5-18, , July 2005.

[shields-hip]

Shields, C. and J. Garcia-Luna-Aceves, "The HIP protocol for hierarchical multicast routing", Proceedings of the seventeenth annual ACM symposium on Principles of distributed computing, pages 257-266. ACM, New York, NY, USA, ISBN: 0-89791-977-7, DOI: 10.1145/277697.277744, 1998.

[tritilanunt-dos]

Tritilanunt, S., Boyd, C., Foo, E., and J. Nieto, "Examining the DoS Resistance of HIP", OTM Workshops (1), volume 4277 of Lecture Notes in Computer Science, pages 616-625, Springer , 2006.

[urien-rfid]

Urien, P., Chabanne, H., Bouet, M., de Cunha, D., Guyot, V., Pujolle, G., Paradinas, P., Gressier, E., and J. Susini, "HIP-based RFID Networking Architecture", IFIP International Conference on Wireless and Optical Communications Networks, DOI: 10.1109/WOCN.2007.4284140, July 2007.

[urien-rfid-draft]

Urien, P., Lee, G., and G. Pujolle, "HIP support for RFIDs", IRTF Working draft [draft-irtf-hiprg-rfid-07](#), April 2013.

[varjonen-split]

Varjonen, S., Komu, M., and A. Gurtov, "Secure and Efficient IPv4/IPv6 Handovers Using Host-Based Identifier-Location Split", Journal of Communications Software and Systems, 6(1), 2010, ISSN: 18456421, 2010.

[xin-hip-lib]

Xin, G., "Host Identity Protocol Version 2.5", Master's Thesis, Aalto University, Espoo, Finland, , June 2012.

[xueyong-hip]

Xueyong, Z., Zhiguo, D., and W. Xinling, "A Multicast Routing Algorithm Applied to HIP-Multicast Model", Proceedings of the 2011 International Conference on Network Computing and Information Security - Volume 01 (NCIS '11), Vol. 1. IEEE Computer Society, Washington, DC, USA, pages 169-174, DOI: 10.1109/NCIS.2011.42, 2011.

[xueyong-secure]

Xueyong, Z. and J. Atwood, "A Secure Multicast Model for Peer-to-Peer and Access Networks Using the Host Identity Protocol", Consumer Communications and Networking Conference. CCNC 2007. 4th IEEE, pages 1098,1102, DOI: 10.1109/CCNC.2007.221, January 2007.

[ylitalo-diss]

Ylitalo, J., "Secure Mobility at Multiple Granularity Levels over Heterogeneous Datacom Networks", Dissertation, Helsinki University of Technology, Espoo, Finland ISBN 978-951-22-9531-9, 2008.

[ylitalo-spinat]

Ylitalo, J., Salmela, P., and H. Tschofenig, "SPINAT: Integrating IPsec into overlay routing", Proceedings of the First International Conference on Security and Privacy for Emerging Areas in Communication Networks (SecureComm 2005). Athens, Greece. IEEE Computer Society, pages 315-326, ISBN: 0-7695-2369-2, September 2005.

[zhang-revocation]

Zhang, D., Kuptsov, D., and S. Shen, "Host Identifier Revocation in HIP", IRTF Working draft [draft-irtf-hiprg-revocation-05](#), Mar 2012.

Authors' Addresses

Robert Moskowitz (editor)
HTT Consulting
Oak Park
Michigan
USA

Email: rgm@labs.htt-consult.com

Miika Komu
Ericsson
Hirsalantie 11
02420 Jorvas
Finland

Email: miika.komu@ericsson.com

