Network Working Group
Internet Draft
Expiration Date: November 2003

Stanislav Shalunov
Benjamin Teitelbaum
Anatoly Karp
Jeff W. Boote
Matthew J. Zekauskas
Internet2
May 2003

A One-way Active Measurement Protocol (OWAMP)
<draft-ietf-ippm-owdp-06.txt>

1. Status of this Memo

This document is an Internet-Draft and is in full conformance with all provisions of Section 10 of RFC2026.

Internet-Drafts are working documents of the Internet Engineering Task Force (IETF), its areas, and its working groups. Note that other groups may also distribute working documents as Internet-Drafts.

Internet-Drafts are draft documents valid for a maximum of six months and may be updated, replaced, or obsoleted by other documents at any time. It is inappropriate to use Internet-Drafts as reference material or to cite them other than as "work in progress."

The list of current Internet-Drafts can be accessed at http://www.ietf.org/ietf/1id-abstracts.txt

The list of Internet-Draft shadow directories can be accessed at http://www.ietf.org/shadow.html

This memo provides information for the Internet community. This memo does not specify an Internet standard of any kind. Distribution of this memo is unlimited.

2. Abstract

With growing availability of good time sources to network nodes, it becomes increasingly possible to measure one-way IP performance metrics with high precision. To do so in an interoperable manner, a common protocol for such measurements is required. The One-Way Active Measurement Protocol (OWAMP) can measure one-way delay, as well as other unidirectional characteristics, such as one-way loss.

3. Motivation and Goals

The IETF IP Performance Metrics (IPPM) working group has proposed draft standard metrics for one-way packet delay [RFC2679] and loss [RFC 2680] across Internet paths. Although there are now several measurement platforms that implement collection of these metrics [SURVEYOR], [RIPE], there is not currently a standard that would permit initiation of test streams or exchange of packets to collect singleton metrics in an interoperable manner.

With the increasingly wide availability of affordable global positioning system (GPS) and CDMA based time sources, hosts increasingly have available to them very accurate time sources--either directly or through their proximity to NTP primary (stratum 1) time servers. By standardizing a technique for collecting IPPM one-way active measurements, we hope to create an environment where IPPM metrics may be collected across a far broader mesh of Internet paths than is currently possible. One particularly compelling vision is of widespread deployment of open OWAMP servers that would make measurement of one-way delay as commonplace as measurement of round-trip time using an ICMP-based tool like ping.

Additional design goals of OWAMP include being hard to detect and manipulate, security, logical separation of control and test functionality, and support for small test packets.

OWAMP test traffic is hard to detect, because it is simply a stream of UDP packets from and to negotiated port numbers with potentially nothing static in the packets (size is negotiated, too). Additionally, OWAMP supports an encrypted mode, that further obscures the traffic, at the same time making it impossible to alter timestamps undetectably.

Security features include optional authentication and/or encryption of control and test messages. These features may be useful to prevent unauthorized access to results or man-in-the-middle attackers who attempt to provide special treatment to OWAMP test streams or who attempt to modify sender-generated timestamps to falsify test results.

3.1. Relationship of Test and Control Protocols

OWAMP actually consists of two inter-related protocols: OWAMP-Control and OWAMP-Test. OWAMP-Control is used to initiate, start and stop test sessions and fetch their results, while OWAMP-Test is used to exchange test packets between two measurement nodes.

Although OWAMP-Test may be used in conjunction with a control protocol other than OWAMP-Control, the authors have deliberately chosen to include both protocols in the same draft to encourage the implementation and deployment of OWAMP-Control as a common denominator control protocol for one-way active measurements. Having a complete and open one-way active measurement solution that is simple to implement and deploy is crucial to assuring a future in which inter-domain one-way active measurement could become as commonplace as ping. We neither anticipate nor recommend that OWAMP-Control form the foundation of a general purpose extensible measurement and monitoring control protocol.

OWAMP-Control is designed to support the negotiation of one-way active measurement sessions and results retrieval in a straightforward manner. At session initiation, there is a negotiation of sender and receiver addresses and port numbers, session start time, session length, test packet size, the mean Poisson sampling interval for the test stream, and some attributes of the very general RFC 2330 notion of `packet type', including packet size and per-hop behavior (PHB) [RFC2474], which could be used to support the measurement of one-way active across diff-serv networks. Additionally, OWAMP-Control supports per-session encryption and authentication for both test and control traffic, measurement servers which may act as proxies for test stream endpoints, and the exchange of a seed value for the pseudo-random Poisson process that describes the test stream generated by the sender.

We believe that OWAMP-Control can effectively support one-way active measurement in a variety of environments, from publicly accessible measurement `beacons' running on arbitrary hosts to network monitoring deployments within private corporate networks. If integration with SNMP or proprietary network management protocols is required, gateways may be created.

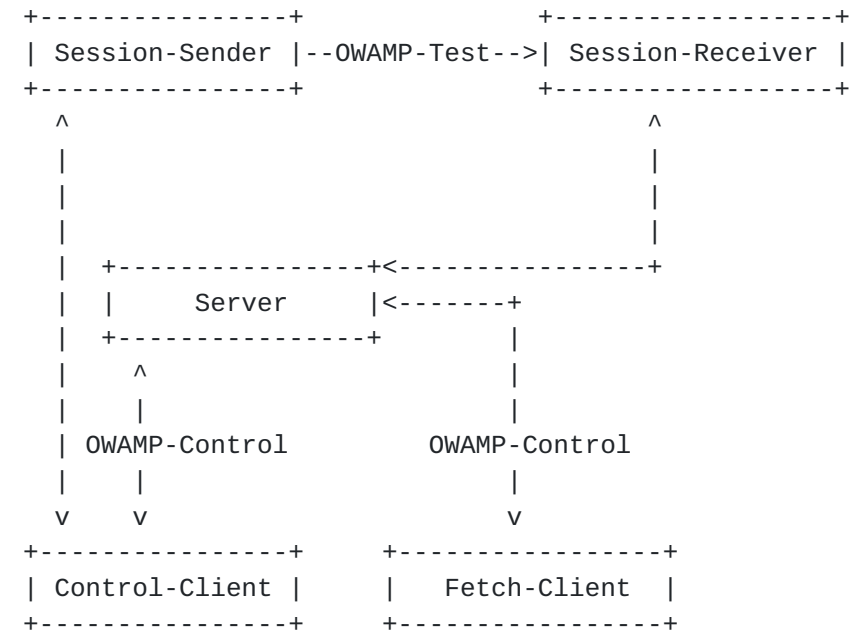
3.2. Logical Model

Several roles are logically separated to allow for broad flexibility in use. Specifically, we define:

Session-Sender	the sending endpoint of an OWAMP-Test session;
Session-Receiver	the receiving endpoint of an OWAMP-Test session;
Server	an end system that manages one or more OWAMP-Test sessions, is capable of configuring per-session state in session endpoints, and is capable of returning the results of a test session;

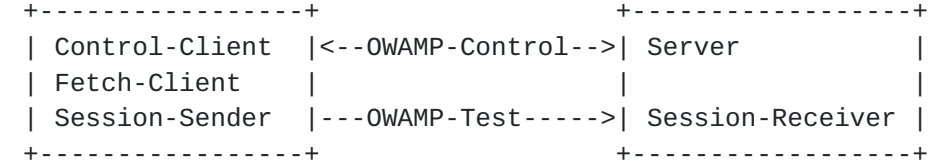
Control-Client	an end system that initiates requests for OWAMP-Test sessions, triggers the start of a set of sessions, and may trigger their termination;
Fetch-Client	an end system that initiates requests to fetch the results of completed OWAMP-Test sessions;

One possible scenario of relationships between these roles is shown below.



(Unlabeled links in the figure are unspecified by this draft and may be proprietary protocols.)

Different logical roles can be played by the same host. For example, in the figure above, there could actually be only two hosts: one playing the roles of Control-Client, Fetch-Client, and Session-Sender, and the other playing the roles of Server and Session-Receiver. This is shown below.



Finally, because many Internet paths include segments that transport IP over ATM, delay and loss measurements can include the effects of ATM segmentation and reassembly (SAR). Consequently, OWAMP has been designed to allow for small test packets that would fit inside the

payload of a single ATM cell (this is only achieved in unauthenticated and encrypted modes).

4. Protocol Overview

As described above, OWAMP consists of two inter-related protocols: OWAMP-Control and OWAMP-Test. The former is layered over TCP and is used to initiate and control measurement sessions and to fetch their results. The latter protocol is layered over UDP and is used to send singleton measurement packets along the Internet path under test.

The initiator of the measurement session establishes a TCP connection to a well-known port on the target point and this connection remains open for the duration of the OWAMP-Test sessions. IANA will be requested to allocate a well-known port number for OWAMP-Control sessions. An OWAMP server SHOULD listen to this well-known port.

OWAMP-Control messages are transmitted only before OWAMP-Test sessions are actually started and after they complete (with the possible exception of an early Stop-Session message).

The OWAMP-Control and OWAMP-Test protocols support three modes of operation: unauthenticated, authenticated, and encrypted. The authenticated or encrypted modes require endpoints to possess a shared secret.

All multi-octet quantities defined in this document are represented as unsigned integers in network byte order unless specified otherwise.

5. OWAMP-Control

Each type of OWAMP-Control message has a fixed length. The recipient will know the full length of a message after examining first 16 octets of it. No message is shorter than 16 octets.

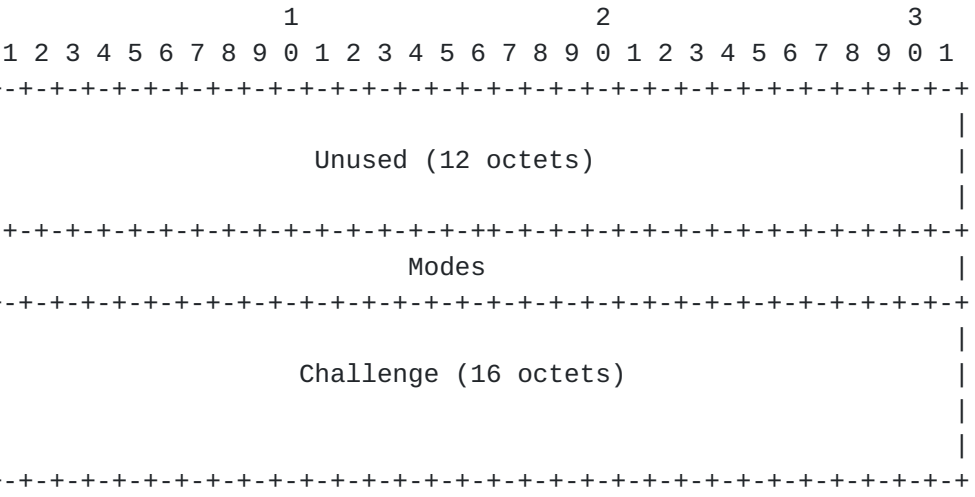
If the full message is not received within 30 minutes after it is expected, connection SHOULD be dropped.

5.1. Connection Setup

Before either a Control-Client or a Fetch-Client can issue commands of a Server, it must establish a connection to the server.

First, a client opens a TCP connection to the server on a well-known

port. The server responds with a server greeting:

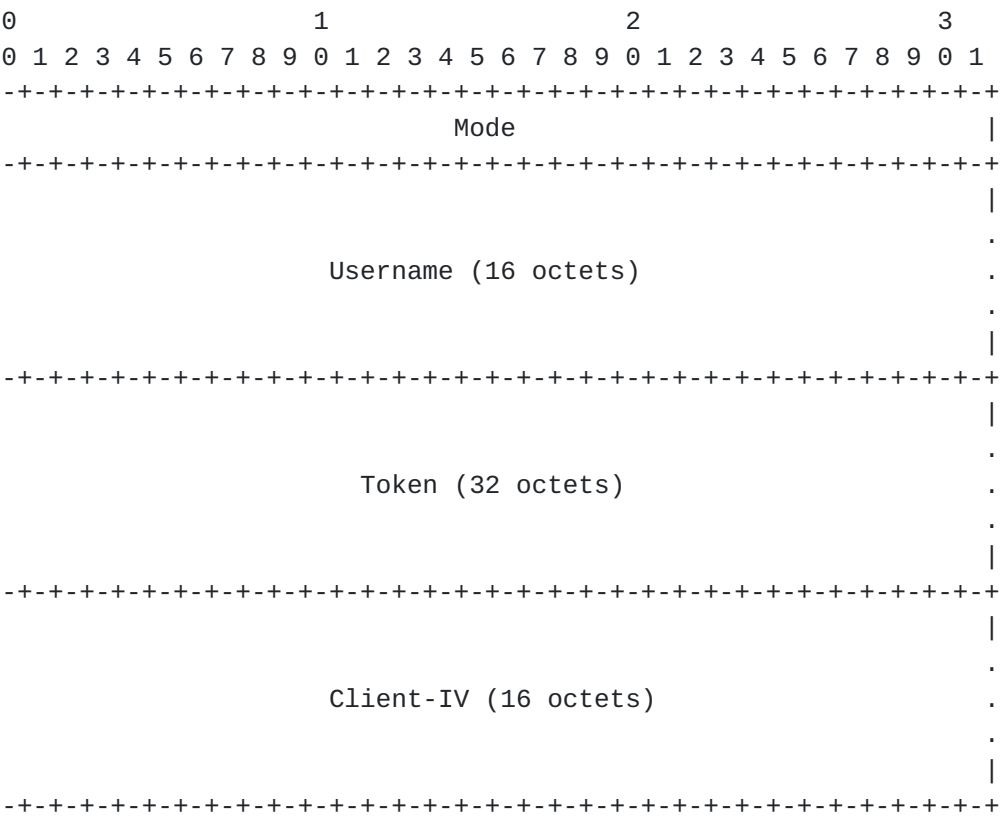


The following mode values are meaningful: 1 for unauthenticated, 2 for authenticated, 4 for encrypted. The value of the Modes field sent by the server is the bit-wise OR of the mode values that it is willing to support during this session. Thus, last three bits of the Modes 32-bit value are used. The first 29 bits MUST be zero. A client MUST ignore the values in the first 29 bits of the Modes value. (This way, the bits are available for future protocol extensions. This is the only intended extension mechanism.)

Challenge is a random sequence of octets generated by the server; it is used subsequently by the client to prove possession of a shared secret in a manner prescribed below.

If Modes value is zero, the server doesn't wish to communicate with the client and MAY close the connection immediately. The client SHOULD close the connection if it gets a greeting with Modes equal to zero. The client MAY close the connection if the client's desired mode is unavailable.

Otherwise, the client MUST respond with the following message:



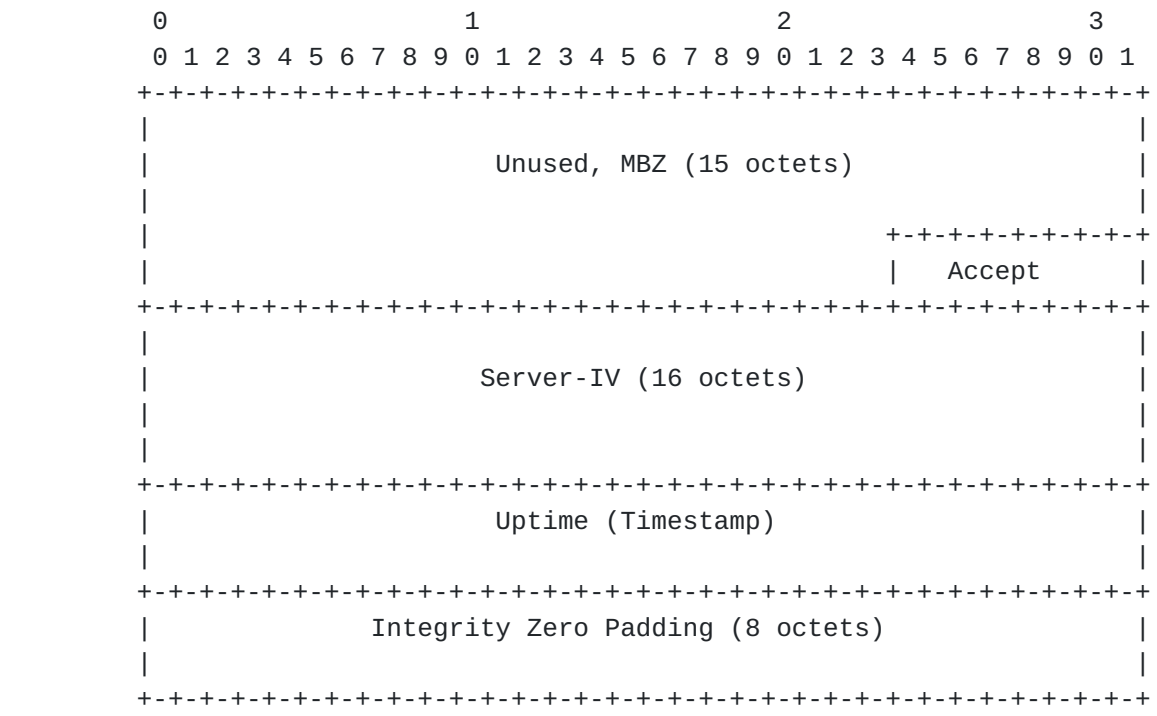
Here Mode is the mode that the client chooses to use during this OWAMP-Control session. It will also be used for all OWAMP-Test sessions started under control of this OWAMP-Control session. In Mode, one or zero bits MUST be set within last three bits. The first 29 bits of Mode MUST be zero. A server MUST ignore the values of the first 29 bits.

In unauthenticated mode, Username, Token, and Client-IV are unused.

Otherwise, Username is a 16-octet indicator of which shared secret the client wishes to use to authenticate or encrypt and Token is the concatenation of a 16-octet challenge and a 16-octet Session-key, encrypted using the AES (Advanced Encryption Standard) [AES] in Cipher Block Chaining (CBC). Encryption MUST be performed using an Initialization Vector (IV) of zero and a key value that is the shared secret associated with Username. The shared secret will typically be provided as a passphrase; in this case, the MD5 sum [RFC1321] of the passphrase (without possible newline character(s) at the end of the passphrase) SHOULD be used as a key for encryption by the client and decryption by the server (the passphrase also SHOULD NOT contain newlines in the middle).

Session-key and Client-IV are generated randomly by the client.

The server MUST respond with the following message:



The Unused 15-octet part MUST be zero. The client MUST ignore its value.

Server-IV is generated randomly by the server. In unauthenticated mode, Server-IV is unused.

A zero value in the Accept field means that the server accepts the authentication and is willing to conduct further transactions. A value of 1 means that the server does not accept the authentication provided by the client or, for some other reason, is not willing to conduct further transactions in this OWAMP-Control session. All other values are reserved. The client MUST interpret all values of Accept other than 0 and 1 as 1. This way, other values are available for future extensions. If a negative response is sent, the server MAY and the client SHOULD close the connection after this message.

Uptime is a timestamp representing the time when the current instantiation of the server started operating. (For example, in a multi-user general purpose operating system, it could be the time when the server process was started.) If Accept is non-zero, Uptime SHOULD be set to a string of zeros. In authenticated and encrypted modes, Uptime is encrypted as described in the next section, unless Accept is non-zero. (authenticated and encrypted mode can not be entered unless the control connection can be initialized.)

Timestamp format is described in `Sender Behavior' section below. The same instantiation of the server SHOULD report the same exact Uptime value to each client in each session.

Integrity Zero Padding is treated the same way as Integrity Zero Padding in the next section and beyond.

The previous transactions constitute connection setup.

5.2. OWAMP-Control Commands

In authenticated or encrypted mode (which are identical as far as OWAMP-Control is concerned, and only differ in OWAMP-Test) all further communications are encrypted with the Session-key, using CBC mode. The client encrypts its stream using Client-IV. The server encrypts its stream using Server-IV.

The following commands are available for the client: Request-Session, Start-Sessions, Stop-Session, Fetch-Session. The command Stop-Session is available to both the client and the server. (The server can also send other messages in response to commands it receives.)

After Start-Sessions is sent/received by the client/server, and before it both sends and receives Stop-Session (order unspecified), it is said to be conducting active measurements.

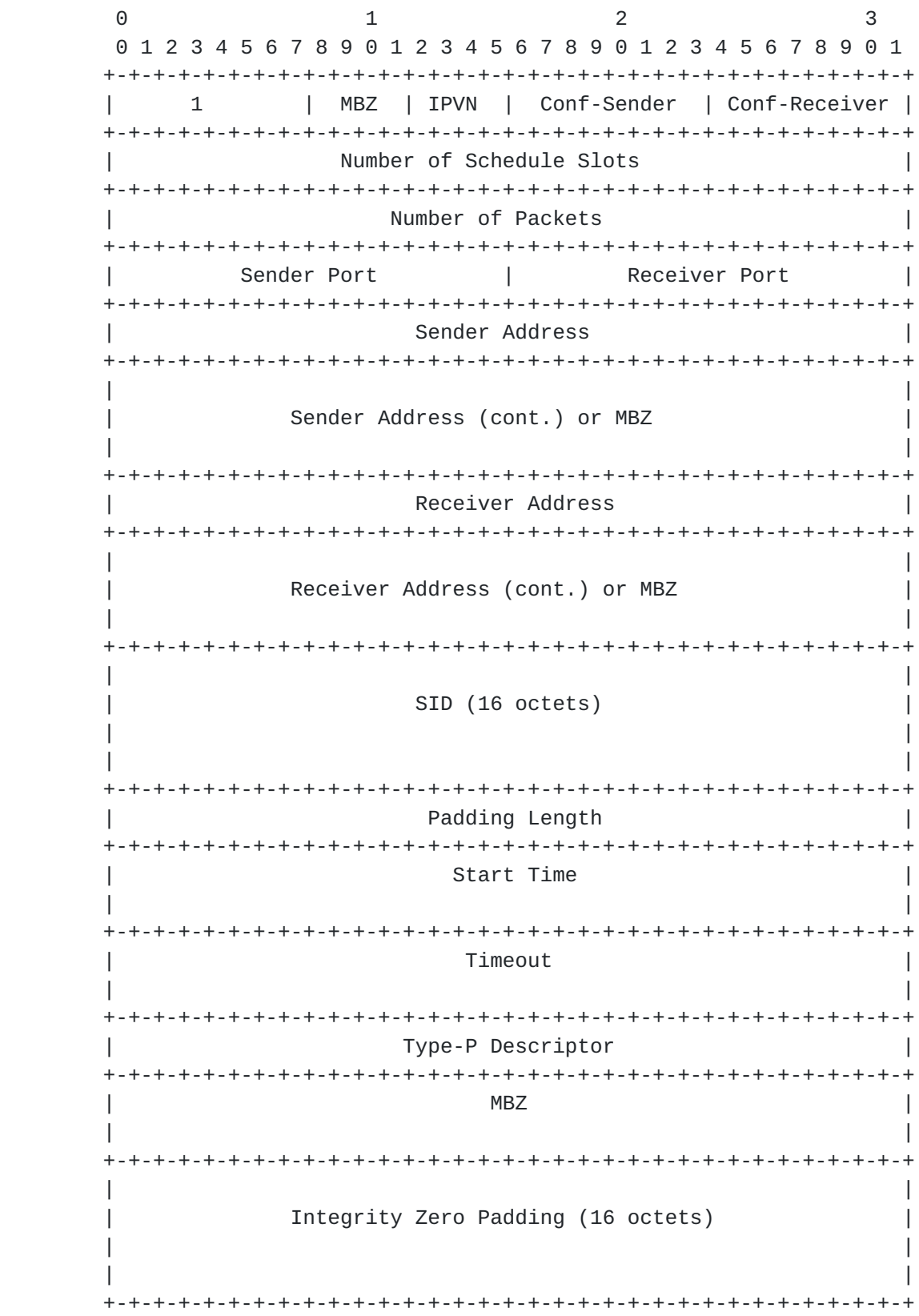
While conducting active measurements, the only command available is Stop-Session.

These commands are described in detail below.

5.3. Creating Test Sessions

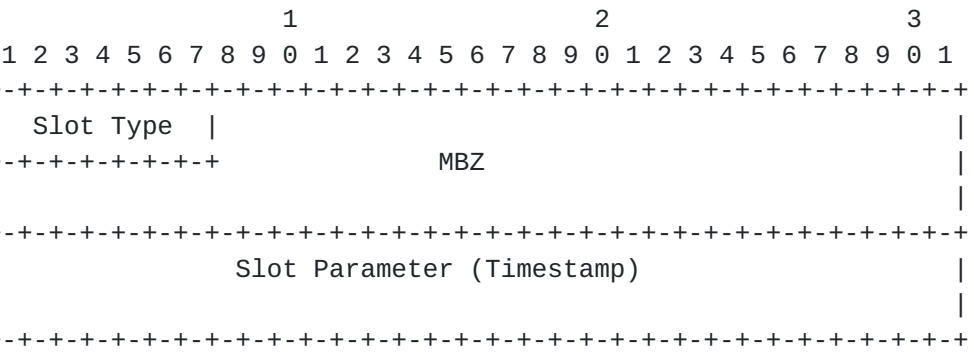
Individual one-way active measurement sessions are established using a simple request/response protocol. An OWAMP client MAY issue zero or more Request-Session messages to an OWAMP server, which MUST respond to each with an Accept-Session message. An Accept-Session message MAY refuse a request.

The format of Request-Session message is as follows:

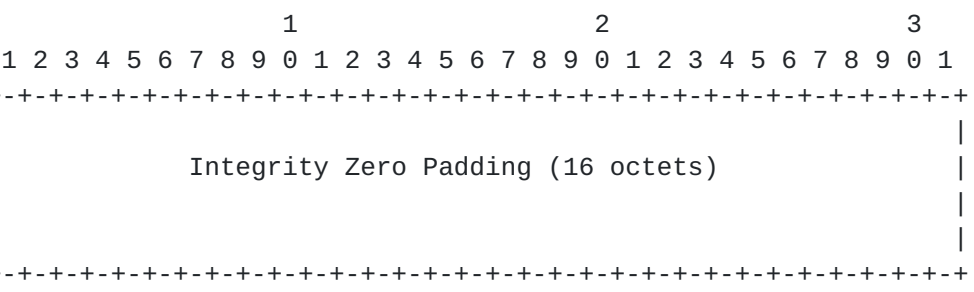


This is immediately followed by one or more schedule slot

descriptions (the number of schedule slots is specified in the `Number of Schedule Slots' field above):



These are immediately followed by Integrity Zero Padding:



All these messages comprise one logical message: the Request-Session command.

Above, the first octet (1) indicates that this is Request-Session command.

IPVN is the IP version numbers for Sender and Receiver. In the case of IP version number being 4, twelve octets follow the four-octet IPv4 address stored in Sender Address and Receiver address. These octets MUST be set to zero by the client and MUST be ignored by the server. Currently meaningful IPVN values are 4 and 6.

Conf-Sender and Conf-Receiver MUST be set to 0 or 1 by the client. The server MUST interpret any non-zero value as 1. If the value is 1, the server is being asked to configure the corresponding agent (sender or receiver). In this case, the corresponding Port value SHOULD be disregarded by the server. At least one of Conf-Sender and Conf-Receiver MUST be 1. (Both can be set, in which case the server is being asked to perform a session between two hosts it can configure.)

Number of Schedule Slots, as mentioned before, specifies the number of slot records that go between the two blocks of Integrity Zero

Padding. It is used by the sender to determine when to send test packets (see next section).

Number of Packets is the number of active measurement packets to be sent during this OWAMP-Test session (note that both server and client can abort the session early).

If Conf-Sender is not set, Sender Port is the UDP port OWAMP-Test packets will be sent from. If Conf-Receiver is not set, Receiver Port is the UDP port OWAMP-Test packets are requested to be sent to.

The Sender Address and Receiver Address fields contain respectively the sender and receiver addresses of the end points of the Internet path over which an OWAMP test session is requested.

SID is the session identifier. It can be used in later sessions as an argument for Fetch-Session command. It is meaningful only if Conf-Receiver is 0. This way, the SID is always generated by the receiving side. See the end of the section for information on how the SID is generated.

Padding length is the number of octets to be appended to normal OWAMP-Test packet (see more on padding in discussion of OWAMP-Test).

Start Time is the time when the session is to be started (but not before Start-Sessions command is issued). This timestamp is in the same format as OWAMP-Test timestamps.

Timeout (or a loss threshold) is an interval of time (expressed as a timestamp). A packet belonging to the test session that is being set up by the current Request-Session command will be considered lost if it is not received during Timeout seconds after it is sent.

Type-P Descriptor covers only a subset of (very large) Type-P space. If the first two bits of Type-P Descriptor are 00, then subsequent 6 bits specify the requested Differentiated Services Codepoint (DSCP) value of sent OWAMP-Test packets as defined in RFC 2474. If the first two bits of Type-P descriptor are 01, then subsequent 16 bits specify the requested Per Hop Behavior Identification Code (PHB ID) as defined in RFC 2836.

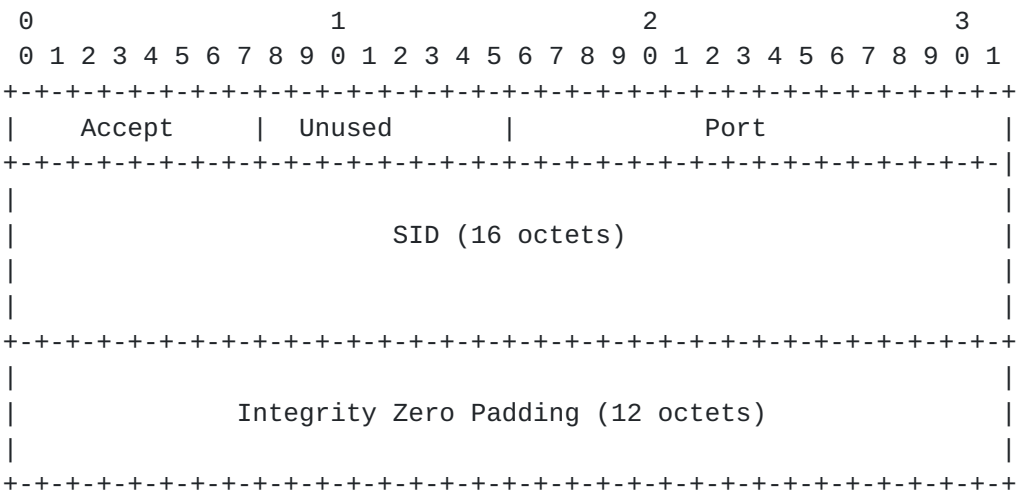
Therefore, the value of all zeros specifies the default best-effort service.

If Conf-Sender is set, Type-P Descriptor is to be used to configure the sender to send packets according to its value. If Conf-Sender is not set, Type-P Descriptor is a declaration of how the sender will be configured.

If Conf-Sender is set and the server doesn't recognize Type-P Descriptor, cannot or does not wish to set the corresponding attributes on OWAMP-Test packets, it SHOULD reject the session request. If Conf-Sender is not set, the server SHOULD accept the session regardless of the value of Type-P Descriptor.

Integrity Zero Padding MUST be all zeros in this and all subsequent messages that use zero padding. The recipient of a message where zero padding is not zero MUST reject the message as it is an indication of tampering with the content of the message by an intermediary (or brokenness). If the message is part of OWAMP-Control, the session MUST be terminated and results invalidated. If the message is part of OWAMP-Test, it MUST be silently ignored. This will ensure data integrity. In unauthenticated mode, Integrity Zero Padding is nothing more than a simple check. In authenticated and encrypted modes, however, it ensures, in conjunction with properties of CBC chaining mode, that everything received before was not tampered with. For this reason, it is important to check the Integrity Zero Padding Field as soon as possible, so that bad data doesn't get propagated.

To each Request-Session message, an OWAMP server MUST respond with an Accept-Session message:



In this message, zero in the Accept field means that the server is willing to conduct the session. A value of 1 indicates rejection of the request. All other values are reserved.

If the server rejects a Request-Session command, it SHOULD not close the TCP connection. The client MAY close it if it gets negative response to Request-Session.

The meaning of Port in the response depends on the values of Conf-

Sender and Conf-Receiver in the query that solicited the response. If both were set, Port field is unused. If only Conf-Sender was set, Port is the port to expect OWAMP-Test packets from. If only Conf-Receiver was set, Port is the port to send OWAMP-Test packets to.

If only Conf-Sender was set, SID field in the response is unused. Otherwise, SID is a unique server-generated session identifier. It can be used later as handle to fetch the results of a session.

SIDs SHOULD be constructed by concatenation of 4-octet IPv4 IP number belonging to the generating machine, 8-octet timestamp, and 4-octet random value. To reduce the probability of collisions, if the generating machine has any IPv4 addresses (with the exception of loopback), one of them SHOULD be used for SID generation, even if all communication is IPv6-based. If it has no IPv4 addresses at all, the last 4 octets of an IPv6 address can be used instead. Note that SID is always chosen by the receiver. If truly random values are not available, it is important that SID be made unpredictable as knowledge of SID might be used for access control.

5.4. Send Schedules

The sender and the receiver need to both know the same send schedule. This way, when packets are lost, the receiver knows when they were sent. It is desirable to compress common schedules and still to be able to use an arbitrary one for the test sessions. In many cases, the schedule will consist of repeated sequences of packets: this way, the sequence performs some test, and the test is repeated a number of times to gather statistics.

To implement this, we have a schedule with a given number of `slots'. Each slots has a type and a parameter. Two types are supported: exponentially distributed pseudo-random quantity (denoted by a code of 0) and a fixed quantity (denoted by a code of 1). The parameter is expressed as a timestamp and specifies a time interval. For a type 0 slot (exponentially distributed pseudo-random quantity) this interval is the mean value (or 1/lambda if the distribution density function is expressed as lambda*exp(-lambda*x) for positive values of x). For a type 1 slot, the parameter is the delay itself. The sender starts with the beginning of the schedule, and `executes' the instructions in the slots: for a slot of type 0, wait exponentially distributed time with mean of the specified parameter and then send a test packet (and proceed to the next slot); for a slot of type 1, wait the specified time and send a test packet (and proceed to the next slot). The schedule is circular: when there are no more slots, the sender returns to the first slot.

The sender and the receiver must be able to reproducibly execute the entire schedule (so if a packet is lost, the receiver can still attach a send timestamp to it). Slots of type 1 are trivial to reproducibly execute. To reproducibly execute slots of type 0, we need to be able to generate pseudo-random exponentially distributed quantities in a reproducible manner. The way this is accomplished is discussed later.

Using this mechanism one can easily specify common testing scenarios:

+ Poisson stream: a single slot of type 0;

+ Periodic stream: a single slot of type 1;

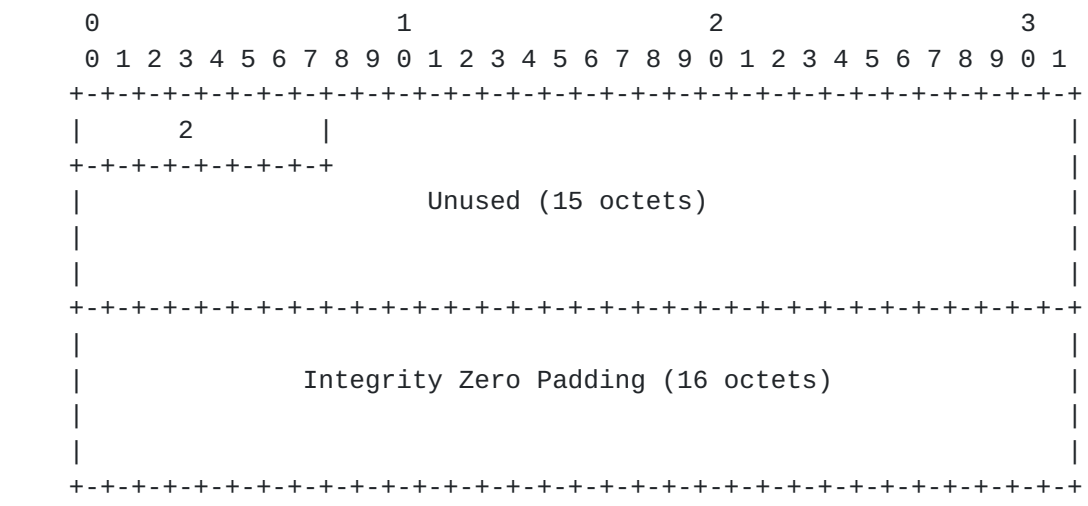
+ Poisson stream of back-to-back packet pairs: two slots -- type 0 with a non-zero parameter and type 1 with a zero parameter.

A completely arbitrary schedule can be specified (albeit inefficiently) by making the number of test packets equal to the number of schedule slots. In this case, the complete schedule is transmitted in advance of an OWAMP-Test session.

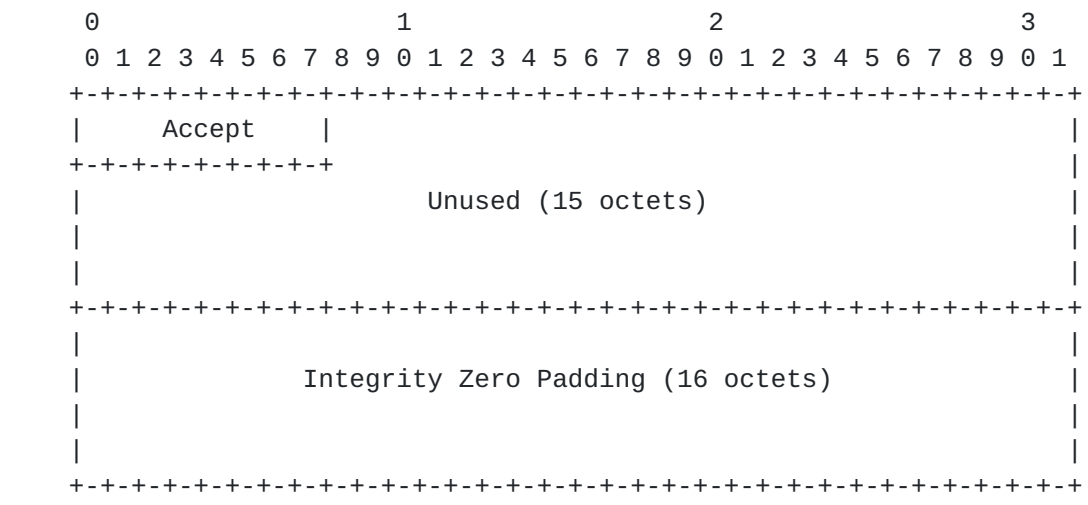
5.5. Starting Test Sessions

Having requested one or more test sessions and received affirmative Accept-Session responses, an OWAMP client may start the execution of the requested test sessions by sending a Start-Sessions message to the server.

The format of this message is as follows:



The server MUST respond with an Control-Ack message (which SHOULD be sent as quickly as possible). Control-Ack messages have the following format:

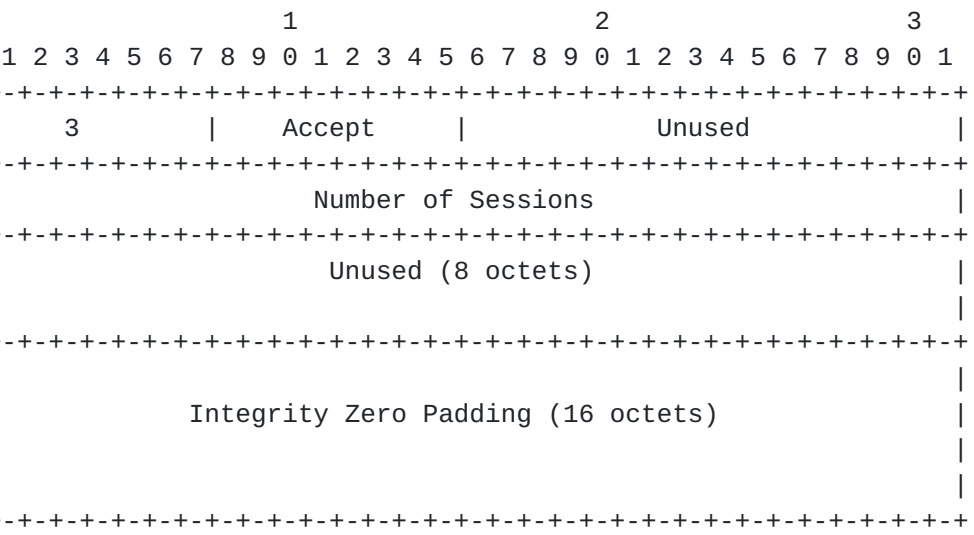


If Accept is 1, the Start-Sessions request was rejected; zero means that the command was accepted. All other values are reserved. The server MAY and the client SHOULD close the connection in the case of a negative response.

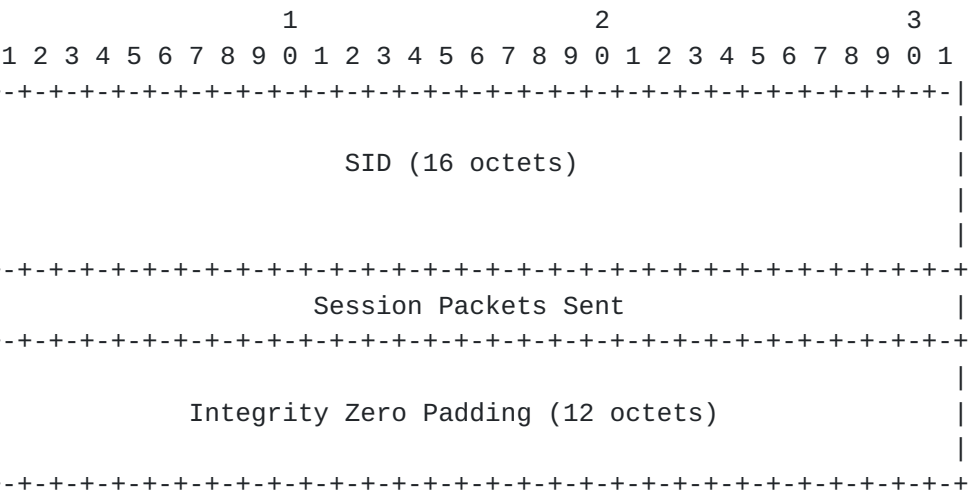
The server SHOULD start all OWAMP-Test streams immediately after it sends the response or immediately after their specified start times, whichever is later. (Note that a client can effect an immediate start by specifying in Request-Session a Start Time in the past.) If the client represents a Sender, the client SHOULD start its OWAMP-Test streams immediately after it sees the Control-Ack response from the Server.

5.6. Stop-Sessions

The Stop-Sessions message may be issued by either the Control-Client or the Server. The format of this command is as follows:



This is immediately followed by 0 or more session packets sent descriptions (the number of session packets sent records is specified in the 'Number of Sessions' field above):



All these messages comprise one logical message: the Stop-Session command.

Above, the first octet (3) indicates that this is the Stop-Session command.

Accept values of 1 indicate a failure of some sort. Zero values indicate normal (but possibly premature) completion. All other

values are reserved.

If Accept had a non-zero value (from either party) results of all OWAMP-Test sessions spawned by this OWAMP-Control session SHOULD be considered invalid, even if a Fetch-Session with SID from this session works for a different OWAMP-Control session. If Accept was not transmitted at all (for whatever reason, including the TCP connection used for OWAMP-Control breaking), the results of all OWAMP-Test sessions spawned by this OWAMP-control session MAY be considered invalid.

Number of Sessions indicates the number of session packets sent records that immediately follow the Stop-Sessions message.

Number of Sessions MUST contain the number of send sessions started by the local side of the control connection that have not been previously terminated by a Stop-Sessions command. (i.e. The Control-Client MUST account for each accepted Request-Session where Conf-Receiver was set. The Control-Server MUST account for each accepted Request-Session where Conf-Sender was set.) If the Stop-Sessions message does not account for all the send sessions controlled by that side, then it is to be considered invalid and the connection SHOULD be closed and any results obtained considered invalid.

Each session packets sent record represents one OWAMP-Test session and contains the session identifier (SID) and the number of packets sent in that session. For completed sessions, Session Packets Sent will equal NumPackets from the Request-Session. Session Packets Sent MAY be all ones (0xFFFFFFFF); in this case, the sender of the Stop-Sessions command could not determine the number of packets sent (perhaps, due to some internal error such as a process crash); this special value SHOULD NOT be sent under normal operating conditions.

If the OWAMP-Control connection associated with an OWAMP-Test receiver receives the (0xFFFFFFFF) special value for the Session Packets Sent, or if the OWAMP-Control connection breaks when the Stop-Sessions command is sent, the receiver MAY not completely invalidate the session results. It MUST discard any records of lost packets that follow (in other words, have greater sequence number than) the last packet that was actually received. This will help differentiate between packet losses that occurred in the network and the sender crashing. When the results of such an OWAMP-Test session or an OWAMP-Test session that was prematurely aborted successfully (with confirmation) are later fetched using Fetch-Session, the original number of packets MUST be supplied in the reproduction of the Request-Session command.

If a receiver of an OWAMP-Test session learns through OWAMP-Control

Stop-Sessions message that the OWAMP-Test sender's last sequence number is lower than any sequence number actually received, the results of the complete OWAMP-Test session MUST be invalidated.

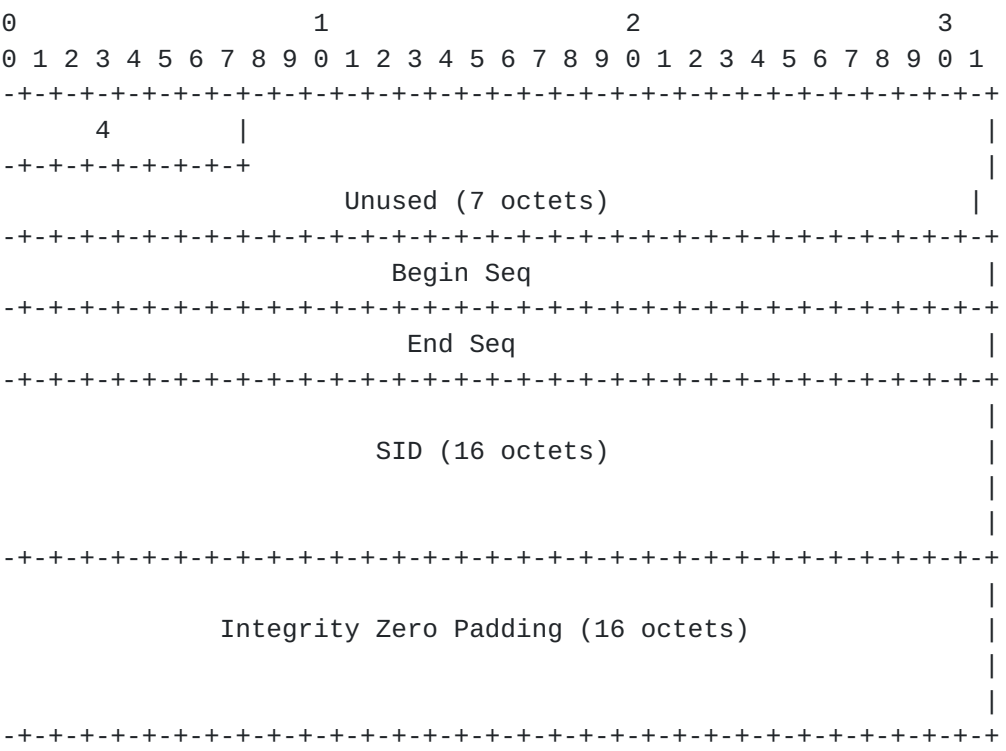
A receiver of an OWAMP-Test session, upon receipt of an OWAMP-Control Stop-Sessions command, MUST discard any packet records -- including lost packet records -- with a (computed) send time that falls between the current time minus timeout and the current time. This ensures statistical consistency for the measurement of loss and duplicates in the event that the timeout is greater than the time it takes for the Stop-Sessions command to take place.

To effect complete sessions, each side of the control connection SHOULD wait until all Sessions are complete before sending the Stop-Sessions message. The completed time of each sessions is determined as Timeout after the scheduled time for the last sequence number. Endpoints MAY add a small increment to the computed completed time for send endpoints to ensure the Stop-Sessions message reaches the receiver endpoint after Timeout.

To effect a premature stop of sessions, the party that initiates this command MUST stop its OWAMP-Test send streams to send the Session Packets Sent values before sending this command. That party SHOULD wait until receiving the response Stop-Sessions message before stopping the receiver streams so that it can use the values from the received Stop-Sessions message to validate the data.

5.7. Fetch-Session

The format of this client command is as follows:



Begin Seq is the sequence number of the first requested packet. End Seq is the sequence number of the last requested packet. If Begin Seq is all zeros and End Seq is all ones, complete session is said to be requested.

If a complete session is requested and the session is still in progress, or has terminated in any way other than normal, the request to fetch session results MUST be denied. If an incomplete session is requested, all packets received so far that fall into the requested range SHOULD be returned. Note that since no commands can be issued between Start-Sessions and Stop-Sessions, incomplete requests can only happen on a different OWAMP-Control connection (from the same or different host as Control-Client).

The server MUST respond with a Control-Ack message. Again, 1 in the Accept field means rejection of command. Zero means that data will follow. All other values are reserved.

If Accept was 0, the server then MUST send the OWAMP-Test session data in question, followed by 16 octets of Integrity Zero Padding.

The OWAMP-Test session data consists of the following (concatenated):

+ A reproduction of the Request-Session command that was used to start the session; it is modified so that actual sender and receiver port numbers that were used by the OWAMP-Test session

always appear in the reproduction.

+ The number of packet records that will follow represented as an unsigned 4-octet integer. This number might be less than the Number of Packets in the reproduction of the Request-Session command because of a session that ended prematurely; or it might be greater because of duplicates.

+ 12 octets of Integrity Zero Padding.

+ Zero or more (as specified) packet records.

Each packet record is 24 octets, and includes 4 octets of sequence number, 8 octets of send timestamp, 2 octets of send timestamp error estimate, 8 octets of receive timestamp, and 2 octets of receive timestamp error estimate (in this order). Packet records are sent out in the same order they are made when the results of the session are recorded. Therefore, the data is in arrival order.

Note that lost packets (if any losses were detected during the OWAMP-Test session) MUST appear in the sequence of packets. They can appear either at the point when the loss was detected or at any later point. Lost packet records are distinguished by the receive timestamp consisting of a string of zero bits and an error estimate with Multiplier=1, Scale=64, and S=0 (see OWAMP-Test description for definition of these quantities and explanation of timestamp format and error estimate format).

The last (possibly full, possibly incomplete) block (16 octets) of data is padded with zeros if necessary. (These zeros are simple padding and should be distinguished from the 16 octets of Integrity Zero Padding that follow the session data and conclude the response to Fetch-Session.)

6. OWAMP-Test

This section describes OWAMP-Test protocol. It runs over UDP using sender and receiver IP and port numbers negotiated during Request-Session exchange.

As OWAMP-Control, OWAMP-Test has three modes: unauthenticated, authenticated, and encrypted. All OWAMP-Test sessions spawned by an OWAMP-Control session inherit its mode.

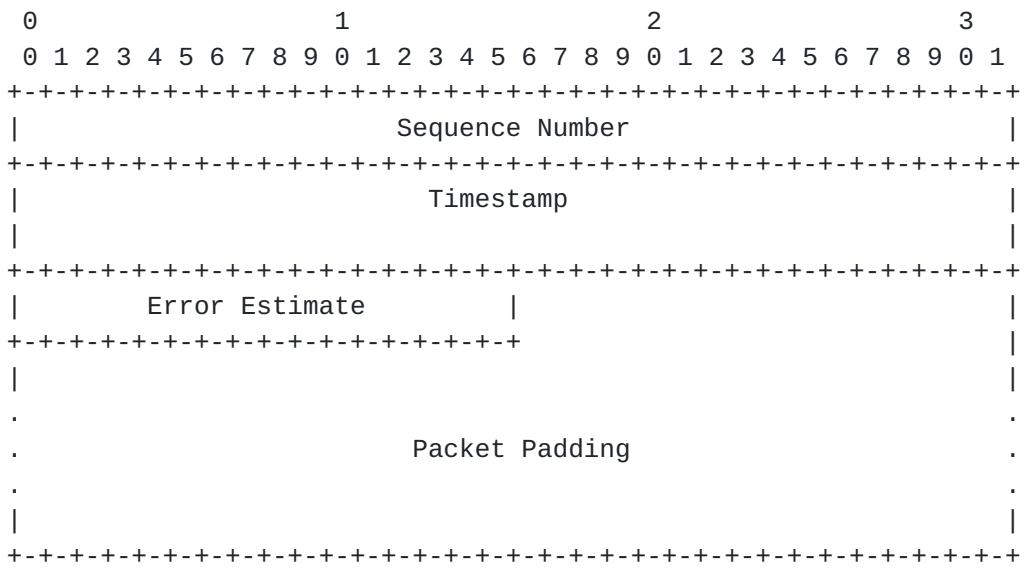
OWAMP-Control client, OWAMP-Control server, OWAMP-Test sender, and OWAMP-Test receiver can potentially all be different machines. (In a

typical case we expect that there will be only two machines.)

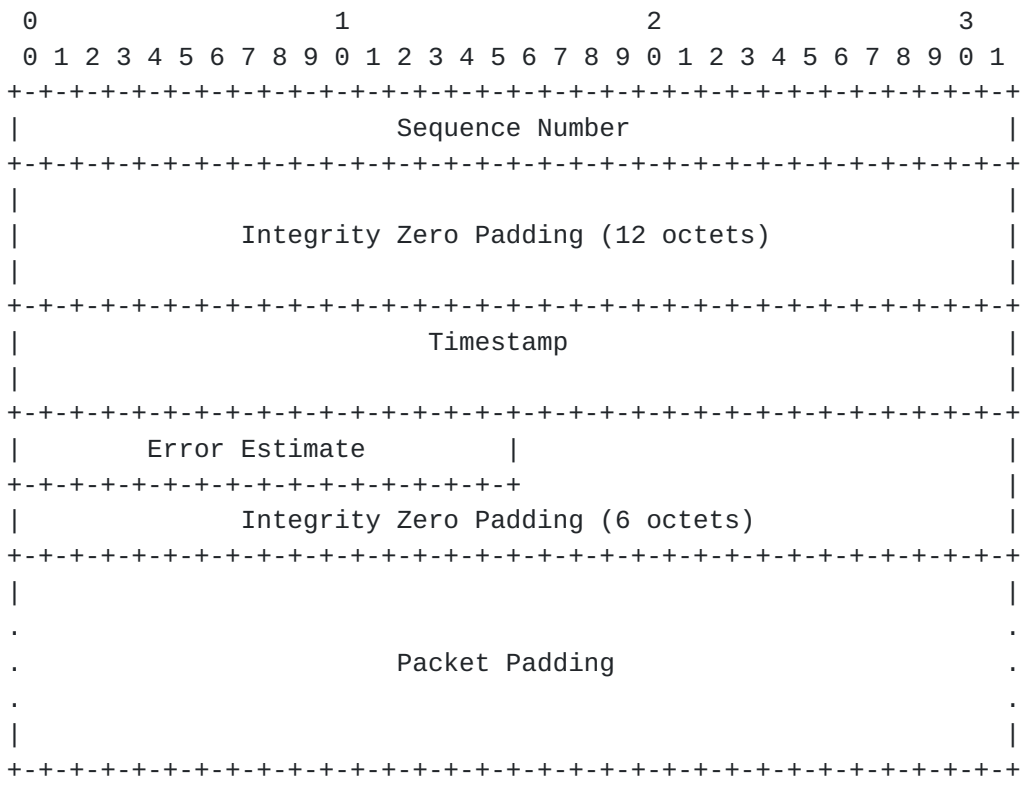
6.1. Sender Behavior

The sender sends the receiver a stream of packets with schedule as specified in the Request-Session command. The format of the body of a UDP packet in the stream depends on the mode being used.

For unauthenticated mode:

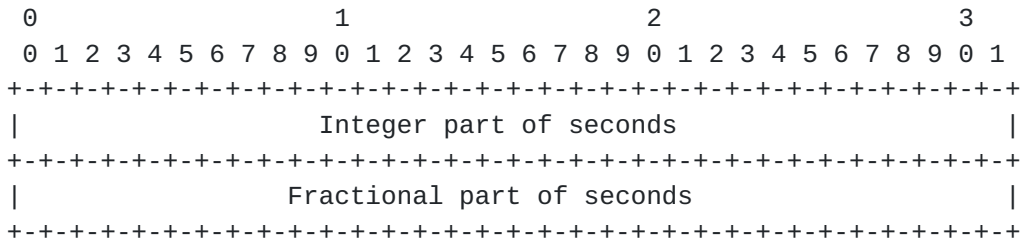


For authenticated and encrypted modes:

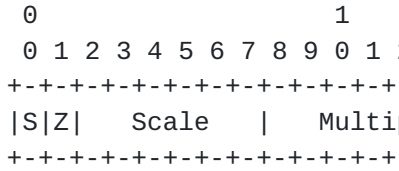


The format of the timestamp is the same as in RFC 1305 and is as follows: first 32 bits represent the unsigned integer number of seconds elapsed since 0h on 1 January 1900; next 32 bits represent the fractional part of a second that has elapsed since then.

So, Timestamp is represented as follows:



The Error Estimate specifies the estimate of the error and synchronization. It has the following format:



The first bit S SHOULD be set if the party generating the timestamp has a clock that is synchronized to UTC using an external source

(e.g., the bit should be set if GPS hardware is used and it indicates that it has acquired current position and time or if NTP is used and it indicates that it has synchronized to an external source, which includes stratum 0 source, etc.); if there is no notion of external synchronization for the time source, the bit SHOULD NOT be set. The next bit has the same semantics as MBZ fields elsewhere: it MUST be set to zero by the sender and ignored by everyone else. The next six bits Scale form an unsigned integer; Multiplier is an unsigned integer as well. They are interpreted as follows: the error estimate is equal to Multiplier*2^(-32)*2^Scale (in seconds). [Notation clarification: 2^Scale is two to the power of Scale.] Multiplier MUST NOT be set to zero. If Multiplier is zero, the packet SHOULD be considered corrupt and discarded.

Sequence numbers start with 0 and are incremented by 1 for each subsequent packet.

The minimum data segment length is therefore 14 octets in unauthenticated mode, and 32 octets in authenticated mode and encrypted modes.

The OWAMP-Test packet layout is the same in authenticated and encrypted modes. The encryption operations are, however, different. The difference is that in encrypted mode both the sequence number and the timestamp are encrypted to provide maximum data integrity protection while in authenticated mode the sequence number is encrypted and the timestamp is sent in clear text. Sending the timestamp in clear text in authenticated mode allows to reduce the time between a timestamp is obtained by a sender and the packet is shipped out. In encrypted mode, the sender has to fetch the timestamp, encrypt it, and send it; in authenticated mode, the middle step is removed improving accuracy (the sequence number can be encrypted before the timestamp is fetched).

In authenticated mode, the first block (16 octets) of each packet is encrypted using AES ECB mode. The key to use is the same key as is used for the corresponding OWAMP-Control session (where it is used in a different chaining mode). Electronic Cookbook (ECB) mode does not involve any actual chaining; this way, lost, duplicated, or reordered packets do not cause problems with deciphering any packet in an OWAMP-Test session.

In encrypted mode, the first two blocks (32 octets) are encrypted using AES CBC mode. The key to use is the same key as is used for the corresponding OWAMP-Control session. Each OWAMP-Test packet is encrypted as a separate stream, with just one chaining operation; chaining does not span multiple packets so that lost, duplicated, or reordered packets do not cause problems.

In unauthenticated mode, no encryption is applied.

Packet Padding in OWAMP-Test SHOULD be pseudo-random (it MUST be generated independently of any other pseudo-random numbers mentioned in this document). However, implementations MUST provide a configuration parameter, an option, or a different means of making Packet Padding consist of all zeros.

The time elapsed between packets is computed according to the slot schedule as mentioned in Request-Session command description. At that point we skipped over the issue of computing exponentially distributed pseudo-random numbers in a reproducible fashion.

7. Computing Exponentially Distributed Pseudo-Random Numbers

Here we describe the way exponential random quantities used in the protocol are generated. While there is a fair number of algorithms for generating exponential random variables, most of them rely on having logarithmic function as a primitive, resulting in potentially different values, depending on the particular implementation of the math library. We use algorithm 3.4.1.S in [KNUTH], which is free of the above mentioned problem, and guarantees the same output on any implementation. The algorithm belongs to the 'ziggurat' family developed in the 1970s by G.Marsaglia, M.Sibuya and J.H.Ahrens [ZIGG]. It replaces the use of logarithmic function by clever bit manipulation, still producing the exponential variates on output.

7.1. High-Level Description of the Algorithm

For ease of exposition, the algorithm is first described with all arithmetic operations being interpreted in their natural sense. Later, exact details on data types, arithmetic, and generation of the uniform random variates used by the algorithm are given. It is an almost verbatim quotation from [KNUTH], p.133.

Algorithm S: Given a real positive number 'mu', produce an exponential random variate with mean 'mu'.

First, the constants

Q[k] = (ln2)/(1!) + (ln2)^2/(2!) + ... + (ln2)^k/(k!), 1 <= k <= 11

are computed in advance. The exact values which MUST be used by all implementations are given in the reference code (see Appendix). This is necessary to insure that exactly the same pseudo-random sequences are produced by all implementations.

S1. [Get U and shift.] Generate a 32-bit uniform random binary fraction

U = (.b0 b1 b2 ... b31) [note the decimal point]

Locate the first zero bit b_j, and shift off the leading (j+1) bits, setting U <- (.b_{j+1} ... b31)

NOTE: in the rare case that the zero has not been found it is prescribed that the algorithm return (mu*32*ln2).

S2. [Immediate acceptance?] If U < ln2, set X <- mu*(j*ln2 + U) and terminate the algorithm. (Note that Q[1] = ln2.)

S3. [Minimize.] Find the least k >= 2 such that U < Q[k]. Generate k new uniform random binary fractions U1,...,Uk and set V <- min(U1,...,Uk).

S4. [Deliver the answer.] Set X <- mu*(j + V)*ln2.

7.2. Data Types, Representation and Arithmetic

The high-level algorithm operates on real numbers -- typically represented as floating point numbers. This specification prescribes that unsigned 64-bit integers be used instead.

u_int64_t integers are interpreted as real numbers by placing the decimal point after the first 32 bits. In other words, conceptually the interpretation is given by the map:

```
u_int64_t u;

u  |--> (double)u / (2**32)
```

The algorithm produces a sequence of such u_int64_t integers which is guaranteed to be the same on any implementation. Any further interpretation (such as given by (1)) is done by the application, and is not part of this specification.

We specify that the u_int64_t representations of the first 11 values of the Q array in the high-level algorithm be as follows:

```
#1      0xB17217F8,
#2      0xEEF193F7,
#3      0xFD271862,
#4      0xFF9D6DD0,
#5      0xFFF4CFD0,
#6      0xFFFEE819,
#7      0xFFFFE7FF,
#8      0xFFFFFE2B,
#9      0xFFFFFFE0,
#10     0xFFFFFFFE,
#11     0xFFFFFFFF
```

For example, Q[1] = ln2 is indeed approximated by 0xB17217F8/(2**32) = 0.693147180601954; for j > 11, Q[j] is 0xFFFFFFFF

Small integer 'j' in the high-level algorithm is represented as u_int64_t value j * (2**32);

Operation of addition is done as usual on u_int64_t numbers; however, the operation of multiplication in the high-level algorithm should be replaced by

```
(u, v) |---> (u * v) >> 32
```

Implementations MUST compute (u * v) exactly. For example, a fragment of unsigned 128-bit arithmetic can be implemented for this purpose (see sample implementation below).

7.3. Uniform Random Quantities

The procedure for obtaining a sequence of 32-bit random numbers (such as 'U' in algorithm S) relies on using AES encryption in counter mode. To describe the exact working of the algorithm we introduce two primitives from Rijndael. Their prototypes and specification are given below, and they are assumed to be provided by the supporting Rijndael implementation, such as [RIJN].

\+ This function initializes a Rijndael key with bytes from 'seed'

```
void KeyInit(unsigned char seed[16]);
```

\+ This function encrypts the 16-octet block 'inblock' with the 'key' returning a 16-octet encrypted block. Here 'keyInstance' is an opaque type used to represent Rijndael keys.

```
void BlockEncrypt(keyInstance key, unsigned char inblock[16]);
```

Algorithm Unif: given a 16-octet quantity seed, produce a sequence of unsigned 32-bit pseudo-random uniformly distributed integers. In OWAMP, the SID (session ID) from Control protocol plays the role of seed.

U1. [Initialize Rijndael key] key <- KeyInit(seed) [Initialize an unsigned 16-octet (network byte order) counter] c <- 0 U2. [Need more random bytes?] Set i <- c mod 4. If (i == 0) set s <- BlockEncrypt(key, c)

U3. [Increment the counter as unsigned 16-octet quantity] c <- c + 1

U4. [Do output] Output the i_th quartet of octets from s starting from high-order octets, converted to native byte order and represented as OWPNum64 value (as in 3.b).

U5. [Loop] Go to step U2.

7.4. Receiver Behavior

Receiver knows when the sender will send packets. The following parameter is defined: Timeout (from Request-Session). Packets that are delayed by more that Timeout are considered lost (or `as good as lost'). Note that there is never an actual assurance of loss by the network: a `lost' packet might still be delivered at any time. The original specification for IPv4 required that packets be delivered within TTL seconds or never (with TTL having a maximum value of 255). To the best of the authors' knowledge, this requirement was never actually implemented (and of course only a complete and universal implementation would ensure that packets don't travel for longer than TTL seconds). Further, IPv4 specification makes no claims about the time it takes the packet to traverse the last link of the path.

The choice of a reasonable value of Timeout is a problem faced by a user of OWAMP protocol, not by an implementor. A value such as two minutes is very safe. Note that certain applications (such as interactive `one-way ping') might wish to obtain the data faster than that.

As packets are received,

+ Timestamp the received packet.

+ In authenticated or encrypted mode, decrypt first block (16 octets) of packet body.

+ Store the packet sequence number, send times, and receive times for the results to be transferred.

+ Packets not received within the Timeout are considered lost. They are recorded with their seqno, presumed send time, and receive time consisting of a string of zero bits.

Packets that are actually received are recorded in the order of arrival. Lost packet records serve as indications of the send times of lost packets. They SHOULD be placed either at the point where the receiver learns about the loss or at any later point; in particular, one MAY place all the records that correspond to lost packets at the very end.

Packets that have send time in the future MUST be recorded normally, without changing their send timestamp, unless they have to be discarded. (Send timestamps in the future would normally indicate clocks that differ by more than the delay. Some data -- such as jitter -- can be extracted even without knowledge of time difference. For other kinds of data, the adjustment is best handled by the data consumer on the basis of the complete information in a measurement session as well as possibly external data.)

Packets with a sequence number that was already observed (duplicate packets) MUST be recorded normally. (Duplicate packets are sometimes introduced by IP networks. The protocol has to be able to measure duplication.)

If any of the following is true, packet MUST be discarded:

+ Send timestamp is more than Timeout in the past or in the future.

+ Send timestamp differs by more than Timeout from the time when the packet should have been sent according to its seqno.

+ In authenticated or encrypted mode, any of the bits of zero padding inside the first 16 octets of packet body is non-zero.

8. Security Considerations

The goal of authenticated mode to let one passphrase-protect service provided by a particular OWAMP-Control server. One can imagine a variety of circumstances where this could be useful. Authenticated mode is designed to prohibit theft of service.

Additional design objective of authenticated mode was to make it impossible for an attacker who cannot read traffic between OWAMP-Test sender and receiver to tamper with test results in a fashion that affects the measurements, but not other traffic.

The goal of encrypted mode is quite different: To make it hard for a party in the middle of the network to make results look `better' than they should be. This is especially true if one of client and server doesn't coincide with neither sender nor receiver.

Encryption of OWAMP-Control using AES CBC mode with blocks of zeros after each message aims to achieve two goals: (i) to provide secrecy of exchange; (ii) to provide authentication of each message.

OWAMP-Test sessions directed at an unsuspecting party could be used for denial of service (DoS) attacks. In unauthenticated mode servers should limits receivers to hosts they control or to the OWAMP-Control client.

OWAMP-Test sessions could be used as covert channels of information. Environments that are worried about covert channels should take this into consideration.

Notice that AES in counter mode is used for pseudo-random number generation, so implementation of AES MUST be included even in a server that only supports unauthenticated mode.

9. IANA Considerations

IANA is requested to allocate a well-known TCP port number for OWAMP-Control part of the OWAMP protocol.

10. Internationalization Considerations

The protocol does not carry any information in a natural language.

11. Appendix: Sample Implementation of Exponential Deviate Computation

```
/*
** Example usage: generate a stream of exponential (mean 1)
** random quantities (ignoring error checking during initialization).
** If a variate with some mean mu other than 1 is desired, the output
** of this algorithm can be multiplied by mu according to the rules
** of arithmetic we described.

** Assume that a 16-octet 'seed' has been initialized
** (as the shared secret in OWAMP, for example)
** unsigned char seed[16];

** OWPrand_context next;

** (initialize state)
** OWPrand_context_init(&next, seed);

** (generate a sequence of exponential variates)
** while (1) {
**    u_int64_t num = OWPexp_rand64(&next);
      <do something with num here>
                ...
** }
*/

#include <stdlib.h>

typedef u_int64_t u_int64_t;

/* (K - 1) is the first k such that Q[k] > 1 - 1/(2^32). */
#define K 12

#define BIT31   0x80000000UL    /* see if first bit in the lower
                                                  32 bits is zero */
#define MASK32(n)       ((n) & 0xFFFFFFFFUL)

#define EXP2POW32       0x100000000ULL

typedef struct OWPrand_context {
        unsigned char counter[16]; /* 16-octet counter (network byte order)  */
        keyInstance key;           /* key used to encrypt the counter.       */
```

```
        unsigned char out[16];     /* the encrypted block is kept there.     */
} OWPrand_context;

/*
** The array has been computed according to the formula:
**
**       Q[k] = (ln2)/(1!) + (ln2)^2/(2!) + ... + (ln2)^k/(k!)
**
** as described in algorithm S. (The values below have been
** multiplied by 2^32 and rounded to the nearest integer.)
** These exact values MUST be used so that different implementation
** produce the same sequences.
*/
static u_int64_t Q[K] = {
        0,          /* Placeholder - so array indices start from 1. */
        0xB17217F8,
        0xEEF193F7,
        0xFD271862,
        0xFF9D6DD0,
        0xFFF4CFD0,
        0xFFFEE819,
        0xFFFFE7FF,
        0xFFFFFE2B,
        0xFFFFFFE0,
        0xFFFFFFFE,
        0xFFFFFFFF
};

/* this element represents ln2 */
#define LN2 Q[1]

/*
** Convert an unsigned 32-bit integer into a u_int64_t number..
*/
u_int64_t
OWPulong2num64(u_int32_t a)
{
        return ((u_int64_t)1 << 32) * a;
}

/*
** Arithmetic functions on u_int64_t numbers.
*/

/*
** Addition.
*/
u_int64_t
```

```
OWPnum64_add(u_int64_t x, u_int64_t y)
{
        return x + y;
}

/*
** Multiplication. Allows overflow. Straightforward implementation
** of Algorithm 4.3.1.M (p.268) from [KNUTH]
*/
u_int64_t
OWPnum64_mul(u_int64_t x, u_int64_t y)
{
        unsigned long w[4];
        u_int64_t xdec[2];
        u_int64_t ydec[2];

        int i, j;
        u_int64_t k, t, ret;

        xdec[0] = MASK32(x);
        xdec[1] = MASK32(x>>32);
        ydec[0] = MASK32(y);
        ydec[1] = MASK32(y>>32);

        for (j = 0; j < 4; j++)
                w[j] = 0;

        for (j = 0;  j < 2; j++) {
                k = 0;
                for (i = 0; ; ) {
                        t = k + (xdec[i]*ydec[j]) + w[i + j];
                        w[i + j] = t%EXP2POW32;
                        k = t/EXP2POW32;
                        if (++i < 2)
                                continue;
                        else {
                                w[j + 2] = k;
                                break;
                        }
                }
        }

        ret = w[2];
        ret <<= 32;
        return w[1] + ret;
}
```

```
/*
** Seed the random number generator using a 16-byte quantity 'seed'
** (== the session ID in OWAMP). This function implements step U1
** of algorithm Unif.
*/

void
OWPrand_context_init(OWPrand_context *next, unsigned char *seed)
{
        int i;

        /* Initialize the key */
        rijndaelKeyInit(next->key, seed);

        /* Initialize the counter with zeros */
        memset(next->out, 0, 16);
        for (i = 0; i < 16; i++)
                next->counter[i] = 0UL;
}


/*
** Random number generating functions.
*/

/*
** Generate and return a 32-bit uniform random string (saved in the less
** significant half of the u_int64_t). This function implements steps U2-U4
** of the algorithm Unif.
*/
u_int64_t
OWPunif_rand64(OWPrand_context *next)
{
        int j;
        u_int8_t  *buf;
        u_int64_t  ret = 0;

        /* step U2 */
        u_int8_t i = next->counter[15] & (u_int8_t)3;
        if (!i)
                rijndaelEncrypt(next->key, next->counter, next->out);

        /* Step U3. Increment next.counter as a 16-octet single quantity
           in network byte order for AES counter mode. */
        for (j = 15; j >= 0; j--)
                if (++next->counter[j])
                        break;
```

```
        /* Step U4. Do output. The last 4 bytes of ret now contain the
           random integer in network byte order */
        buf = &next->out[4*i];
        for(j=0;j<4;j++){
                ret <<= 8;
                ret += *buf++;
        }
        return ret;
}

/*
** Generate a mean 1 exponential deviate.
*/
u_int64_t
OWPexp_rand64(OWPrand_context *next)
{

        unsigned long i, k;
        u_int32_t j = 0;
        u_int64_t U, V, J, tmp;

        /* Step S1. Get U and shift */
        U = OWPunif_rand64(next);

        while ((U & BIT31) && (j < 32)){ /* shift until find first '0' */
                U <<= 1;
                j++;
        }
        /* remove the '0' itself */
        U <<= 1;

        U = MASK32(U);  /* Keep only the fractional part. */
        J = OWPulong2num64(j);

        /* Step S2. Immediate acceptance? */
        if (U < LN2)       /* return  (j*ln2 + U) */
                return OWPnum64_add(OWPnum64_mul(J, LN2), U);

        /* Step S3. Minimize. */
        for (k = 2; k < K; k++)
                if (U < Q[k])
                        break;
        V = OWPunif_rand64(next);
        for (i = 2; i <= k; i++){
                tmp = OWPunif_rand64(next);
                if (tmp < V)
                        V = tmp;
        }
```

```
        /* Step S4. Return (j+V)*ln2 */
        return OWPnum64_mul(OWPnum64_add(J, V), LN2);
}
```

12. Normative References

[AES] Advanced Encryption Standard (AES), http://csrc.nist.gov/encryption/aes/

[RFC1305] D. Mills, `Network Time Protocol (Version 3) Specification, Implementation and Analysis', RFC 1305, March 1992.

[RFC1321] R. Rivest, `The MD5 Message-Digest Algorithm', RFC 1321, April 1992.

[RFC2026] S. Bradner, `The Internet Standards Process -- Revision 3', RFC 2026, October 1996.

[RFC2119] S. Bradner, `Key words for use in RFCs to Indicate Requirement Levels', RFC 2119, March 1997.

[RFC2330] V. Paxon, G. Almes, J. Mahdavi, M. Mathis, `Framework for IP Performance Metrics' RFC 2330, May 1998.

[RFC2474] K. Nichols, S. Blake, F. Baker, D. Black, `Definition of the Differentiated Services Field (DS Field) in the IPv4 and IPv6 Headers', RFC 2474, December 1998.

[RFC2679] G. Almes, S. Kalidindi, and M. Zekauskas, `A One-way Delay Metric for IPPM', RFC 2679, September 1999.

[RFC2680] G. Almes, S. Kalidindi, and M. Zekauskas, `A One-way Packet Loss Metric for IPPM', RFC 2680, September 1999.

[RFC2836] S. Brim, B. Carpenter, F. Le Faucheur, `Per Hop Behavior Identification Codes', RFC 2836, May 2000.

13. Informative References

[ZIGG] G. Marsaglia, M. Sibuya and J.H. Ahrens, Communications of ACM, 15 (1972), 876-877

[KNUTH] D. Knuth, The Art of Computer Programming, vol.2, 3rd edition, 1998

[RIJN] Reference ANSI C implementation of Rijndael
http://www.esat.kuleuven.ac.be/~rijmen/rijndael/rijndaelref.zip

[RIPE] RIPE NCC Test-Traffic Measurements home,
http://www.ripe.net/test-traffic/.

[RIPE-NLUUG] H. Uijterwaal and O. Kolkman, `Internet Delay Measurements Using Test-Traffic', Spring 1998 Dutch Unix User Group Meeting, http://www.ripe.net/test-traffic/Talks/9805_nluug.ps.gz.

[SURVEYOR] Surveyor Home Page, http://www.advanced.org/surveyor/.

[SURVEYOR-INET] S. Kalidindi and M. Zekauskas, `Surveyor: An Infrastructure for Network Performance Measurements', Proceedings of INET'99, June 1999.
http://www.isoc.org/inet99/proceedings/4h/4h_2.htm

14. Authors' Addresses

Stanislav Shalunov <shalunov@internet2.edu>

Benjamin Teitelbaum <ben@internet2.edu>

Anatoly Karp <karp@math.wisc.edu>

Jeff Boote <boote@internet2.edu>

Matthew J. Zekauskas <matt@internet2.edu>

Expiration date: November 2003