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Teredo: Tunneling IPv6 over UDP through NATs

Status of this memo

Abstract

We propose here a service that enables nodes located behind one or more IPv4 NATs to obtain IPv6 connectivity by tunneling packets over UDP; we call this the Teredo service. Running the service requires the help of "Teredo servers" and "Teredo relays"; the Teredo servers are stateless, and only have to manage a small fraction of the traffic between Teredo clients; the Teredo relays act as IPv6 routers between the Teredo service and the "native" IPv6 Internet; the relays can also provide interoperability with hosts using other transition mechanisms such as "6to4".

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1 Introduction

Classic tunneling methods envisaged for IPv6 transition operate by sending IPv6 packets as payload of IPv4 packets; the 6to4 proposal [RFC3056] proposes automatic discovery in this context. A problem with these methods is that they don't work when the IPv6 candidate node is isolated behind a Network Address Translator (NAT) device: NATs are typically not programmed to allow the transmission of arbitrary payload types; even when they are, the local address cannot be used in a 6to4 scheme. 6to4 will work with a NAT if the NAT and 6to4 router functions are in the same box; we want to cover the relatively frequent case when the NAT cannot be readily upgraded to provide a 6to4 router function.

A possible way to solve the problem is to rely on a set of "tunnel brokers." There are however limits to any solution that is based on such brokers: the quality of service may be limited, since the traffic follows a "dog leg" route from the source to the broker and then the destination; the broker has to provide sufficient transmission capacity to relay all packets and thus suffers a high cost. For these two reasons, it may be desirable to have solutions that allow for "automatic tunneling", i.e. let the packets follow a direct path to the destination.

The automatic tunneling requirement is indeed at odds with some of the specificities of NATs. Establishing a direct path supposes that the IPv6 candidate node can retrieve a "globally routable" address that results from the translation of its local address by one or more NATs; it also supposes that we can find a way to bypass the various "per destination protections" that many NATs implement. In this memo, we will explain how IPv6 candidates located behind NATs use "Teredo servers" to learn their "global address" and to obtain connectivity, exchange packets with native IPv6 hosts through "Teredo relays", and how clients, servers and relays can be organized in Teredo networks.

The specification is organized as follows. Section 2 contains the definition of the terms used in the memo. Section 3 presents the hypotheses on NAT behavior used in the design, as well as the operational requirements that the design should meet. Section 4 presents the IPv6 address format used by Teredo. Section 5 contains the format of the messages and the specification of the protocol. Section 6 presents guidelines for further work on configured tunnels that would be complementary to the current approach. Section 7 contains a security discussion, section 8 a discussion of the so called "UNSAF" issues, and section 9 contains IANA considerations.

2 Definitions

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

This specification uses the following definitions:

2.1 Teredo service

The transmission of IPv6 packets over UDP, as defined in this memo.

2.2 Teredo Client

A node that has some access to the IPv4 Internet and wants to gain access to the IPv6 Internet.

2.3 Teredo Server

A node that has access to the IPv4 Internet through a globally routable address, and is used as a helper to provide IPv6 connectivity to Teredo clients.

2.4 Teredo Relay

An IPv6 router that can receive traffic destined to Teredo clients and forward it using the Teredo service.

2.5 Teredo IPv6 service prefix

An IPv6 addressing prefix which is used to construct the IPv6 address of Teredo clients.

2.6 Global Teredo IPv6 service prefix

An IPv6 addressing prefix whose value is XXXX:XXXX:/32.
(TBD IANA; experiments use the value 3FFE:831F::/32, taken from a

range of experimental IPv6 prefixes assigned to Microsoft.)

2.7 Teredo UDP port

The UDP port number at which Teredo Servers are waiting for packets. The value of this port is 3544.

2.8 Teredo bubble

A Teredo bubble is a minimal IPv6 packet, made of an IPv6 header and a null payload - the payload type is set to 59, No Next Header, as per [RFC2460]. The Teredo clients and relays may send bubbles in order to create a mapping in a NAT.

2.9 Teredo service port

The port from which the Teredo client sends Teredo packets. This port is attached to one of the client's IPv4 addresses. The IPv4 address may or may not be globally routable, as the client may be located behind one or more NAT.

2.10 Teredo server address

The IPv4 address of the Teredo server selected by a particular client.

2.11 Teredo mapped address and Teredo mapped port

A global IPv4 address and a UDP port that results from the translation of the IPv4 address and UDP port of a client's Teredo service port by one or more NATs. The client learns these values through the Teredo protocol described in this memo.

2.12 Teredo IPv6 client prefix

A global scope IPv6 prefix composed of the Teredo IPv6 service prefix and the Teredo server address.

2.13 Teredo node identifier

A 64 bit identifier that contains the UDP port and IPv4 address at which a client can be reached through the Teredo service, as well as a flag indicating the type of NAT through which the client accesses the IPv4 Internet.

2.14 Teredo IPv6 address

A Teredo IPv6 address obtained by combining a Teredo IPv6 client

prefix and a Teredo node identifier.

2.15 Teredo Refresh Interval

The interval during which a Teredo IPv6 Address is expected to remain valid in the absence of "refresh" traffic. For a client located behind a NAT, the interval depends on configuration parameters of the local NAT, or the combination of NATs in the path to the Teredo server. By default, clients assume an interval value of 30 seconds; a longer value may be determined by local tests, as described in section 5.

2.16 Teredo secondary port

A UDP port used to send or receive packets in order to determine the appropriate value of the refresh interval, but not used to carry any Teredo traffic.

2.17 Teredo IPv4 Discovery Address

An IPv4 multicast address used to discover other Teredo clients on the same IPv4 subnet. The value of this address is X.X.X.X. (TBD IANA; experiments use the value 224.0.0.252.)

3 Design goals, requirements, and model of operation

The proposed solution transports IPv6 packets as the payload of UDP packets. This is based on the observation that TCP and UDP are the only protocols guaranteed to cross the majority of NAT devices. Tunneling packets over TCP would be possible, but would result in a poor quality of service; encapsulation over UDP is a better choice.

The design of our solution is based on a set of hypotheses and observations on the behavior of NATs, our desire to provide an "IPv6 provider of last resort", and a list of operational requirements. It results in a model of operation in which the Teredo service is enabled by a set of servers and relays.

3.1 Hypotheses about NAT behavior

NAT devices typically incorporate some support for UDP, in order to enable users in the natted domain to use UDP based applications. The NAT will typically allocate a "mapping" when it sees a UDP packet coming through for which there is not yet an existing mapping. The handling of UDP "sessions" by NAT devices differs by two important parameters, the type and the duration of the mappings.

The type of mappings is analyzed in [RFC3489], which distinguishes between "Cone NAT", "restricted cone NAT", "port restricted cone NAT" and "symmetric NAT". The Teredo solution ensures connectivity for clients located behind cone NATs, restricted cone NATs or port-restricted cone NATs.

Transmission of regular IPv6 packets only takes places after an exchange of "bubbles" between the parties. This exchange would often fail for clients behind symmetric NAT, because their peer cannot predict the UDP port number that the NAT expect.
Clients located behind a symmetric NAT will only be able to use Teredo if they can somehow program the NAT and reserve a Teredo service port for each client, for example using the DMZ functions of the NAT. This is obviously an onerous requirement, at odds with the design goal of an automatic solution. However, measurement campaigns and studies of documentations have shown that, at least in simple "unmanaged" networks, symmetric NATs are a small minority; moreover, it seems that new NAT models or firmware upgrades avoid the "symmetric" design.

Investigations on the performance of [RFC3489] have shown the relative frequency of a particular NAT design, which we might call "port conserving". In this design, the NAT tries to keep the same port number inside and outside, unless the "outside" port number is already in use for another mapping with the same host. Port conserving NAT appear as "cone" or "restricted cone NAT" most of the time, but they will behave as "symmetric NAT" when multiple internal hosts use the same port number to communicate to the same server.

The Teredo design minimizes the risk of encountering the "symmetric" behavior by asking multiple hosts located behind the same NAT to use different Teredo service ports.

Other investigation in the behavior of NAT also outlined the "probabilistic rewrite" behavior. Some brands of NAT will examine all packets for "embedded addresses", IP addresses and port numbers present in application payloads. They will systematically replace 32 bits value that match a local address by the corresponding mapped address. The Teredo specification includes an "obfuscation" procedure in order to avoid this behavior.

Regardless of their types, UDP mappings are not kept forever. The typical algorithm is to remove the mapping if no traffic is observed on the specified port for a "lifetime" period. The Teredo client that wants to maintain a mapping open in the NAT will have to send some "keep alive" traffic before the lifetime expires. For that, it needs an estimate of the "lifetime" parameter used in the NAT. We

observed that the implementation of lifetime control can vary in several ways.

Most NATs implement a "minimum lifetime" which is set as a parameter of the implementation. Our observations of various boxes showed that this parameter can vary between about 45 seconds and several minutes.

In many NATs, mappings can be kept for a duration that exceeds this minimum, even in the absence of traffic. We suspect that many implementation perform "garbage collection" of unused mappings on special events, e.g. when the overall number of mappings exceeds some limit.

In some cases, e.g. NATs that manage ISDN or dial-up connections, the mappings will be released when the connection is released, i.e. when no traffic is observed on the connection for a period of a few minutes.

Any algorithm used to estimate the lifetime of mapping will have to be robust against these variations.

In some cases, clients are located behind multiple NAT. The Teredo procedures will ensure communications between clients between multiple NATs and clients "on the other side" of these NAT. They will also ensure communication when clients are located in a single subnet behind the same NAT.

The procedures do not make any hypothesis about the type of IPv4 address used behind a NAT, and in particular do not assume that these are private addresses defined in [RFC1918].

3.2 IPv6 provider of last resort

Teredo is designed to provide an "IPv6 access of last resort" to nodes that need IPv6 connectivity but cannot use any of the other IPv6 transition schemes. This design objective has several consequences on when to use Teredo, how to program clients, and what to expect of servers. Another consequence is that we expect to see a point in time at which the Teredo technology ceases to be used.

3.2.1 When to use Teredo?

Teredo is designed to robustly enable IPv6 traffic through NATs, and the price of robustness is a reasonable amount of overhead, due to UDP encapsulation and transmission of bubbles. Nodes that want to connect to the IPv6 Internet SHOULD only use the Teredo service as a

"last resort" option: they SHOULD prefer using direct IPv6 connectivity if it is locally available, if it is provided by a 6to4 router co-located with the local NAT, or if it is provided by a configured tunnel service; and they SHOULD prefer using the less onerous "6to4" encapsulation if they can use a global IPv4 address.

3.2.2 Autonomous deployment

In an IPv6-enabled network, the IPv6 service is configured automatically, by using mechanisms such as IPv6 Stateless Address Autoconfiguration [RFC2462] and Neighbor Discovery [RFC2461]. A design objective is to configure the Teredo service as automatically as possible. In practice, it is however required that the client learn the IPv4 address of a server that is willing to serve them; some servers may also require some form of access control.

3.2.3 Minimal load on servers

During the peak of the transition, there will be a requirement to deploy Teredo servers supporting a large number of Teredo clients. Minimizing the load on the server is a good way to facilitate this deployment. To achieve this goal, servers should be as stateless as possible, and they should also not be required to carry any more traffic than necessary. To achieve this objective, we require only that servers enable the packet exchange between clients, but we don't require servers to carry the actual data packets: these packets will have to be exchanged directly between the Teredo clients, or through a destination-selected relay for exchanges between Teredo clients and other IPv6 clients.

3.2.4 Automatic sunset

Teredo is meant as a short-term solution to the specific problem of providing IPv6 service to nodes located behind a NAT. The problem is expected to be resolved over time by transforming the "IPv4 NAT" into an "IPv6 router". This can be done in one of two ways: upgrading the NAT to provide 6to4 functions, or upgrading the Internet connection used by the NAT to a native IPv6 service, and then adding IPv6 router functionality in the NAT. In either case,

the former NAT can present itself as an IPv6 router to the systems behind it. These systems will start receiving the "router advertisements"; they will notice that they have IPv6 connectivity, and will stop using Teredo.

3.3 Operational Requirements

3.3.1 Robustness requirement

The Teredo service is designed primarily for robustness: packets are carried over UDP in order to cross as many NAT implementations as possible. The servers are designed to be stateless, which means that they can easily be replicated. We expect indeed to find many such servers replicated at multiple Internet locations.

3.3.2 Minimal support cost

The service requires the support of Teredo servers and Teredo relays. In order to facilitate the deployment of these servers and relays, the Teredo procedures are designed to minimize the amount of coordination required between servers and relays.

Meeting this objective implies that the Teredo addresses will incorporate the IPv4 address and UDP port through which a Teredo client can be reached. This creates an implicit limit on the stability of the Teredo addresses, which can only remain valid as long as the underlying IPv4 address and UDP port remains valid.

3.3.3 Protection against denial of service attacks

The Teredo clients obtain mapped addresses and ports from the Teredo servers. The service must be protected against denial of service attacks in which a third party spoofs a Teredo server and sends improper information to the client.

3.3.4 Protection against distributed denial of service attacks

Teredo relays will act as a relay for IPv6 packets. Improperly designed packet relays can be used by denial of service attackers to hide their address, making the attack untraceable. The Teredo service must include adequate protection against such misuse.

3.3.5 Compatibility with ingress filtering

Routers may perform ingress filtering by checking that the source address of the packets received on a given interface is "legitimate", i.e. belongs to network prefixes from which traffic is expected at a network interface. Ingress filtering is a recommended practice, as it thwarts the use of forged source IP addresses by malfeasant hackers, notably to cover their tracks during denial of service attacks. The Teredo specification must not force networks to disable ingress filtering.

3.4 Model of operation

The operation of Teredo involves four types of nodes: Teredo clients, Teredo servers, Teredo relays, and "plain" IPv6 nodes.

Teredo clients start operation by interacting with a Teredo server, performing a "qualification procedure". During this procedure, the client will discover whether it is behind a cone, restricted cone or symmetric NAT. If the client is not located behind a symmetric NAT, the procedure will be successful and the client will configure a "Teredo address".

The Teredo IPv6 address embeds the "mapped address and port" through which the client can receive IPv4/UDP packets encapsulating IPv6 packets. If the client is not located behind a cone NAT, transmission of regular IPv6 packets must be preceded by an exchange of "bubbles" that will install a mapping in the NAT. This document specifies how the bubbles can be exchanged between Teredo clients in order to enable transmission along a direct path.

Teredo clients can exchange IPv6 packets with plain IPv6 nodes (e.g. native nodes or 6to4 nodes) through Teredo relays. Teredo relays advertise reachability of the Teredo prefix to a certain subset of the IPv6 Internet: a relay set up by an ISP will typically serve only the IPv6 customers of this ISP; a relay set-up for a site will only serve the IPv6 hosts of this site. Dual-stack hosts may implement a "local relay", allowing them to communicate directly with Teredo hosts by sending IPv6 packets over UDP and IPv4 without having to advertise a Teredo IPv6 address.

Teredo clients have to discover the relay that is closest to each native IPv6 or 6to4 peer. They have to perform this discovery for each native IPv6 or 6to4 peer with which they communicate. In order to prevent spoofing, the Teredo clients perform a relay discovery procedure by sending an ICMP echo request to the native host. This message is a regularly formatted IPv6 ICMP packet, which is encapsulated in UDP and sent by te client to its Teredo server; the server decapsulates the IPv6 message and forwards it to the intended IPv6 destination. The payload of the echo request contains a large random number. The echo reply is sent by the peer to the IPv6 address of the client, and is forwarded through standard IPv6 routing mechanisms. It will naturally reach the Teredo relay closest to the native or 6to4 peer, and will be forwarded by this relay using the Teredo mechanisms. The Teredo client will discover the IPv4 address and UDP port used by the relay to send the echo reply, and will send further IPv6 packets to the peer by encapsulating them in UDP packets sent to this IPv4 address and port. In order to prevent spoofing, the Teredo client verifies that the payload of the echo reply contains the proper random number.

The procedures are designed so that the Teredo server only

participates in the qualification procedure and in the exchange of bubbles and ICMP echo requests. The Teredo server never carries actual data traffic. There are two rationales for this design: reduce the load on the server in order to enable scaling; and avoid privacy issues that could occur if a Teredo server kept copies of the client's data packets.

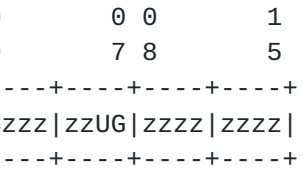
4 Teredo Addresses

The Teredo addresses are composed of 5 components:

- Prefix: the 32 bit Teredo service prefix.
- Server IPv4: the IPv4 address of a Teredo server.
- Flags: a set of 16 bits that document type of address and NAT.
- Port: the obfuscated "mapped UDP port" of the Teredo service at the client
- Client IPv4: the obfuscated "mapped IPv4 address" of the client

In this format, both the "mapped UDP port" and "mapped IPv4 address" of the client are obfuscated. Each bit in the address and port number is reversed; this can be done by an exclusive OR of the 16-bit port number with the hexadecimal value 0xFFFF, and an exclusive OR of the 32-bit address with the hexadecimal value 0xFFFFFFFF.

The IPv6 addressing rules specify that "for all unicast addresses, except those that start with binary value 000, Interface IDs are required to be 64 bits long and to be constructed in Modified EUI-64 format." This dictates the encoding of the flags, 16 intermediate bits which should correspond to valid values of the most significant 16 bits of a Modified EUI-64 ID:



In this format:

- The bits "UG" should be set to the value "00", indicating a non-global unicast identifier;
- The bit "C" (cone) should be set to 1 if the client believes it is behind a cone NAT, to 0 otherwise; these values determine different server behavior during the qualification procedure, as specified in section 5.2.1, as well as different bubble processing

by clients and relays.

- The bits indicated with "z" must be set to sent as zero and

ignored on receipt.

There are thus two currently specified values of the Flags field: "0x0000" (all null) if the cone bit is set to 0, and "0x8000" if the cone bit is set to 1. (Further versions of this specification may assign new values to the reserved bits.)

In some cases, Teredo nodes use link-local addresses. These addresses contain a link local prefix (FE80::/64) and a 64 bit identifier, constructed using the same format as presented above. A difference between link-local addresses and global addresses is that the identifiers used in global addresses MUST include a global scope unicast IPv4 address, while the identifiers used in link-local addresses MAY include a private IPv4 address.

5 Specification of clients, servers and relays

The Teredo service is realized by having clients interact with Teredo servers through the Teredo service protocol. The clients will also receive IPv6 packets through Teredo relays. The client behavior is specified in section 5.2.

The Teredo server is designed to be stateless. It waits for Teredo requests and for IPv6 packets on the Teredo UDP port; it processes the requests by sending a response to the appropriate address and port; it forwards some Teredo IPv6 packets to the appropriate IPv4 address and UDP port, or to native IPv6 peers of Teredo clients. The precise behavior of the server is specified in section 5.3.

The Teredo relay advertises reachability of the Teredo service prefix over IPv6. The scope of advertisement may be the entire Internet, or a smaller subset such as an ISP network or an IPv6 site; it may even be as small as a single host in the case of "local relays". The relay forwards Teredo IPv6 packets to the appropriate IPv4 address and UDP port. The relay behavior is specified in section 5.3.

Teredo clients, servers and relays must implement the sunset procedure defined in section 5.5.

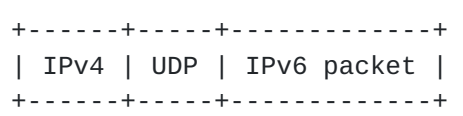
5.1 Message formats

5.1.1 Teredo IPv6 packet encapsulation

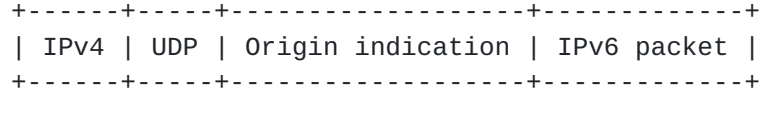
Teredo IPv6 packets are transmitted as UDP packets [RFC768] within IPv4 [RFC791]. The source and destination IP addresses and UDP ports take values that are specified in this section. Packets can come in one of two formats, simple encapsulation and encapsulation

with origin indication.

When simple encapsulation is used, the packet will have a simple format, in which the IPv6 packet is carried as the payload of a UDP datagram:



When relaying some packets received from third parties, the server may insert an origin indication in the first bytes of the UDP payload:



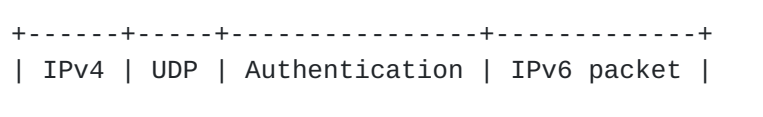
The origin indication encapsulation is an 8-octet element, with the following content:

The first two octets of the origin indication are set to a null value; this is used to discriminate between the simple encapsulation, in which the first 4 bits of the packet contain the indication of the IPv6 protocol, and the origin indication.

The following 16 bits contain the obfuscated value of the port number from which the packet was received, in network byte order. The next 32 bits contain the obfuscated IPv4 address from which the packet was received, in network byte order. In this format, both the original "IPv4 address" and "UDP port" of the client are obfuscated. Each bit in the address and port number is reversed; this can be done by an exclusive OR of the 16-bit port number with the hexadecimal value 0xFFFF, and an exclusive OR of the 32-bit address with the hexadecimal value 0xFFFFFFFF.

For example, if the original UDP port number was 337 (hexadecimal 0151) and original IPv4 address was 1.2.3.4 (hexadecimal: 01020304), the origin indication would contain the value "0000FEAEFEFDFCFB".

When exchanging Router Solicitation and Router Advertisement messages between a client and its server, the packets may include an authentication parameter:



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  +------+-----+----------------+-------------+
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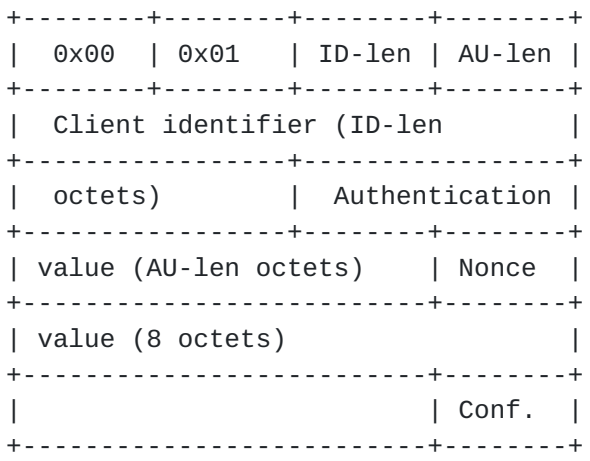
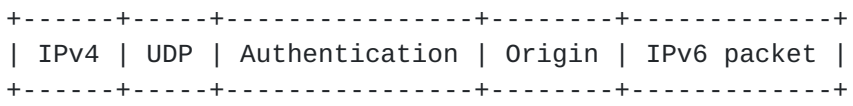
The authentication encapsulation is a variable length-element, containing a client identifier, an authentication value, a nonce value, and a confirmation byte.



The first octet of the authentication encapsulation is set to a null value, and the second octet is set to the value 1; this enables differentiation from IPv6 packets and from origin information indication encapsulation. The third octet indicates the length in bytes of the client identifier; the fourth octet indicates the length in bytes of the authentication value. The computation of the authentication value is specified in section 5.2.2. The authentication value is followed by an 8-octet nonce, and by a confirmation byte.

Both ID-len and AU-len can be set to null values if the server does not require an explicit authentication of the client.

Authentication and origin indication encapsulations may sometimes be combined, for example in the RA responses sent by the server. In this case, the authentication encapsulation MUST be the first element in the UDP payload:



5.1.2 Maximum Transmission Unit

Since Teredo uses UDP as an underlying transport, a Teredo Maximum Transmission Unit (MTU) could potentially be as large as the payload of the largest valid UDP datagram (65507 bytes). However, since Teredo packets can travel on unpredictable paths over the Internet, it is best to contain this MTU to a small size, in order to minimize the effect of IPv4 packet fragmentation and reassembly.

The default link MTU assumed by a host, and the link MTU supplied by a Teredo server during router advertisement SHOULD normally be set to the minimum IPv6 MTU size of 1280 bytes [RFC2460].

Teredo implementations SHOULD NOT set the Don't Fragment (DF) bit of the encapsulating IPv4 header.

5.2 Teredo Client specification

Before using the Teredo service, the client must be configured with:

- the IPv4 address of a server.
- a secondary IPv4 address of that server.

If secure discovery is required, the client must also be configured with:

- a client identifier,
- a secret value, shared with the server,
- an authentication algorithm, shared with the server.

A Teredo client expects to exchange IPv6 packets through a UDP port, the Teredo service port. To avoid problems when operating behind a "port conserving" NAT, different clients operating behind the same NAT should use different service port numbers. This can be achieved through explicit configuration or, in the absence of configuration, by picking the service port number at random.

The client will maintain the following variables that reflect the state of the Teredo service:

- Teredo connectivity status,
- Mapped address and port number associated with the Teredo service port,
- Teredo IPv6 prefix associated with the Teredo service port,
- Teredo IPv6 address or addresses derived from the prefix,
- Link local address,
- Date and time of the last interaction with the Teredo server,
- Teredo Refresh Interval,
- Randomized Refresh Interval,
- List of recent Teredo peers.

Before sending any packets, the client must perform the Teredo qualification procedure, which determines the Teredo connectivity status, the mapped address and port number, and the Teredo IPv6 prefix; it should then perform the cone NAT determination procedure, which determines the cone NAT status and may alter the value of the prefix. If the qualification is successful, the client may use the Teredo service port to transmit and receive IPv6 packets, according to the transmission and reception procedures. These procedures use the "list of recent peers". For each peer, the list contains:

- The IPv6 address of the peer,
- The mapped IPv4 address and mapped UDP port of the peer,

- The status of the mapped address, i.e. trusted or not,

- The value of the last "nonce" sent to the peer,
- The date and time of the last reception from the peer,
- The date and time of the last transmission to the peer,
- The number of bubbles transmitted to the peer.

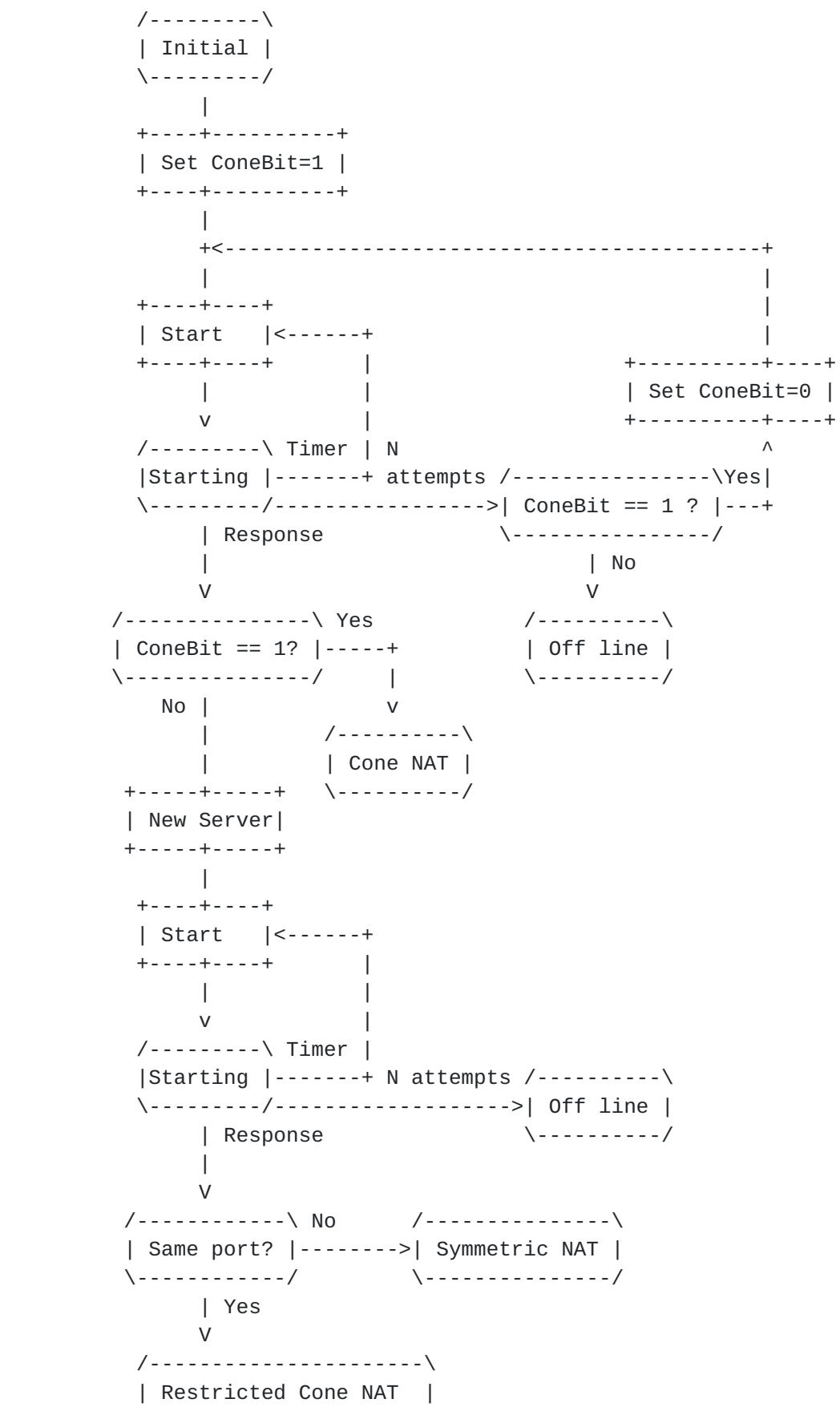
The list of peers is used to enable the transmission of IPv6 packets by using a "direct path" for the IPv6 packets. The list of peers could grow over time. Clients should implement a list management strategy, for example deleting the least recently used entries. Clients should make sure that the list has a sufficient size, to avoid unnecessary exchanges of bubbles.

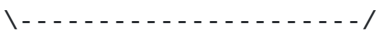
The client must regularly perform the maintenance procedure in order to guarantee that the Teredo service port remains usable; the need to use this procedure or not depends on the delay since the last interaction with the Teredo server. The refresh procedure takes as a parameter the "Teredo refresh interval". This parameter is initially set to 30 seconds; it can be updated as a result of the optional "interval determination procedure." The randomized refresh interval is set to a value randomly chosen between 75% and 100% of the refresh interval.

In order to avoid triangle routing for stations that are located behind the same NAT, the Teredo clients MAY use the optional local client discovery procedure defined in section 5.2.8. Using this procedure will also enhance connectivity when the NAT cannot do "hairpin" routing, i.e. cannot redirect a packet sent from one internal host to the mapped address and port of another internal host.

5.2.1 Qualification procedure

The purpose of the qualification procedure is to establish the status of the local IPv4 connection, and to determine the Teredo IPv6 client prefix of the local Teredo interface. The procedure starts when the service is in the "initial" state, and results in a "qualified" state if successful, and in an "off-line" state if unsuccessful.


Initial
Set ConeBit=1
Start
Timer
Starting
Response
Set ConeBit=0
attempts
ConeBit == 1 ?
Yes
No
ConeBit == 1?
Off line
Cone NAT
New Server
N attempts
Same port?
Symmetric NAT
Restricted Cone NAT



Initially, the Teredo connectivity status is set to "Initial".

When the interface is initialized, the system first performs the "start action" by sending a Router Solicitation message, as defined in [RFC2461]. The client picks a link-local address and uses it as the IPv6 source of the message; the "cone" bit in the address is set to 1 (see section 4 for the address format); the IPv6 destination of the RS is the all-routers multicast address; the packet will be sent over UDP from the service port to the Teredo server's IPv4 address and Teredo UDP port. The connectivity status moves then to "Starting".

In the starting state, the client waits for a router advertisement from the Teredo server. If no response comes within a time-out T, the client should repeat the start action, by resending the Router Solicitation message. If no response has arrived after N repetitions, the client concludes that it is not behind a cone NAT. It sets the "cone" bit to 0, and repeats the procedure. If after N other timer expirations and retransmissions there is still no response, the client concludes that it cannot use UDP, and that the Teredo service is not available; the status is set to "Off-line." In accordance with [RFC2461], the default time-out value is set to T=4 seconds, and the maximum number of repetitions is set to N=3.

If a response arrives, the client checks that the response contains an origin indication and a valid router advertisement as defined in [RFC2461], that the IPv6 destination address is equal to the link-local address used in the router solicitation, and that the router advertisement contains exactly one advertised Prefix Information option. This prefix should be a valid Teredo IPv6 server prefix: the first 32 bits should contain the global Teredo IPv6 service prefix, and the next 32 bits should contain the server's IPv4 address. If this is the case, the client learns the Teredo mapped address and Teredo mapped port from the origin indication. The IPv6 source address of the Router Advertisement is a link-local server address of the Teredo server. (Responses that are not valid advertisements are simply discarded.)

If the client has received an RA with the "Cone" bit in the IPv6 destination address set to 1, it is behind a cone NAT and is fully qualified. If the RA is received with the Cone bit set to 0, the client does not know whether the local NAT is restricted or symmetric. The client selects the secondary IPv4 server address, and repeats the procedure, the cone bit remaining to the value zero. If the client does not receive a response, it detects that the service is not usable. If the client receives a response, it compares the mapped address and mapped port in this second response to the first received values. If the values are different, the client detects a symmetric NAT: it cannot use the Teredo service. If the values are

the same, the client detects a port-restricted or restricted cone NAT: the client is qualified to use the service. (Teredo operates

the same way for restricted and port-restricted NAT.)

If the client is qualified, it builds a Teredo IPv6 address using the Teredo IPv6 server prefix learned from the RA and the obfuscated values of the UDP port and IPv4 address learned from the origin indication. The cone bit should be set to the value used to receive the RA, i.e. 1 if the client is behind a cone NAT, 0 otherwise. The client can start using the Teredo service.

5.2.2 Secure qualification

The client may be required to perform secured qualification. The client will perform exactly the algorithm described in 5.2.1, but it will incorporate an authentication encapsulation in the UDP packet carrying the router solicitation message, and it will verify the presence of a valid authentication parameter in the UDP message that carries the router advertisement provided by the sender.

In these packets, the nonce value is chosen by the client, and is repeated in the response from the server; the client identifier is a value with which the client was configured.

A first level of protection is provided by just checking that the value of the nonce in the response matches the value initially sent by the client; if they don't match, the packet MUST be discarded. If no other protection is used, the authentication payload does not contain any identifier or authentication field; the ID-len and AU-len fields are set to a null value. When stronger protection is required, the authentication payload contains the identifier and location fields, as explained in the following paragraphs.

The confirmation byte is set to 0 by the client. A null value returned by the server indicates that the client's key is still valid; a non-null value indicates that the client should obtain a new key.

When stronger authentication is provided, the client and the server are provisioned with a client identifier, a shared secret, and the identification of an authentication algorithm. Before transmission, the authentication value is computed according to the specified algorithm; on reception, the same algorithm is used to compute a target value from the content of the receive packet. The receiver deems the authentication successful if the two values match. If hey don't, the packet MUST be discarded.

To maximize interoperability, this specification defines a default algorithm in which the authentication value is computed according the HMAC specification [RFC2104] and the SHA1 function [FIPS-180]. Clients and servers may agree to use HMAC combined with a different

function, or to use a different algorithm altogether, such as for example AES-XCBC-MAC-96 [RFC3566].

The default authentication algorithm is based on the HMAC algorithm according to the following specifications:

- the hash function shall be the SHA1 function [FIPS-180].
- the secret value shall be the shared secret with which the client was configured

The clear text to be protected includes:

- the nonce value,
- the confirmation byte,
- the origin indication encapsulation, if it is present,
- the IPv6 packet.

The HMAC procedure is applied to the concatenation of these four components, without any additional padding.

5.2.3 Packet reception

The Teredo client receives packets over the Teredo interface. The role of the packet reception procedure, besides receiving packets, is to maintain the date and time of the last interaction with the Teredo server, and the "list of recent peers."

When a UDP packet is received over the Teredo service port, the Teredo client checks that it is encoded according to the packet encoding rules defined in 5.1.1, and that it contains either a valid IPv6 packet, or the combination of a valid origin indication encapsulation and a valid IPv6 packet, possibly protected by a valid authentication encapsulation. If this is not the case, the packet is silently discarded.

An IPv6 packet is deemed valid if it conforms to [RFC2460]: the protocol identifier should indicate an IPv6 packet and the payload length should be consistent with the length of the UDP datagram in which the packet is encapsulated. In addition, the client should check that the IPv6 destination address correspond to its own Teredo address.

Then, the Teredo client examines the IPv4 source address and UDP port number from which the packet is received. If these values match the IPv4 address of the server and the Teredo port, the client updates the "date and time of the last interaction with the Teredo server" to the current date and time; if an origin indication is present, the client should perform the "direct IPv6 connectivity test" described in section 5.2.9.

If the IPv4 source address and UDP port number are different from the IPv4 address of the server and the Teredo port, the client examines the IPv6 source address of the packet:

1) If there is an entry for the source IPv6 address in the list of

peers whose status is trusted, the client compares the mapped IPv4 address and mapped port in the entry with the source IPv4 address and source port of the packet. If the values match, the packet is accepted; the date and time of the last reception from the peer is updated.

2) If there is an entry for the source IPv6 address in the list of peers whose status is not trusted, the client checks whether the packet is an ICMPv6 echo reply. If this is the case, and if the ICMPv6 data of the reply matches the "nonce" stored in the peer entry, the packet should be accepted; the status of the entry should be changed to "trusted", the mapped IPv4 and mapped port in the entry should be set to the source IPv4 address and source port from which the packet was received, and the date and time of the last reception from the peer should be updated; any packet queued for this IPv6 peer (as specified in 5.2.4) should be de-queued and forwarded to the newly learned IPv4 address and UDP port.

3) If the source IPv6 address is a Teredo address, the client compares the mapped IPv4 address and mapped port in the source address with the source IPv4 address and source port of the packet. If the values match, the client MUST create a peer entry for the IPv6 source address in the list of peers; it should update the entry if one already existed; the mapped IPv4 address and mapped port in the entry should be set to the value from which the packet was received, and the status should be set to "trusted". If a new entry is created, the last transmission date is set to 30 seconds before the current date, and the number of bubbles to zero. If the packet is a bubble, it should be discarded after this processing; otherwise, the packet should be accepted. In all cases, the client must de-queue and forward any packet queued for that destination.

4) If the IPv4 destination address through which the packet was received is the Teredo IPv4 Discovery Address, the source address is a valid Teredo address, and the destination address is the "all nodes on link" multicast address, the packet should be treated as a local discovery bubble. If no local entry already existed for the source address, a new one is created, but its status is set to "not trusted". The client SHOULD reply with a unicast Teredo bubble, sent to the source IPv4 address and source port of the local discovery bubble; the IPv6 source address of the bubble will be set to local Teredo IPv6 address; the IPv6 destination address of the bubble should be set to the IPv6 source address of the local discovery bubble. (Clients that do not implement the optional local discovery procedure will not process local discovery bubbles.)

5) If the source IPv6 address is a Teredo address, and the mapped IPv4 address and mapped port in the source address do not match the source IPv4 address and source port of the packet, the client checks

whether there is an existing "local" entry for that IPv6 address. If there is such an entry, and if the local IPv4 address and local port indicated in that entry match the source IPv4 address and source

port of the packet, the client updates the "local" entry, whose status should be set to "trusted". If the packet is a bubble, it should be discarded after this processing; otherwise, the packet should be accepted. In all cases, the client must de-queue and forward any packet queued for that destination.

6) In the other cases, the packet may be accepted, but the client should be conscious that the source address may be spoofed; before processing the packet, the client should perform the "direct IPv6 connectivity test" described in section 5.2.9.

Whatever the IPv4 source address and UDP source port, the client that receives an IPv6 packet MAY send a Teredo bubble towards that target, as specified in section 5.2.6.

5.2.4 Packet transmission

When a Teredo client has to transmit a packet over a Teredo interface, it examines the destination IPv6 address. The client checks first if there is an entry for this IPv6 address in the list of recent Teredo peers, and if the entry is still valid: an entry associated with a local peer is valid if the last reception date and time associated with that list entry is less that 30 seconds from the current time; an entry associated with a non-local peer is valid if the last reception date and time associated with that list entry is less that 30 seconds from the current time. (Local peer entries can only be present if the client uses the local discovery procedure discussed in section 5.2.8.)

The client then performs the following:

1) If there is an entry for that IPv6 address in the list of peers, and if the status of the entry is set to "trusted", the IPv6 packet should be sent over UDP to the IPv4 address and UDP port specified in the entry. The client updates the date of last transmission in the peer entry.

2) If the destination is not a Teredo IPv6 address, the packet is queued, and the client performs the "direct IPv6 connectivity test" described in section 5.2.9. The packet will be de-queued and forwarded if this procedure completes successfully. If the direct IPv6 connectivity test fails to complete within a 2 second time-out, it should be repeated up to 3 times.

3) If the destination is the Teredo IPv6 address of a local peer (i.e. a Teredo address from which a local discovery bubble has been received in the last 600 seconds), the packet is queued. The client sends a unicast Teredo bubble to the local IPv4 address and local port specified in the entry, and a local Teredo bubble to the Teredo

IPv4 discovery address.

4) If the destination is a Teredo IPv6 address in which the cone bit

is set to 1, the packet is sent over UDP to the mapped IPv4 address and mapped UDP port extracted from that IPv6 address.

5) If the destination is a Teredo IPv6 address in which the cone bit is set to 0, the packet is queued. If the client is not located behind a cone NAT, it sends a direct bubble to the Teredo destination, i.e. to the mapped IP address and mapped port of the destination. In all cases, the client sends an indirect bubble to the Teredo destination, sending it over UDP to the server address and to the Teredo port. The packet will be de-queued and forwarded when the client receives a bubble or another packet directly from this Teredo peer. If no bubble is received within a 2 second time-out, the bubble transmission should be repeated up to 3 times.

In cases 4 and 5, before sending a packet over UDP, the client MUST check that the IPv4 destination address is in the format of a global unicast address; if this is not the case, the packet MUST be silently discarded. (Note that a packet can legitimately be sent to a non-global unicast address in case 1, as a result of the local discovery procedure.)

The global unicast address check is designed to thwart a number of possible attacks in which an attacker tries to us a Teredo host to attack either a single local IPv4 target, or a set of such targets. For the purpose of this specification, and IPv4 address is deemed to be a global unicast address if it does not belong to or match:

- the "local" subnet 0.0.0.0/8,
- the "loopback" subnet 127.0.0.0/8,
- the local addressing ranges 10.0.0.0/8,
- the local addressing ranges 172.16.0.0/12,
- the local addressing ranges 192.168.0.0/16,
- the link local block 169.254.0.0/16,
- the block reserved for 6to4 anycast addresses 192.88.99.0/24,
- the multicast address block 224.0.0.0/4,
- the "limited broadcast" destination address 255.255.255.255,
- the directed broadcast addresses corresponding to the subnets to which the host is attached.

A list of special-use IPv4 addresses is provided in [RFC3330].

For reliability reasons, clients MAY decide to ignore the value of the "cone" bit in the flag, skip the "case 4" test and always perform the "case 5", i.e. treat all Teredo peers as if they were located behind non-cone NAT. This will result in some increase in traffic, but may avoid reliability issues if the determination of the NAT status was for some reason erroneous. For the same reason, clients MAY also decide to always send a direct bubble in case 5, even if they do not believe that they are located behind a non-cone NAT.

5.2.5 Maintenance

The Teredo client must ensure that the mappings that it uses remain valid. It does so by checking that packets are regularly received from the Teredo server.

At regular intervals, the client MUST check the "date and time of the last interaction with the Teredo server", to ensure that at least one packet has been received in the last Randomized Teredo Refresh Interval. If this is not the case, the client SHOULD send a router solicitation message to the server, as specified in 5.2.1; the client should use the same value of the "cone" bit that resulted in the reception of an RA during the qualification procedure.

When the router advertisement is received, the client SHOULD check its validity as specified in 5.2.1; invalid advertisements are silently discarded. If the advertisement is valid, the client MUST check that the mapped address and port correspond to the current Teredo address. If this is not the case, the mapping has changed; the client must mark the old address as invalid, and start using the new address.

5.2.6 Sending Teredo Bubbles

The Teredo client may have to send a bubble towards another Teredo client, either after a packet reception or after a transmission attempt, as explained in sections 5.2.3 and 5.2.4. There are two kinds of bubbles: direct bubbles, that are sent directly to the mapped IPv4 address and mapped UDP port of the peer, and indirect bubbles that are sent through the Teredo server of the peer.

When a Teredo client attempts to send a direct bubble, it extracts the mapped IPv4 address and mapped UDP port from the Teredo IPv6 address of the target. It then checks whether there is already an entry for this IPv6 address in the current list of peers. If there is no entry, the client MUST create a new list entry for the address, setting the last reception date and the last transmission date to 30 seconds before the current date, and the number of bubbles to zero.

When a Teredo client attempts to send an indirect bubble, it extracts the Teredo server IPv4 address from the Teredo prefix of the IPv6 address of the target (different clients may be using different servers); the bubble will be sent to that IPv4 address and the Teredo UDP port.

Bubbles may be lost in transit, and it is reasonable to enhance the reliability of the Teredo service by allowing multiple transmissions; however, bubbles will also be lost systematically in certain NAT configurations. In order to strike a balance between reliability and unnecessary retransmissions, we specify the

following:

- The client MUST NOT send a bubble if the last transmission date

and time is less than 2 seconds before the current date and time;

- The client MUST NOT send a bubble if it has already sent 4 bubbles to the peer in the last 300 seconds without receiving a direct response.

In the other cases, the client MAY proceed with the transmission of the bubble. When transmitting the bubble, the client MUST update the last transmission date and time to that peer, and must also increment the number of transmitted bubbles.

5.2.7 Optional Refresh Interval Determination Procedure

In addition to the regular client resources described in the beginning of this section, the refresh interval determination procedure uses an additional UDP port, the Teredo secondary port, and the following variables:

- Teredo secondary connectivity status,
- Mapped address and port number of the Teredo secondary port,
- Teredo secondary IPv6 prefix associated with the secondary port,
- Teredo secondary IPv6 address derived from this prefix,
- Date and time of the last interaction on the secondary port,
- Maximum Teredo Refresh Interval.
- Candidate Teredo Refresh Interval.

The secondary connectivity status, mapped address and prefix are determined by running the qualification procedure on the secondary port. When the client uses the interval determination procedure, the qualification procedure MUST be run for the secondary port immediately after running it on the service port. If the secondary qualification fails, the interval determination procedure will not be used, and the interval value will remain to the default value, 30 seconds. If the secondary qualification succeeds, the maximum refresh interval is set to 120 seconds, and the candidate Teredo refresh interval is set to 60 seconds, i.e. twice the Teredo refresh interval. The procedure is then performed at regular intervals, until it concludes:

1) wait until the candidate refresh interval is elapsed after the last interaction on the secondary port;

2) send a Teredo bubble to the Teredo secondary IPv6 address, through the service port.

3) wait for reception of the bubble on the secondary port. If a timer of 2 seconds elapses without reception, repeat step 2 at most three times. If there is still no reception, the candidate has failed; if there is a reception, the candidate has succeeded.

4) if the candidate has succeeded, set the Teredo refresh interval to the candidate value, and set a new candidate value to the minimum of

twice the new refresh interval, or the average of the refresh interval and the maximum refresh interval.

5) if the candidate has failed, set the maximum refresh interval to the candidate value. If the current refresh interval is larger than or equal to 75% of the maximum, the determination procedure has concluded; otherwise, set a new candidate value to the average of the refresh interval and the maximum refresh interval.

6) if the procedure has not concluded, perform the maintenance procedure on the secondary port, which will reset the date and time of the last interaction on the secondary port, and may result in the allocation of a new Teredo secondary IPv6 address; this would not affect the values of the refresh interval, candidate interval or maximum refresh interval.

The secondary port MUST NOT be used for any other purpose than the interval determination procedure. It should be closed when the procedure ends.

5.2.8 Optional local client discovery procedure

It is desirable to enable direct communication between Teredo clients that are located behind the same NAT, without forcing a systematic relay through a Teredo server. It is hard to design a general solution to this problem, but we can design a partial solution when the Teredo clients are connected through IPv4 to the same link.

A Teredo client who wishes to enable local discovery SHOULD join the IPv4 multicast group identified by Teredo IPv4 Discovery Address. The client SHOULD wait for discovery bubbles to be received on the Teredo IPv4 Discovery Address. The client SHOULD send local discovery bubbles to the Teredo IPv4 Discovery Address at random intervals, uniformly distributed between 200 and 300 seconds. A local Teredo bubble has the following characteristics:

- IPv4 source address: the IPv4 address of the sender

- IPv4 destination address: the Teredo IPv4 Discovery Address

- IPv4 ttl: 1

- UDP source port: the Teredo service port of the sender

- UDP destination port: the Teredo UDP port

- UDP payload: a minimal IPv6 packet, as follows

- IPv6 source: the global Teredo IPv6 address of the sender

- IPv6 destination: the all-nodes on-link multicast address

- IPv6 payload type: 59 (No Next Header, as per [RFC2460])

- IPv6 payload length: 0

- IPv6 hop limit: 1

The local discovery procedure carries a denial of service risk, as malevolent nodes could send fake bubbles to unsuspecting parties, and thus capture the traffic originating from these parties. The risk is mitigated by the filtering rules described in section 5.2.5, and also by "link only" multicast scope of the Teredo IPv4 Discovery Address, which implies that packets sent to this address will not be forwarded across routers.

To benefit from the "link only multicast" protection, the clients should silently discard all local discovery bubbles that are received over a unicast address. To further mitigate the denial of service risk, the client MUST silently discard all local discovery bubbles whose IPv6 source address is not a well-formed Teredo IPv6 address, or whose IPv4 source address does not belong to the local IPv4 subnet; the client MAY decide to silently discard all local discovery bubbles whose Teredo IPv6 address do not include the same mapped IPv4 address as its own.

If the bubble is accepted, the client checks whether there is an entry in the list of recent peers that correspond to the mapped IPv4 address and mapped UDP port associated with the source IPv6 address of the bubble. If there is such an entry, the client MUST update the local peer address and local peer port parameters to reflect the IPv4 source address and UDP source port of the bubble. If there is no entry, the client MUST create one, setting the local peer address and local peer port parameters to reflect the IPv4 source address and UDP source port of the bubble, the last reception date to the current date and time, the last transmission date to 30 seconds before the current date, and the number of bubbles to zero; the state of the entry is set to "not trusted".

Upon reception of a discovery bubble, clients reply with a unicast bubble as specified in section 5.2.3.

5.2.9 Direct IPv6 connectivity test

The Teredo procedures are designed to enable direct connections between a Teredo host and a Teredo relay. Teredo hosts located behind a cone NAT will receive packets directly from relays; other Teredo hosts will learn the original addresses and UDP ports of third parties through the local Teredo server. In all of these cases, there is a risk that the IPv6 address of the source be spoofed by a malevolent party. Teredo hosts must make two decisions,

whether to accept the packet for local processing, and whether to transmit further packets to the IPv6 address through the newly

learned IPv4 address and UDP port. The basic rule is that the hosts should be generous in what they accept, and careful in what they send. Refusing to accept packets due to spoofing concerns would compromise connectivity, and should only be done when there is a near certainty that the source address is spoofed; on the other hand, sending packets to the wrong address should be avoided.

When the client wants to send a packet to a native IPv6 node or a 6to4 node, it should check whether a valid peer entry already exists for the IPv6 address of the destination. If this is not the case, the client will pick a random number (a nonce) and format an ICMPv6 Echo Request message whose source is the local Teredo address, whose destination is the address of the IPv6 node, and whose Data field is set to the nonce. (It is recommended to use a random number at least 64 bit long.) The nonce value and the date at which the packet was sent will be documented in a provisional peer entry for the IPV6 destination. The ICMPv6 packet will then be sent encapsulated in a UDP packet destined to the Teredo server IPv4 address, and to the Teredo port. The rules of section 5.2.3 specify how the reply to this packet will be processed.

5.2.10 Working around symmetric NAT

The client procedures are designed to enable IPv6 connectivity through the most common types of NAT, which are commonly called "Cone NAT" and "restricted cone NAT" [RFC3489]. Some NAT employ a different design; they are often called "symmetric NAT". The qualification algorithm in section 5.2.1 will not succeed when the local NAT is a symmetric NAT.

In many cases, it is possible to work around the limitations of these NAT by explicitly reserving a UDP port for Teredo service on a client, using a function often called "DMZ" in the NAT's manual. This port will become the "service port" used by the Teredo hosts. The implementers of Teredo functions in hosts must make sure that the value of the service port can be explicitly provisioned, so that user can provision the same value in the host and in the NAT.

The reservation procedure guarantees that the port mapping will remain the same for all destinations. After the explicit reservation, the qualification algorithm in section 5.2.1 will succeed, and the Teredo client will behave as if behind a "cone NAT".

When different clients use Teredo behind a single symmetric NAT, each of these clients must reserve and use a different service port.

5.3 Teredo Server specification

The Teredo server is designed to be stateless. The Teredo server waits for incoming UDP packets at the Teredo Port, using the IPv4 address that has been selected for the service. In addition, the

server is able to receive and transmit some packets using a different IPv4 address and a different port number.

The Teredo server acts as an IPv6 router. As such, it will receive Router Solicitation messages, to which it will respond with Router Advertisement messages as explained in section 5.3.2; it may also receive other packets, for example ICMPv6 messages and Teredo bubbles, which are processed according to the IPv6 specification.

By default, the routing functions of the Teredo server are limited. Teredo servers are expected to relay Teredo bubbles, ICMPv6 Echo requests and ICMPv6 Echo replies, but they are not expected to relay other types of IPv6 packets. Operators may however decide to combine the functions of "Teredo server" and "Teredo relay", as explained in section 5.4.

5.3.1 Processing of Teredo IPv6 packets

Before processing the packet, the Teredo server MUST check the validity of the encapsulated IPv6 source address, the IPv4 source address and the UDP source port:

1) If the UDP content is not a well formed Teredo IPv6 packet, as defined in section 5.1.1, the packet MUST be silently discarded.

2) If the UDP packet is not a Teredo bubble or an ICMPv6 message, it SHOULD be discarded. (The packet may be processed if the Teredo server also operates as a Teredo relay, as explained in section 5.4.)

3) If the IPv4 source address is not in the format of a global unicast address, the packet MUST be silently discarded (see section 5.2.4 for a definition of global unicast addresses).

4) If the IPv6 source address is an IPv6 link-local address, the IPv6 destination address is the link-local scope all routers multicast address (FF02::2), and the packet contains an ICMPv6 Router Solicitation message, the packet MUST be accepted; it MUST be discarded if the server requires secure qualification and the authentication encapsulation is absent or verification fails.

5) If the IPv6 source address is a Teredo IPv6 address, and if the IPv4 address and UDP port embedded in that address match the IPv4 source address and UDP source port, the packet SHOULD be accepted.

6) If the IPv6 source address is not a Teredo IPv6 address, and if the IPv6 destination address is a Teredo address allocated through this server, the packet SHOULD be accepted.

7) In all other cases, the packet MUST be silently discarded.

The Teredo server will then check the IPv6 destination address of the encapsulated IPv6 packet:

If the IPv6 destination address is the link-local scope all routers multicast address (FF02::2), or the link-local address of the server, the Teredo server processes the packet; it may have to process Router Solicitation messages and ICMPv6 Echo Request messages.

If the destination IPv6 address is not a global scope IPv6 address, the packet MUST NOT be forwarded.

If the destination address is not a Teredo IPv6 address the packet should be relayed to the IPv6 Internet using regular IPv6 routing.

If the IPv6 destination address is a valid Teredo IPv6 address as defined in 2.13, the Teredo Server MUST check that the IPv4 address derived from this IPv6 address is in the format of a global unicast address; if this is not the case, the packet MUST be silently discarded.

If the address is valid, the Teredo server encapsulates the IPv6 packet in a new UDP datagram, in which the following parameters are set:

- The destination IPv4 address is derived from the IPv6 destination.

- The source IPv4 address is the Teredo server IPv4 address.

- The destination UDP port is derived from the IPv6 destination.

- The source UDP port is set to the Teredo UDP Port.

If the destination IPv6 address is a Teredo client whose address is serviced by this specific server, the server should insert an origin indication in the first bytes of the UDP payload, as specified in section 5.1.1. (To verify that the client is served by this server, the server compares bits 32-63 of the client's Teredo IPv6 address to the server's IPv4 address.)

5.3.2 Processing of router solicitations

When the Teredo server receives a Router Solicitation message (RS, [RFC2461]), it retains the IPv4 address and UDP port from which the solicitation was received; these become the Teredo mapped address and Teredo mapped port of the client. The router uses these values to compose the origin indication encapsulation that will be sent with the response to the solicitation.

The Teredo server responds to the router solicitation by sending a

Router Advertisement message [RFC2461]. The router advertisement MUST advertise the Teredo IPv6 prefix composed from the service

prefix and the server's IPv4 address. The IPv6 source address should be set to a Teredo link-local server address associated to the local interface; this address is derived from the IPv4 address of the server and from the Teredo port, as specified in section 4; the C bit is set to 1. The IPv6 destination address is set to the IPv6 source address of the RS. The Router Advertisement message must be sent over UDP to the Teredo mapped address and Teredo mapped port of the client; the IPv4 source address and UDP source port should be set to the server's IPv4 address and Teredo Port. If the cone bit of the client's IPv6 address is set to 1, the RA must be sent from a different IPv4 source address than the server address over which the RS was received; if the cone bit is set to zero, the response must be sent back from the same address.

Before sending the packet, the Teredo server MUST check that the IPv4 destination address is in the format of a global unicast address; if this is not the case, the packet MUST be silently discarded (see section 5.2.4 for a definition of global unicast addresses).

If secure qualification is required, the server MUST insert a valid authentication parameter in the UDP packet carrying the router advertisement. The client identifier and the nonce value used in the authentication parameter MUST be the same identifier and nonce as received in the router solicitation; the confirmation byte MUST be set to zero if the client identifier is still valid, and a non-null value otherwise; the authentication value SHOULD be computed using the secret that corresponds to the client identifier.

5.4 Teredo Relay specification

Teredo relays are IPv6 routers that advertise reachability of the Teredo service IPv6 prefix through the IPv6 routing protocols. (A minimal Teredo relay may serve just a local host, and would not advertise the prefix beyond this host.) Teredo relays will receive IPv6 packets bound to Teredo clients. Teredo relays should be able to receive packets sent over IPv4 and UDP by Teredo clients; they may apply filtering rules, e.g. only accept packets from Teredo clients if they have previously sent traffic to these Teredo clients.

The receiving and sending rules used by Teredo relays are very similar to those of Teredo clients. Teredo relays must use a Teredo service port to transmit packets to Teredo clients; they must maintain a "list of peers", identical to the list of peers maintained by Teredo clients.

5.4.1 Transmission by relays to Teredo clients

When a Teredo relay has to transmit a packet to a Teredo client, it examines the destination IPv6 address. By definition, the Teredo relays will only send over UDP IPv6 packets whose IPv6 destination

address is a valid Teredo IPv6 address.

Before processing these packets, the Teredo Relay MUST check that the IPv4 destination address embedded in the Teredo IPv6 address is in the format of a global unicast address; if this is not the case, the packet MUST be silently discarded (see section 5.2.4 for a definition of global unicast addresses).

The relay then checks if there is an entry for this IPv6 address in the list of recent Teredo peers, and if the entry is still valid. The relay then performs the following:

1) If there is an entry for that IPv6 address in the list of peers, and if the status of the entry is set to "trusted", the IPv6 packet should be sent over UDP to the mapped IPv4 address and mapped UDP port of the entry. The relay updates the date of last transmission in the peer entry.

2) If there is no trusted entry in the list of peers, and if the destination is a Teredo IPv6 address in which the cone bit is set to 1, the packet is sent over UDP to the mapped IPv4 address and mapped UDP port extracted from that IPv6 address.

3) If there is no trusted entry in the list of peers, and if the destination is a Teredo IPv6 address in which the cone bit is set to 0, the Teredo relay creates a bubble whose source address is set to a local IPv6 address, and whose destination address is set to the Teredo IPv6 address of the packet's destination. The bubble is sent to the server address corresponding to the Teredo destination. The entry becomes trusted when a bubble or another packet is received from this IPv6 address; if no such packet is received before a time-out of 2 seconds, the Teredo relay may repeat the bubble, up to three times. If the relay fails to receive a bubble after these repetitions, the entry is removed from the list of peers. The relay MAY queue packets bound to untrusted entries; the queued packets SHOULD be de-queued and forwarded when entry become trusted; they SHOULD be deleted if the entry is deleted. To avoid denial of service attacks, the relays SHOULD limit the number of packets in such queues.

In cases 2 and 3, the Teredo relay should create a peer entry for the IPv6 address; the entry status is marked as trusted in case 2 (cone NAT), not trusted in case 3. In case 3, if the Teredo relay happens to be located behind a non-cone NAT, it should also send a bubble directly to the mapped IPv4 address and mapped port number of the Teredo destination; this will "open the path" for the return bubble from the Teredo client.

For reliability reasons, relays MAY decide to ignore the value of

the "cone" bit in the flag, and always perform the "case 3", i.e. treat all Teredo peers as if they were located behind non-cone NAT. This will result in some increase in traffic, but may avoid

reliability issues if the determination of the NAT status was for some reason erroneous. For the same reason, relays MAY also decide to always send a direct bubble to the mapped IPv4 address and mapped port number of the Teredo destination, even if they do not believe that they are located behind a non-cone NAT.

5.4.2 Reception from Teredo clients

The Teredo relay may receive packets from Teredo clients; the packets should normally only be sent by clients to which the relay previously transmitted packets, i.e. clients whose IPv6 address is present in the list of peers. Relays, like clients, use the packet reception procedure to maintain the date and time of the last interaction with the Teredo server, and the "list of recent peers."

When a UDP packet is received over the Teredo service port, the Teredo relay checks that it contains a valid IPv6 packet as specified in [RFC2460]. If this is not the case, the packet is silently discarded.

Then, the Teredo relay examines whether the IPv6 source address is a valid Teredo address, and if the mapped IPv4 address and mapped port match the IPv4 source address and port number from which the packet is received. If this is not the case, the packet is silently discarded.

The Teredo relay then examines whether there is an entry for the IPv6 source address in the list of recent peers. If this is not the case, the packet may be silently discarded. If this is the case, the entry status is set to "trusted"; the relay updates the "date and time of the last interaction" to the current date and time.

Finally, the relay examines the destination IPv6 address. If the destination belongs to a range of IPv6 addresses served by the relay, the packet SHOULD be accepted and forwarded to the destination. In the other cases, the packet SHOULD be silently discarded.

5.4.3 Difference between Teredo Relays and Teredo Servers

Because Teredo servers can relay Teredo packets over IPv6, all Teredo servers must be capable of behaving as Teredo relays. There is however no requirement that Teredo relays behave as Teredo servers.

The dual-role of server and relays implies an additional complexity for the programming of servers: the processing of incoming packets should be a combination of the server processing rules defined in 5.3.1, and the relay processing rules defined in 5.4.2. (Section 5.3 only specifies the rules implemented by a pure server, not a

combination relay+server.)

5.5 Implementation of automatic sunset

Teredo is designed as an interim transition mechanism, and it is important that it should not be used any longer than necessary. The "sunset" procedure will be implemented by Teredo clients, servers and relays, as specified in this section.

The Teredo-capable nodes MUST NOT behave as Teredo clients if they already have IPv6 connectivity through any other means, such as native IPv6 connectivity; in particular, nodes that have a global IPv4 address SHOULD obtain connectivity through the 6to4 service rather than through the Teredo service. The classic reason why a node that does not need connectivity would still enable the Teredo service is to guarantee good performance when interacting with Teredo clients; however, a Teredo-capable node that has IPv4 connectivity and that has obtained IPv6 connectivity outside the Teredo service MAY decide to behave as a Teredo relay, and still obtain good performance when interacting with Teredo clients.

The Teredo servers are expected to participate in the sunset procedure by announcing a date at which they will stop providing the service. This date depends on the availability of alternative solutions to their clients, such as "dual-mode" gateways that behave simultaneously as IPv4 NATs and IPv6 routers. Most Teredo servers will not be expected to operate more than a few years.
Teredo relays are expected to have the same life span as Teredo servers.

6 Further study, use of Teredo to implement a tunnel service

Teredo defines a NAT traversal solution that can be provided using very little resource at the server. Ongoing IETF discussions have outlined the need for both a solution like Teredo and a more controlled NAT traversal solution, using configured tunnels to a service provider [RFC3904]. This section provides a tentative analysis of how Teredo could be extended to also support a configured tunnel service.

It may be possible to design a tunnel server protocol that is compatible with Teredo, in the sense that the same client could be used either in the Teredo service or with a tunnel service. In fact, this could be done by configuring the client with:

- The IPv4 address of a Teredo server that acts as a tunnel broker
- A client identifier
- A shared secret with that server
- An agreed upon authentication algorithm.

The Teredo client would use the secure qualification procedure, as

specified in section 5.2.2. Instead of returning a Teredo prefix in the router advertisement, the server would return a globally routable IPv6 prefix; this prefix could be permanently assigned to

the client, which would provide the client with a stable address. The server would have to keep state, i.e. memorize the association between the prefix assigned to the client and the mapped IPv4 address and mapped UDP port of the client.

The Teredo server would advertise reachability of the client prefix to the IPv6 Internet. Any packet bound to that prefix would be transmitted to the mapped IPv4 address and mapped UDP port of the client.

The Teredo client, when it receives the prefix, would notice that this prefix is a global IPv6 prefix, not in the form of a Teredo prefix. The client would at that point recognize that it should operate in tunnel mode. A client that operates in tunnel mode would execute a much simpler transmission procedure: it would forward any packet sent to the Teredo interface to the IPv4 address and Teredo UDP port of the server.

The Teredo client would have to perform the maintenance procedure described in section 5.2.5. The server would receive the router solicitation, and could notice a possible change of mapped IPv4 address and mapped UDP port that could result from the reconfiguration of the mappings inside the NAT. The server should continue advertising the same IPv6 prefix to the client, and should update the mapped IPv4 address and mapped UDP port associated to this prefix, if necessary.

There is yet no consensus that a tunnel-mode extension to Teredo should be developed. This section is only intended to provide suggestions to the future developers of such services. Many details would probably have to be worked out before a tunnel-mode extension would be agreed upon.

7 Security Considerations

The main objective of Teredo is to provide nodes located behind a NAT with a globally routable IPv6 address. The Teredo nodes can use IP security (IPsec) services such as IKE, AH or ESP [RFC2409, RFC2402, RFC2406], without the configuration restrictions still present in the Negotiation of NAT-Traversal in IKE [RFC3947]. As such, we can argue that the service has a positive effect on network security. However, the security analysis must also envisage the negative effects of the Teredo services, which we can group in four categories: security risks of directly connecting a node to the IPv6 Internet, spoofing of Teredo servers to enable a man-in-the-middle attack, potential attacks aimed at denying the Teredo service to a Teredo client, and denial of service attacks against non-Teredo participating nodes that would be enabled by the Teredo service.

In the following, we review in detail these four types of issues, and we present mitigating strategies for each of them.

7.1 Opening a hole in the NAT

The very purpose of the Teredo service is to make a machine reachable through IPv6. By definition, the machine using the service will give up whatever "firewall" service was available in the NAT box, however limited this service may be [RFC2993]. The services that listen to the Teredo IPv6 address will become potential target of attacks from the entire IPv6 Internet. This may sound scary, but there are three mitigating factors.

The first mitigating factor is the possibility to restrict some services to only accept traffic from local neighbors, e.g. using link local addresses. Teredo does not support communication using link local addresses. This implies that link-local services will not be accessed through Teredo, and will be restricted to whatever other IPv6 connectivity may be available, e.g. direct traffic with neighbors on the local link, behind the NAT.

The second mitigating factor is the possible use of a "local firewall" solution, i.e. a piece of software that performs locally the kind of inspection and filtering that is otherwise performed in a perimeter firewall. Using such software is recommended.

The third mitigating factor, is the availability of IP security (IPsec) services such as IKE, AH or ESP [RFC2409, RFC2402, RFC2406]. Using these services in conjunction with Teredo is a good policy, as it will protect the client from possible attacks in intermediate servers such as the NAT, the Teredo server, or the Teredo relay. (These services can however only be used if the parties in the communication can negotiate a key, which requires agreeing on some credentials; this is known to be a hard problem.)

7.2 Using the Teredo service for a man-in-the-middle attack

The goal of the Teredo service is to provide hosts located behind a NAT with a globally reachable IPv6 address. There is a possible class of attacks against this service in which an attacker somehow intercepts the router solicitation, responds with a spoofed router advertisement, and provides a Teredo client with an incorrect address. The attacker may have one of two objectives: it may try to deny service to the Teredo client by providing it with an address that is in fact unreachable, or it may try to insert itself as a relay for all client communications, effectively enabling a variety of "man-in-the-middle" attack.

7.2.1 Attacker spoofing the Teredo Server

The simple nonce verification procedure described in section 5.2.2 provides a first level of protection against attacks in which a

third party tries to spoof the server. In practice, the nonce procedure can only be defeated if the attacker is "on path".

If client and server share a secret and agree on an authentication algorithm, the secure qualification procedure described in section 5.2.2 provides further protection. To defeat this protection, the attacker could try to obtain a copy of the secret shared between client and server. The most likely way to obtain the shared secret is to listen to the traffic and mount an offline dictionary attack; to protect against this attack, the secret shared between client and server should contain sufficient entropy. (This probably requires some automated procedure for provisioning the shared secret and the algorithm.)

If the shared secret contains sufficient entropy, the attacker would have to defeat the one-way function used to compute the authentication value. This specification suggests a default algorithm combining HMAC and MD5. If the protection afforded by MD5 was not deemed sufficient, clients and servers can be agree to use a different algorithm, e.g. SHA1.

Another way to defeat the protection afforded by the authentication procedure is to mount a complex attack, as follows:

1) Client prepares router solicitation, including authentication encapsulation.

2) Attacker intercepts the solicitation, and somehow manages to prevent it from reaching the server, for example by mounting a short duration DoS attack against the server.

3) Attacker replaces the source IPv4 address and source UDP port of the request by one of its own addresses and port, and forwards the modified request to the server.

4) Server dutifully notes the IPv4 address from which the packet is received, verifies that the Authentication encapsulation is correct, prepares a router advertisement, signs it, and sends it back to the incoming address, i.e. the attacker.

5) Attacker receives the advertisement, takes note of the mapping, replaces the IPv4 address and UDP port by the original values in the intercepted message, and sends the response to the client.

6) Client receives the advertisement, notes that the authentication header is present and is correct, and uses the proposed prefix and the mapped addresses in the origin indication encapsulation.

The root cause of the problem is that the NAT is, in itself, a man-in-the-middle attack. The Authentication encapsulation covers the encapsulated IPv6 packet, but does not cover the encapsulating IPv4 header and UDP header. It is very hard to devise an effective authentication scheme, since the attacker does not do anything else

than what the NAT legally does!

There are however several mitigating factors that lead us to avoid worrying too much about this attack. In practice, the gain from the attack is to either deny service to the client, or obtain a "man-in-the-middle" position; however, in order to mount the attack, the attacker must be able to suppress traffic originating from the client, i.e. have denial of service capability; the attacker must also be able to observe the traffic exchanged between client and inject its own traffic in the mix, i.e. have man-in-the-middle capacity. In summary, the attack is very hard to mount, and the gain for the attacker in terms of "elevation of privilege" is minimal.

A similar attack is described in detail in the security section of [RFC3489].

7.2.2 Attacker spoofing a Teredo relay

An attacker may try to use Teredo to either pass itself for another IPv6 host, or place itself as a man-in-the-middle between a Teredo host and a native IPv6 host. The attacker will mount such attacks by spoofing a Teredo relay, i.e. by convincing the Teredo host that packets bound to the native IPv6 host should be relayed to the IPv4 address of the attacker.

The possibility of the attack derives from the lack of any algorithmic relation between the IPv4 address of a relay and the native IPv6 addresses served by these relay. A Teredo host cannot decide just by looking at the encapsulating IPv4 and UDP header whether a relay is legitimate or not. If a Teredo host decided to simply trust the incoming traffic, it would easily fall prey to a relay-spoofing attack.

The attack is mitigated by the "Direct IPv6 connectivity test" specified in section 5.2.9. The test specifies a relay discovery procedure secured by a nonce. The nonce is transmitted from the Teredo host to the destination through Teredo server, which the client normally trusts. The response arrives through the "natural" relay, i.e. the relay closest to the IPv6 destination. Sending traffic to this relays will place it out of reach of attackers that are not on the direct path between the Teredo host and its IPv6 peer.

End-to-end security protections are required to defend against spoofing attacks if the attacker is on the direct path between the Teredo host and its peer.

7.2.3 End-to-end security

The most effective line of defense of a Teredo client is probably not to try to secure the Teredo service itself: even if the mapping

can be securely obtained, the attacker would still be able to listen to the traffic and send spoofed packets. Rather, the Teredo client should realize that, because it is located behind a NAT, it is in a

situation of vulnerability; it should systematically try to encrypt its IPv6 traffic, using IPsec. Even if the IPv4 and UDP headers are vulnerable, the use of IPsec will effectively prevent spoofing and listening of the IPv6 packets by third parties. By providing each client with a global IPv6 address, Teredo enables the use of IPsec without the configuration restrictions still present in the Negotiation of NAT-Traversal in IKE [RFC3947]and ultimately enhances the security of these clients.

7.3 Denial of the Teredo service

Our analysis outlines five ways to attack the Teredo service. There are counter-measures for each of these attacks.

7.3.1 Denial of service by a rogue relay

An attack can be mounted on the IPv6 side of the service by setting up a rogue relay, and letting that relay advertise a route to the Teredo IPv6 prefix. This is an attack against IPv6 routing, which can also be mitigated by the same kind of procedures used to eliminate spurious route advertisements. Dual stack nodes that implement "host local" Teredo relays are impervious to this attack.

7.3.2 Denial of service by server spoofing

In section 7.2, we discussed the use of spoofed router advertisements to insert an attacker in the middle of a Teredo conversation. The spoofed router advertisements can also be used to provision a client with an incorrect address, pointing to either a non-existing IPv4 address or to the IPv4 address of a third party.

The Teredo client will detect the attack when it fails to receive traffic through the newly acquired IPv6 address. The attack can be mitigated by using the authentication encapsulation.

7.3.3 Denial of service by exceeding the number of peers

A Teredo client manages a cache of recently-used peers, which makes it stateful. It is possible to mount an attack against the client by provoking it to respond to packets that appear to come from a large number of Teredo peers, thus trashing the cache and effectively denying the use of direct communication between peers. The effect will only last as long as the attack is sustained.

7.3.4 Attacks against the local discovery procedure

There is a possible denial of service attack against the local peer discovery procedure, if attackers can manage to send spoofed local discovery bubbles to a Teredo client. The checks described in section 5.2.8 mitigate this attack. Clients who are more interested

in security than in performance could decide to disable the local discovery procedure; however, if local discovery is disabled,

traffic between local nodes will end up being relayed through a server external to the local network, which has questionable security implications.

7.3.5 Attacking the Teredo servers and relays

It is possible to mount a brute force denial of service attack against the Teredo servers by sending them a very large number of packets. This attack will have to be "brute force", since the servers are stateless, and can be designed to process all the packets that are sent on their access line.

The brute force attack against the Teredo servers is mitigated if clients are ready to "failover" to another server. Bringing down the servers will however force the clients that change servers to renumber their Teredo address.

It is also possible to mount a brute force attack against a Teredo relay. This attack is mitigated if the relay under attack stops announcing the reachability of the Teredo service prefix to the IPv6 network: the traffic will be picked up by the next relay.

An attack similar to 7.3.2 can be mounted against a relay. An IPv6 host can send IPv6 packets to a large number of Teredo destinations, forcing the relay to establish state for each of these destinations. Teredo relays can obtain some protection by limiting the range of IPv6 clients that they serve, and by limiting the amount of state used for "new" peers.

7.4 Denial of service against non-Teredo nodes

There is a widely expressed concern that transition mechanisms such as Teredo can be used to mount denial of service attacks, by injecting traffic at locations where it is not expected. These attacks fall in three categories: using the Teredo servers as a reflector in a denial of service attack, using the Teredo server to carry a denial of service attack against IPv6 nodes, and using the Teredo relays to carry a denial of service attack against IPv4 nodes. The analysis of these attacks follows. A common mitigating factor in all cases is the "regularity" of the Teredo traffic, which contains highly specific patterns such as the Teredo UDP port, or the Teredo IPv6 prefix. In case of attacks, these patterns can be used to quickly install filters and remove the offending traffic.

We should also note that none of the listed possibilities offer any noticeable amplification.

7.4.1 Laundering DoS attacks from IPv4 to IPv4

An attacker can use the Teredo servers as reflectors in a denial of

service attack aimed at an IPv4 target. The attacker can do this in one of two ways. The first way is to construct a Router Solicitation

message and post it to a Teredo server, using as IPv4 source address the spoofed address of the target; the Teredo server will then send a Router advertisement message to the target. The second way is to construct a Teredo IPv6 address using the Teredo prefix, the address of a selected server, the IPv4 of the target, and an arbitrary UDP port, and to then send packets bound to that address to the selected Teredo server.

Reflector attacks are discussed in [REFLECT], which outlines various mitigating techniques against such attacks. One of these mitigations is to observe that 'the traffic generated by the reflectors [has] sufficient regularity and semantics that it can be filtered out near the victim without the filtering itself constituting a denial-of-service to the victim ("collateral damage").' The traffic reflected by the Teredo servers meets this condition: it is clearly recognizable, since it originates from the Teredo UDP port; it can be filtered out safely if the target itself is not a Teredo user. In addition, the packets relayed by servers will carry an Origin indication encapsulation, which will help determining the source of the attack.

7.4.2 DOS attacks from IPv4 to IPv6

An attacker may use the Teredo servers to launch a denial of service attack against an arbitrary IPv6 destination. The attacker will build an IPv6 packet bound for the target, and will send that packet to the IPv4 address and UDP port of a Teredo server, to be relayed from there to the target over IPv6.

The address checks specified in section 5.3.1 provide some protection against this attack, as they ensure that the IPv6 source address will be consistent with the IPv4 source address and UDP source port used by the attacker: if the attacker cannot spoof the IPv4 source address, the target will be able to determine the origin of the attack.

The address checks ensure that the IPv6 source address of packets forwarded by servers will start with the IPv6 Teredo prefix. This is a mitigating factor, as sites under attack could use this to filter out all packets sourced from that prefix during an attack. This will result in a partial loss of service, as the target will not be able to communicate with legitimate Teredo hosts that use the same prefix; however, the communication with other IPv6 hosts will remain unaffected, and the communication with Teredo hosts will be able to resume when the attack has ceased.

7.4.3 DOS attacks from IPv6 to IPv4

An attacker with IPv6 connectivity may use the Teredo relays to

launch a denial of service attack against an arbitrary IPv4 destination. The attacker will compose a Teredo IPv6 address using the Teredo prefix, a "cone" flag set to 1, the IPv4 address of the

target, and an arbitrary UDP port.

In the simplest variation of this attack, the attacker sends IPv6 packets to the Teredo destination using regular IPv6 routing. The packets are picked by the nearest relay, which will forward them to the IPv4 address of the target. In a more elaborate variant, the attacker tricks a Teredo into sending packets to the target, either by sending a first packet with a spoofed IPv6 address and letting the Teredo host reply, or by publishing a spoofed IPv6 address in a name service.

There are three types of IPv4 addresses that an attacker may embed in the spoofed Teredo address. It may embed a multicast or broadcast address, an local unicast address, or a global unicast address.

With multicast or broadcast addresses, the attacker can use the multiplying effect of multicast routing. By sending a single packet, it can affect a large number of hosts, in a way reminiscent of the "smurf" attack.

By using local addresses, the attacker can reach hosts that are not normally reachable from the Internet, for example hosts connected to the a Teredo relay by a private subnet. This creates an exposure for, at a minimum, a denial of service attack against these otherwise protected host. This is similar to attack variants using source routing to breach a perimeter.

The address checks specified in 5.2.4, 5.3.1 and 5.4.1 are verify that packets are only relayed to a global IPv4 address. They are designed to eliminate the possibility of using broadcast, multicast or local addresses in denial of service or other attacks. In what follows, we will only consider attacks targeting globally reachable unicast addresses.

The attacks can be targeted at arbitrary UDP ports, such as for example the DNS port of a server. The UDP payload must be a well-formed IPv6 packet, and is thus unlikely to be accepted by any well-written UDP service; in most case, the only effect of the attack will be to overload the target with random traffic.

A special case occurs if the attack is directed to an echo service. The service will echo the packets. Since the echo service sees the request coming from the IPv4 address of the relay, the echo replies will be sent back to the same relay. According to the rules specified in 5.4, these packets will be discarded by the Teredo relay. This is not a very efficient attack against the Teredo relays - establishing a legitimate session with an actual Teredo host would create more traffic.

The IPv6 packets sent to the target contain the IPv6 address used by the attacker. If ingress filtering is used in the IPv6 network, this

address will be hard to spoof. If ingress filtering is not used, the attacker can be traced if the IPv6 routers use a mechanism similar to ICMP Traceback. The ICMP messages will normally be collected by the same relays that forward the traffic from the attacker; the relays can use these messages to identify the source of an ongoing attack. The details of this solution will have to be developed in further research.

8 IAB considerations

The IAB has studied the problem of "Unilateral Self Address Fixing" (UNSAF), which is the general process by which a client attempts to determine its address in another realm on the other side of a NAT through a collaborative protocol reflection mechanism [RFC3424]. Teredo is an example of a protocol that performs this type of function. The IAB has mandated that any protocols developed for this purpose document a specific set of considerations. This section meets those requirements.

8.1 Problem Definition

From [RFC3424], any UNSAF proposal must provide a precise definition of a specific, limited-scope problem that is to be solved with the UNSAF proposal. A short term fix should not be generalized to solve other problems; this is why "short term fixes usually aren't".

The specific problem being solved by Teredo is the provision of IPv6 connectivity for hosts that cannot obtain IPv6 connectivity natively and cannot make use of 6to4 because of the presence of a NAT between them and the 6to4 relays.

8.2 Exit Strategy

From [RFC3424], any UNSAF proposal must provide the description of an exit strategy/transition plan. The better short term fixes are the ones that will naturally see less and less use as the appropriate technology is deployed.

Teredo comes with its own built in exit strategy: as soon as a client obtains IPv6 connectivity by other means, either 6to4 or native IPv6, it can cease using the Teredo service. In particular, we expect that the next generation of home routers will provide an IPv6 service in complement to the current IPv4 NAT service, e.g. by relaying connectivity obtained from the ISP, or by using a configured or automatic tunnel service.

As long as Teredo is used, there will be a need to support Teredo relays so that the remaining Teredo hosts can communicate with native IPv6 hosts. As Teredo usage declines, the traffic load on the relays will decline. Over time, managers will observe a reduce

traffic load on their relays and will turn them off, effectively increasing the pressure on the remaining Teredo hosts to upgrade to

another form of connectivity.

The exit strategy is facilitated by the nature of Teredo, which provides an IP level solution. IPv6 aware applications do not have to be updated to use or not use Teredo. The absence of impact on the applications makes it easier to migrate out of Teredo: network connectivity suffices.

There would appear to be reasons why a Teredo implementation might decide to continue usage of the Teredo service even if it already has obtained connectivity by some other means, for example:

1. When a client is dual homed, and it wishes to improve the service when communicating with other teredo hosts that are "nearby" on the IPv4 network. If the client only used its native IPv6 service, the teredo hosts would be reached only through the relay. By maintaining teredo, the teredo hosts can be reached by direct transmission over IPv4.

2. If, for some reason, the Teredo link is providing the client with better service than the native IPv6 link, in terms of bandwidth, packet loss, etc.

The design of Teredo mitigates the dual-homing reason. A host that wishes to communicate with Teredo peers can implement an "host based relay", which is effectively an un-numbered Teredo interface. As such, the dual-homed host will obtain Teredo connectivity with those hosts that must use Teredo, but will not inadvertently encourage other dual homed hosts to keep using the Teredo service.

The bubbles and the UDP encapsulation used by Teredo introduce a significant overhead. It would take exceptional circumstances for native technologies to provide a lesser service than Teredo. These exceptional circumstances, or other unforeseen reasons, may induce hosts to keep using the Teredo service despite the availability of native IPv6 connectivity. However, these circumstances are likely to be rare and transient. Moreover, if the primary reason to use Teredo fades away, one can expect that Teredo relays will be progressively turned off, and that the quality of the Teredo service will progressively degrade, reducing the motivation to use the Teredo service.

8.3 Brittleness Introduced by Teredo

From [RFC3424], any UNSAF proposal must provide a discussion of specific issues that may render systems more "brittle". For example, approaches that involve using data at multiple network layers create more dependencies, increase debugging challenges, and make it harder to transition.

Teredo introduces brittleness into the system in several ways: the discovery process assumes a certain classification of devices based

on their treatment of UDP; the mappings need to be continuously refreshed; and addressing structure may cause some hosts located behind a common NAT to be unreachable from each other.

There are many similarities between these points and those introduced by STUN [RFC3489]; however, Teredo is probably somewhat less brittle than STUN. The reason is that all Teredo packets are sent from the local IPv4 teredo service port, including discovery, bubbles and actual encapsulated packets. This is different from STUN, where NAT type detection and binding allocation use different local ports (ephemeral, in both cases).

Teredo assumes a certain classification of devices based on their treatment of UDP, e.g. cone, protected cone and symmetric. There could be devices that would not fit into one of these molds, and hence would be improperly classified by Teredo.

The bindings allocated from the NAT need to be continuously refreshed. Since the timeouts for these bindings is very implementation specific, the refresh interval cannot easily be determined. When the binding is not being actively used to receive traffic, but to wait for an incoming message, the binding refresh will needlessly consume network bandwidth.

The use of the Teredo server as an additional network element introduces another point of potential security attack. These attacks are largely prevented by the security measures provided by Teredo, but not entirely.

The use of the Teredo server as an additional network element introduces another point of failure. If the client cannot locate a Teredo server, or if the server should be unavailable due to failure, the Teredo client will not be able to obtain IPv6 connectivity.

The communication with non Teredo hosts relies on the availability of Teredo relays. The Teredo design assumes that there are multiple Teredo relays; the Teredo service will discover the relay closest to the non-Teredo peer. If that relay becomes unavailable, or misbehaving, communication between the Teredo hosts and the peers close to that relay will fail. This reliability issue is somewhat mitigated by the possibility to deploy many relays, arbitrarily close from the native IPv6 hosts that require connectivity with Teredo peers.

Teredo imposes some restrictions on the network topologies for proper operation. In particular, if the same NAT is on the path between two clients and the Teredo server, these clients will only be able to interoperate if they are connected to the same link, or

if the common NAT is capable "hairpinning", i.e. "looping" packets sent by one client to another.

There are also additional points of brittleness that are worth mentioning:

- Teredo service will not work through NATs of the symmetric variety.

- Teredo service depends on the Teredo server running on a network that is a common ancestor to all Teredo clients; typically this is the public Internet. If the teredo server is itself behind a NAT, teredo service will not work to certain peers

- Teredo introduces jitter into the IPv6 service it provides, due to the queuing of packets while bubble exchanges take place. This jitter can negatively impact applications, particularly latency sensitive ones, such as VoIP.

8.4 Requirements for a Long Term Solution

From [RFC3424], any UNSAF proposal must identify requirements for longer term, sound technical solutions -- contribute to the process of finding the right longer term solution.

Our experience with Teredo has led to the following requirements for a long term solution to the NAT problem: the devices that implement the IPv4 NAT services should in the future also become IPv6 routers.

9 IANA Considerations

This memo documents a request to IANA to allocate a 32 bit Teredo IPv6 service prefix, as specified in section 2.6, and a Teredo IPv4 multicast address, as specified in section 2.17.

10 Acknowledgements

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