MEF Standard
MEF 66

SOAM for IP Services

July 2020

Disclaimer

The information in this publication is freely available for reproduction and use by any recipient and is believed to be accurate as of its publication date. Such information is subject to change without notice and MEF Forum (MEF) is not responsible for any errors. MEF does not assume responsibility to update or correct any information in this publication. No representation or warranty, expressed or implied, is made by MEF concerning the completeness, accuracy, or applicability of any information contained herein and no liability of any kind shall be assumed by MEF as a result of reliance upon such information.

The information contained herein is intended to be used without modification by the recipient or user of this document. MEF is not responsible or liable for any modifications to this document made by any other party.

The receipt or any use of this document or its contents does not in any way create, by implication or otherwise:

a) any express or implied license or right to or under any patent, copyright, trademark or trade secret rights held or claimed by any MEF member which are or may be associated with the ideas, techniques, concepts or expressions contained herein; nor

b) any warranty or representation that any MEF members will announce any product(s) and/or service(s) related thereto, or if such announcements are made, that such announced product(s) and/or service(s) embody any or all of the ideas, technologies, or concepts contained herein; nor

c) any form of relationship between any MEF member and the recipient or user of this document.

Implementation or use of specific MEF standards or recommendations and MEF specifications will be voluntary, and no Member shall be obliged to implement them by virtue of participation in MEF Forum. MEF is a non-profit international organization to enable the development and worldwide adoption of agile, assured and orchestrated network services. MEF does not, expressly or otherwise, endorse or promote any specific products or services.

Table of Contents

List of Figures

List of Tables

1 List of Contributing Members

The following members of the MEF participated in the development of this document and have requested to be included in this list.

Member Company
Bell Canada
Cisco Systems
EXFO Inc.
Nokia
Spirent Communications
Telecom Italia S.p.a.
ZTE

Table 1 – Contributing Members

2 Abstract

This document specifies Service Operations, Administration, and Maintenance (SOAM) of IP Services described using the IP Service Attributes as defined in MEF 61.1 [25]. This covers both Fault Management (FM) and Performance Monitoring (PM) of IP services.

The goal of this document is to define a set of specific fault and performance measurement methods that are recommended to be implemented by equipment providers and Service Providers. The methods defined include Proactive and On-demand Fault Management and active Performance Monitoring.

The focus of FM is on Bidirectional Forwarding Detection (BFD) as defined in RFC 5880 [11], RFC 5881 [12], and RFC 5883 [13] for Proactive monitoring. Ping and traceroute using ICMP as defined in RFC 792 [2] and RFC 4443 [8] are used for On-demand monitoring and defect localization. These tools are well defined and broadly implemented today. This document defines options, modes, and parameters for these tools based on defined use cases. The focus of PM for Active Measurement is on Two-Way Active Measurement Protocol (TWAMP) and TWAMP Light as defined in RFC 5357 [10] and Simple Two-way Active Measurement Protocol (STAMP) as defined in RFC 8762 [18]. TWAMP, TWAMP Light, and STAMP are included in the scope to cover both complex and more simplified implementations.

3 Terminology and Abbreviations

This section defines the terms used in this document. In many cases, the normative definitions to terms are found in other documents. In these cases, the third column is used to provide the reference that is controlling, in other MEF or external documents.

In addition, terms defined in MEF 35.1 [23] and in MEF 61.1 [25] are included in this document by reference, and are not repeated in the table below.

Term	Definition	Reference
BFD	Bidirectional Forwarding Detection	IETF RFC 5880 [11]
Bidirectional Forwarding Detection	A protocol intended to detect faults in the bidirectional path between two forwarding engines, including interfaces, data link(s), and to the extent possible the forwarding engines themselves, with potentially very low latency.	IETF RFC 5880 [11]
Controller MP	The MP that initiates IP SOAM Packets. Term is applicable to both Dual-Ended and Single-Ended PM Functions. In a Single-Ended PM Function, the Controller MP also receives responses from the Responder MP.	This Document
DA	Destination IP Address	This Document
ICM	Infrastructure Control and Management	MEF 55 [24]
ICMP	Internet Control Message Protocol	IETF RFC 792 [1] IETF RFC 4443 [8]
ICMP Ping	A common term for a tool that uses an ICMP Echo or Echo Reply Message as defined in RFC 792 [2] for IPv4 and RFC 4443 [8] for IPv6.	This document
ICMP Traceroute	A common term that refers to the ability to use the Echo and Time Exceeded messages defined in RFC 792 [2] for IPv4 and RFC 4443 [8] for IPv6 to determine the routing path from the source address to the destination address.	This document

Term	Definition	Reference
Infrastructure Control and Management	The set of functionality providing domain specific network and topology view resource management capabilities including configuration, control and supervision of the network infrastructure. ICM is responsible for providing coordinated management across the network resources within a specific management and control domain. For example, a system supporting ICM capabilities provides connection management across a specific subnetwork domain. Such capabilities may be provided within systems such as subnetwork managers, SDN controllers, etc.	MEF 55 [24]
IP SOAM FM Packet	IP Service OAM Packet specifically for Fault Management. Examples include: BFD [11], ICMP Echo/Reply [2].	This Document
IP SOAM Packet	IP Service OAM Packet. An IP SOAM FM Packet or an IP SOAM PM Packet.	This Document
IP SOAM PM Packet	IP Service OAM Packet specifically for Performance Monitoring. Examples include: TWAMP [10], OWAMP [9], and STAMP [18].	This Document
MD5	Message Digest Algorithm	IETF RFC 1321 [3]
Measurement Point	An actively managed SOAM entity associated with a specific service instance that can generate and receive IP SOAM Packets and track any responses.	This document
MP	Measurement Point	This document
MPLS	Multi-Protocol Label Switching	IETF RFC 3031 [5]
Responder MP	In a Single-Ended PM Session, the MP that receives IP SOAM PM Packets from the Controller MP and transmits responses to the Controller MP.	This Document
Service Operations, Administration, and Maintenance	Fault Management and Performance Monitoring of services and devices used to implement services.	This document

Term	Definition	Reference
Service Orchestration Functionality	The set of service management layer functionality supporting an agile framework to streamline and automate the service lifecycle in a sustainable fashion for coordinated management supporting design, fulfillment, control, testing, problem management, quality management, usage measurements, security management, analytics, and policy-based management capabilities providing coordinated end-to-end management and control of Layer 2 and Layer 3 Connectivity Services.	MEF 55 [24]
Session-Reflector	The endpoint of a TWAMP-Test or STAMP session that has the capability to create and send a measurement packet when it receives a measurement packet.	IETF RFC 5357 [10], IETF RFC 8762 [18]
Session-Sender	The sending endpoint of an TWAMP-Test or STAMP session	IETF RFC 5357 [10], IETF RFC 8762 [18]
SHA1	Secure Hash Algorithm	IETF RFC 3174 [6]
Sink MP	In a Dual-Ended PM Session, the MP that receives IP SOAM PM Packets from the Controller MP and performs the performance calculations.	This Document
SM	State Machine	This document
SOAM	Service Operations, Administration, and Maintenance	This document
SOF	Service Orchestration Functionality	MEF 55 [24]
STAMP	Simple Two-way Active Measurement Protocol	IETF RFC 8762 [18]
Stateful Reflector	The mode of a Session-Reflector in which it counts packets received in a test session.	This Document
Stateless Reflector	The mode of a Session-Reflector in which it does not count the number of packets received in a test session.	This Document
TCA	Threshold Crossing Alert	GR-253 [26]
TWAMP	Two-way Active Measurement Protocol	IETF RFC 5357 [10]
TWAMP Light	TWAMP Light is significantly simplified mode of TWAMP-Test part of TWAMP.	IETF RFC 5357, Appendix I [10]
UTC	Coordinated Universal Time	ISO 8601 [19]

Table 2 – Terminology and Abbreviations

4 Compliance Levels

The key words "**MUST**", "**MUST NOT**", "**REQUIRED**", "**SHALL**", "**SHALL NOT**", "**SHOULD**", "**SHOULD NOT**", "**RECOMMENDED**", "**NOT RECOMMENDED**", "**MAY**", and "**OPTIONAL**" in this document are to be interpreted as described in BCP 14 (RFC 2119 [4], RFC 8174 [16]) when, and only when, they appear in all capitals, as shown here. All key words must be in bold text.

Items that are **REQUIRED** (contain the words **MUST** or **MUST NOT**) are labeled as **[Rx]** for required. Items that are **RECOMMENDED** (contain the words **SHOULD** or **SHOULD NOT**) are labeled as **[Dx]** for desirable. Items that are **OPTIONAL** (contain the words **MAY** or **OPTIONAL**) are labeled as **[Ox]** for optional**.**

A paragraph preceded by **[CRa]<** specifies a conditional mandatory requirement that **MUST** be followed if the condition(s) following the "<" have been met. For example, "**[CR1]<**[D38]" indicates that Conditional Mandatory Requirement 1 must be followed if Desirable Requirement 38 has been met. A paragraph preceded by **[CDb]<** specifies a Conditional Desirable Requirement that **SHOULD** be followed if the condition(s) following the "<" have been met. A paragraph preceded by **[COc]<** specifies a Conditional Optional Requirement that **MAY** be followed if the condition(s) following the "<" have been met.

5 Numerical Prefix Conventions

This document uses the prefix notation to indicate multiplier values as shown in Table 3.

Decimal		**Binary**	
Symbol	**Value**	**Symbol**	**Value**
k	10^3	Ki	2^{10}
M	10^6	Mi	2^{20}
G	10^9	Gi	2^{30}
T	10^{12}	Ti	2^{40}
P	10^{15}	Pi	2^{50}
E	10^{18}	Ei	2^{60}
Z	10^{21}	Zi	2^{70}
Y	10^{24}	Yi	2^{80}

Table 3 – Numerical Prefix Conventions

6 Introduction

SOAM provides the protocols, mechanisms, and procedures for monitoring faults and the performance of an IP Virtual Connection (IPVC), as specified in MEF 61.1 [25]. The use of SOAM in IP Services is not standardized although IP Services are widespread. This document describes the tools that are needed, allowing equipment providers to understand what features and functions to include in their equipment, and provides recommendations to IP Service Providers (SP) on how to use these tools.

The document is divided into several sections covering Fault Management, Performance Monitoring, and Hybrid Measurement. The Fault Management section includes Use Cases, FM Tool requirements, and FM reporting. The Performance Monitoring section includes Use Cases, PM requirements, PM Tool requirements, and PM reporting. The Hybrid Measurement section includes informative discussion of Alternate Marking used for Hybrid Measurement. These sections reference previous MEF work, other Standards Bodies work, or might expand upon that work to support IP services.

For FM, Proactive monitoring and On-demand monitoring are specified. Proactive monitoring is defined as SOAM actions that are carried on continuously to permit timely reporting of fault and/or performance status. Within this document, Bidirectional Forwarding Detection (BFD) is specified as the tool to be used for Proactive Fault Management. Recommendations for BFD options are included.

On-demand monitoring is defined as SOAM actions that are initiated via manual intervention for a limited time to carry out diagnostics. On-demand Fault Management is used to isolate a fault when one has been detected by Proactive monitoring or as a replacement for Proactive monitoring. Ping and traceroute are the tools used for On-demand Fault Management. Transmission and reception of ping and traceroute can use ICMP. Recommendations for options for these are included in this document.

For PM, Active Measurement using TWAMP Light/STAMP/TWAMP is specified. An Active Measurement method depends on a dedicated measurement packet stream and observations of the packets in that stream. These packets are used to measure packet delay, and packet loss. MEF 61.1 [25] specifies One-way performance metrics which require Time of Day (ToD) clock synchronization for PD measurements. Since ToD clock synchronization is often difficult to implement, Two-way measurements, divided in half and identified as derived measurements can be acceptable. Options for TWAMP, TWAMP Light, and STAMP are specified within the document. One Way Active Measurement Protocol (OWAMP) as defined in RFC 4656 [9] is not included in the scope of this document and is not recommended for use to perform PM due to the requirement to implement the control protocol at each end of the service.

Passive Measurement depends solely on observation of one or more existing packet streams. The streams are only used for measurement when they are observed for that purpose but are present whether or not measurements take place. Passive Measurement is not within the scope of this document.

A Hybrid Measurement method is a combination of Active and Passive Measurement which makes observations on a dedicated measurement stream using header or marked bits included

with an existing stream. The requirements for Hybrid Measurements are not discussed in this document. However, Section 9 describes one example of the Hybrid method, Alternate Marking. Hybrid Measurement methods such as Alternate Marking (AltM) are in the process of being defined at the time of writing. As other SDOs complete work on these methods, this document may be updated to include them.

6.1 Document Structure

This document is structured by measurement type. The Fault Management section contains use cases, tool requirements, implementation recommendations, and reporting requirements. The Performance Monitoring section contains use cases, Common PM Requirements, Storage Requirements, Threshold Crossing Alert Requirements, PM Tool requirements, implementation recommendations, and reporting requirements. The Hybrid Monitoring section provides an overview of AltM. Various appendices are provided to further assist with tool and implementation decisions.

6.2 Use Cases

The use cases described in this document provide examples of how FM (section 7.1), PM (section 8.1), and AltM (section 9) can be used in an SP's network. These use cases are not all encompassing. Understanding how and why the SOAM tools are used will assist in understanding the requirements and recommendations that are provided in this document. The use cases are based on the concepts and constructs used to describe Subscriber IP Services, as specified in MEF 61.1 [25], such as UNIs, IPVCs, and IPVC EPs.

Note that SOAM for Operator IP Services is not in scope for this revision of the document but may be addressed in a future version.

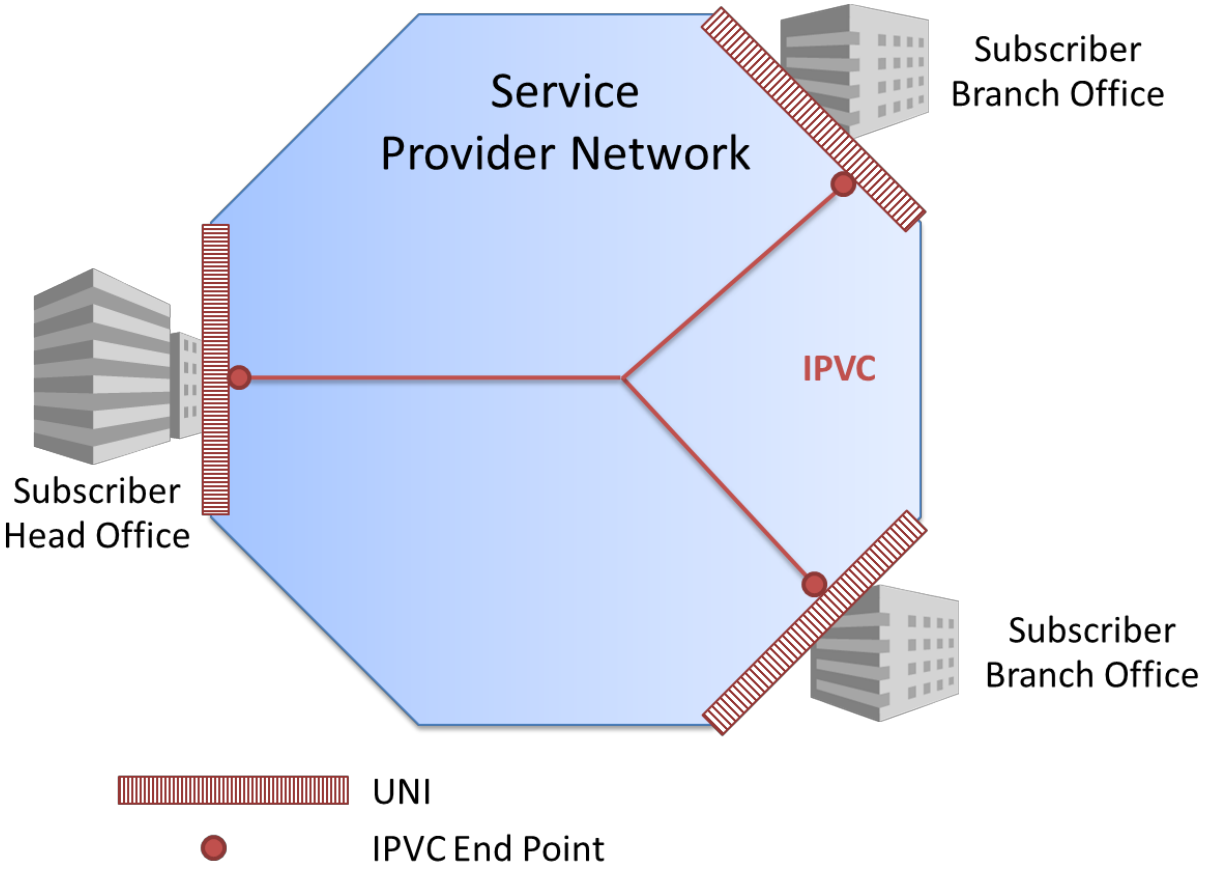

Figure 1 – Example of an IPVC connecting three UNIs

Figure 1 shows a basic Subscriber IP Service. For the purposes of this document, this basic Subscriber IP Service will be discussed in the use cases within this document. The single IPVC represented in Figure 1 connects three Subscriber locations. The SP desires to monitor faults and performance of this IPVC. The use cases within this document are used as examples and are provided as information only.

7 Fault Management

Fault Management (FM) provides the ability to detect failures within IP Services. This section contains the Use Cases, Tool Requirements, and Implementation Recommendations for FM for IP Services.

7.1 FM Use Cases

Faults that impact IP services include loss of connectivity due to network events, routing issues, equipment failures or other events. A fault is characterized as a failure to pass packets as opposed to a performance degradation where packets can still pass but with excessive loss or delay. As mentioned previously in this document, BFD is the recommended tool for Proactive FM. BFD is a mature protocol that is widely implemented in CEs and PEs. For more information on BFD see section 7.2.1.

In the context of SOAM, BFD is used to detect faults across the network, typically over multiple IP hops. BFD is also often used to detect faults on a single hop within a network. The use of BFD across a single physical link is out of scope except where used to detect faults on a UNI Access Link that is a single hop.

To support On-demand FM, tools such as ICMP Ping and ICMP Traceroute are used. These tools allow localization and isolation of a fault to be performed as needed. For more information on these tools see section 7.2.2.

There are several ways that FM can be used to support IP services. Examples of these are described in the following sections.

7.1.1 End-to-End Monitoring

An example of monitoring from UNI to UNI, for UNIs that have IPVC EPs in the same IPVC, is shown in Figure 2. In this case, Provider-Managed CEs are used (see MEF 61.1 [25]). In other words, the SP places demarcation equipment (CEs) at the customer premises that support BFD, which is configured to run between each of the BFD Implementations at some regular interval.

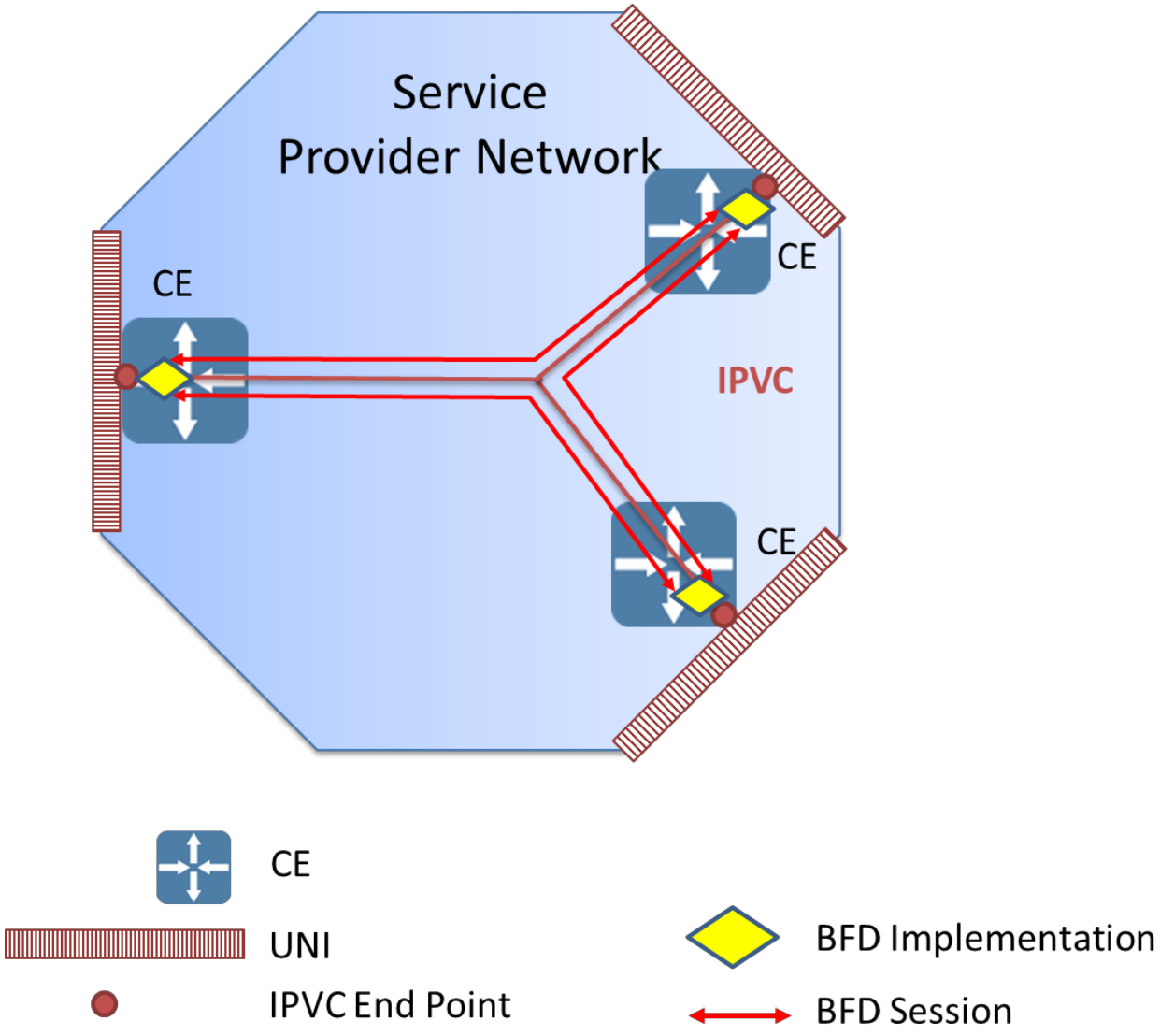

Figure 2 – End-to-End BFD

Figure 2 shows BFD sessions between each pair of UNIs that have IPVC EPs in the same IPVC. Any failures of connectivity that are longer than the BFD timer value across the IPVC are detected. Examples of failures include loss of connectivity that occur between two UNIs, high packet loss between two UNIs that results in loss of consecutive BFD packets, or a fault in the CE that causes the BFD implementation to fail at an IPVC EP. Once the CEs are notified that a fault has occurred, they can take corrective action to reroute the packets to an alternate path. Depending on the transmission interval of BFD packets, fault detection can occur faster than routing protocol fault detection. In this example, the SP is able to configure a BFD session between the pair of CEs because the CEs are Provider-Managed. In the case of Subscriber-Managed CE, the SP is not able to configure a BFD session between the pair of CEs , but could instead configure BFD sessions between pairs of PEs as described in section 7.1.2.

7.1.2 IPVC Monitoring

An alternative to monitoring the entire IPVC as described in section 7.1.1, from UNI to UNI, is to monitor a segment of the IPVC from PE to PE. This may be the only option if the SP does not place any IP-capable equipment at the Subscriber's location, as could be the case with Subscriber-Managed CEs. Even in the case of Provider-Managed CEs, the SP may decide for operational reasons to monitor instead from PE to PE. This can be done by configuring BFD sessions between the PEs. If this approach is used, the segment of the IPVC between the each UNI and its associated PE is not monitored by these BFD sessions.

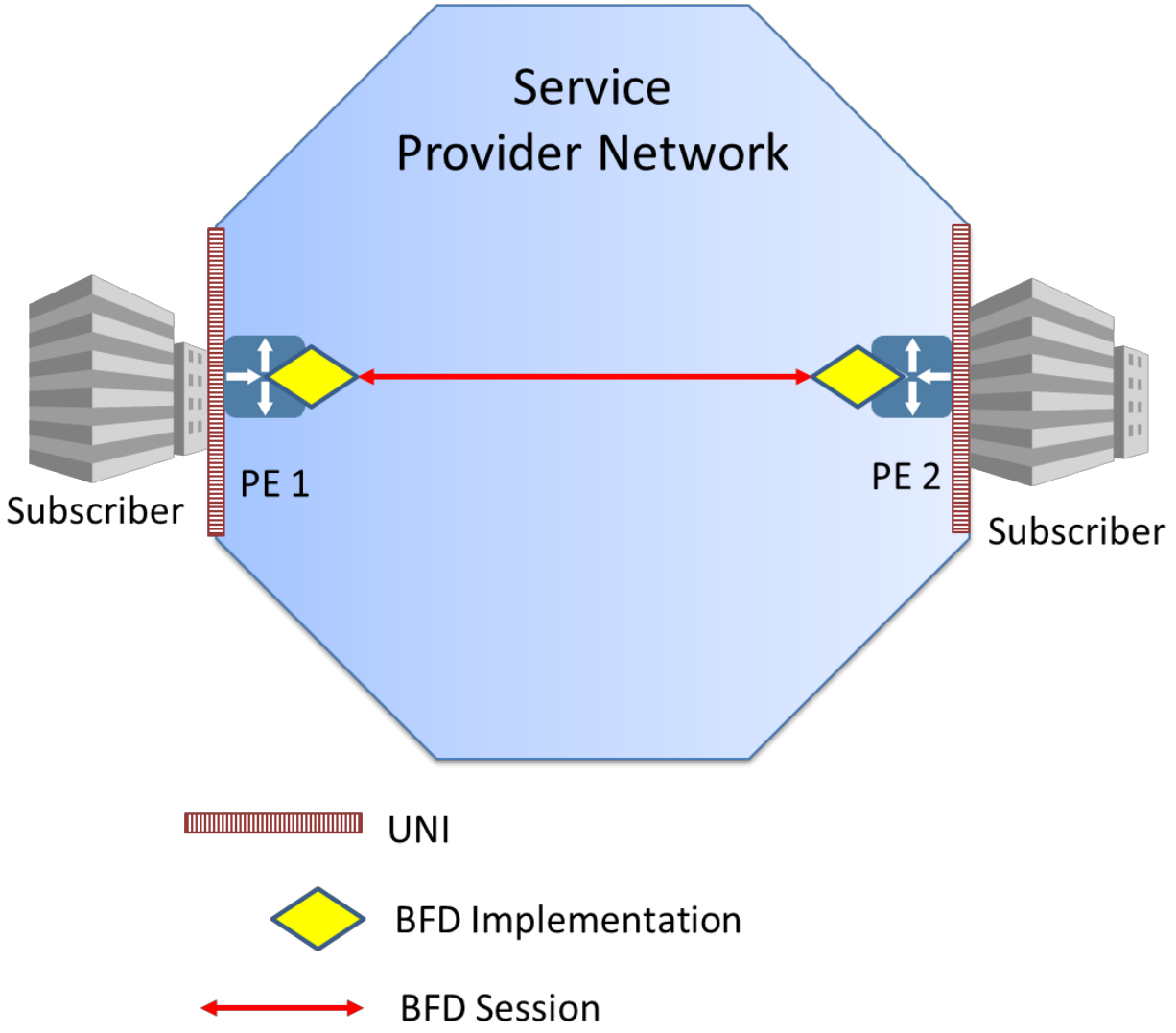

Figure 3 – PE-PE BFD Session

In the use case presented in Figure 3, the SP uses BFD to monitor an IPVC from PE to PE since this is the most complete view of the service that they have. BFD is provisioned over the IPVC between the PEs, BFD control packets are exchanged, and IPVC loss of continuity between the PEs is detected. Examples of failures that can be detected include a loss of connectivity between PEs, a failure to reconverge after a failure, or a failure in a PE. BFD can detect faults faster than

typical routing protocols and BFD can trigger routing protocols to reconverge reestablishing connectivity. At least two paths need to exist between the PEs for reconvergence. If the SP has other protection mechanisms at lower levels, the BFD timer intervals need to take into account protection mechanism timers at these lower levels to ensure that the lower levels act before the BFD timer triggers a reconvergence.

7.1.3 UNI Access Link

BFD can be configured to run between the Subscriber's CE and the SP's PE or between a Provider-Managed CE and other Subscriber equipment across the UNI Access Link. MEF 61.1 [25] defines the UNI Access Link BFD Service Attribute which is used to define the BFD session attributes. In this Use Case, as depicted in Figure 4, BFD is being used to detect faults that occur on the UNI Access Link versus the CE to CE connectivity as discussed in section 7.1.1.

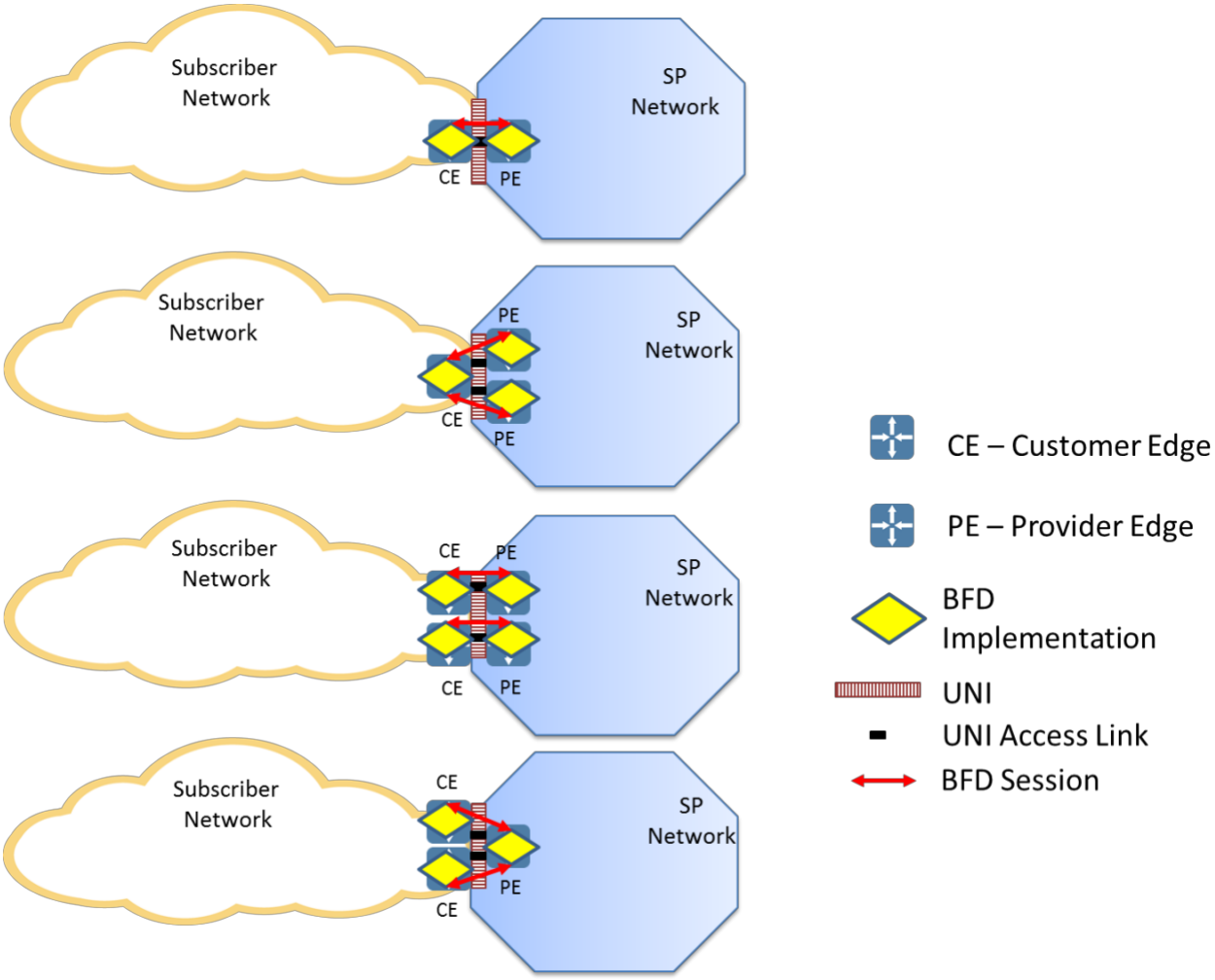

Figure 4 – UNI Access Link BFD with Subscriber Managed CE

Figure 4 shows several different UNI Access Link configurations when the CE is Subscriber-Managed. BFD sessions between the CE and the PE are configured and are used to detect faults on the UNI Access Link. Note that the examples shown in Figure 3 are not exhaustive and other configurations are also possible.

Figure 5 shows similar UNI Access Link configurations but in these configurations the CE is Provider-Managed.

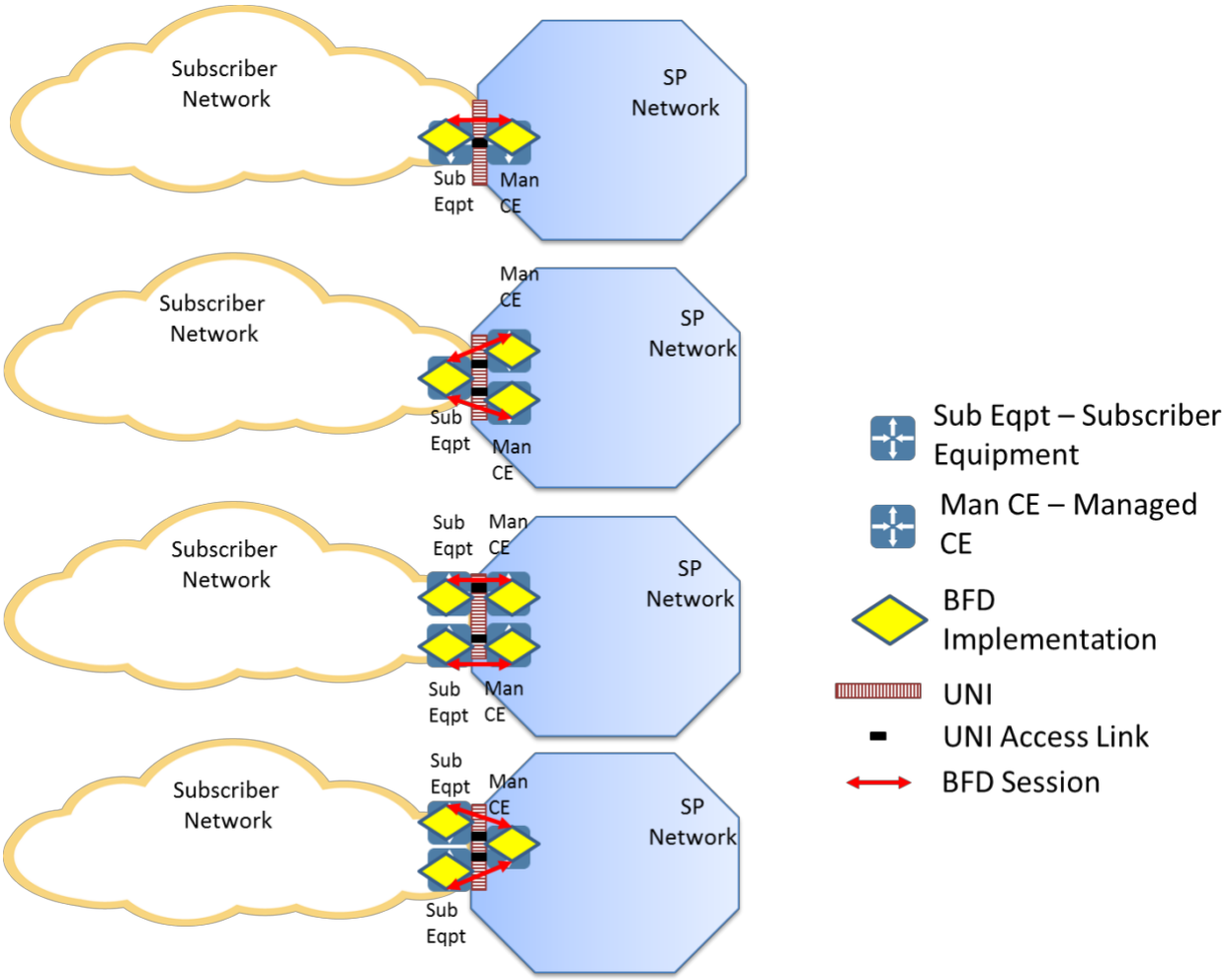

Figure 5 – UNI Access Link BFD with Provider Managed CE

The BFD session is configured between the managed CE and designated Subscriber equipment on the other side of the UNI Access Link. Note that as above, the examples shown in Figure 5 are not exhaustive and other configurations are also possible.

Using BFD to monitor the UNI Access Link can be required if the physical connection between the CE and PE does not provide fault notification. The connection appears as a single hop and BFD is implemented as described in IETF RFC 5881 [12].

A BFD session that is active on the UNI Access Link can be used to detect faults that cause a rerouting of the Subscriber's traffic to another UNI Access Link (in the same or a different UNI).

Such re-routing can occur only when there is an additional UNI Access Link that is not impacted by the fault.

Faults detected by the BFD session(s) in these Use Cases may be caused by UNI interface failures, UNI physical connectivity failure, or CE, PE, or Subscriber Equipment failure.

7.1.4 On-Demand Monitoring

On-demand Fault Management can be used to isolate a fault location, determine the approximate Two-way delay between two points, to verify connectivity between two points in the service, or to determine the path of a flow. On-demand FM uses ICMP Ping for continuity and delay measurements and ICMP Traceroute to identify the path of a flow. The delay is measured as the Round Trip Delay and thus is the approximation of the delay that a data packet experiences, as it includes the processing time at the far end.

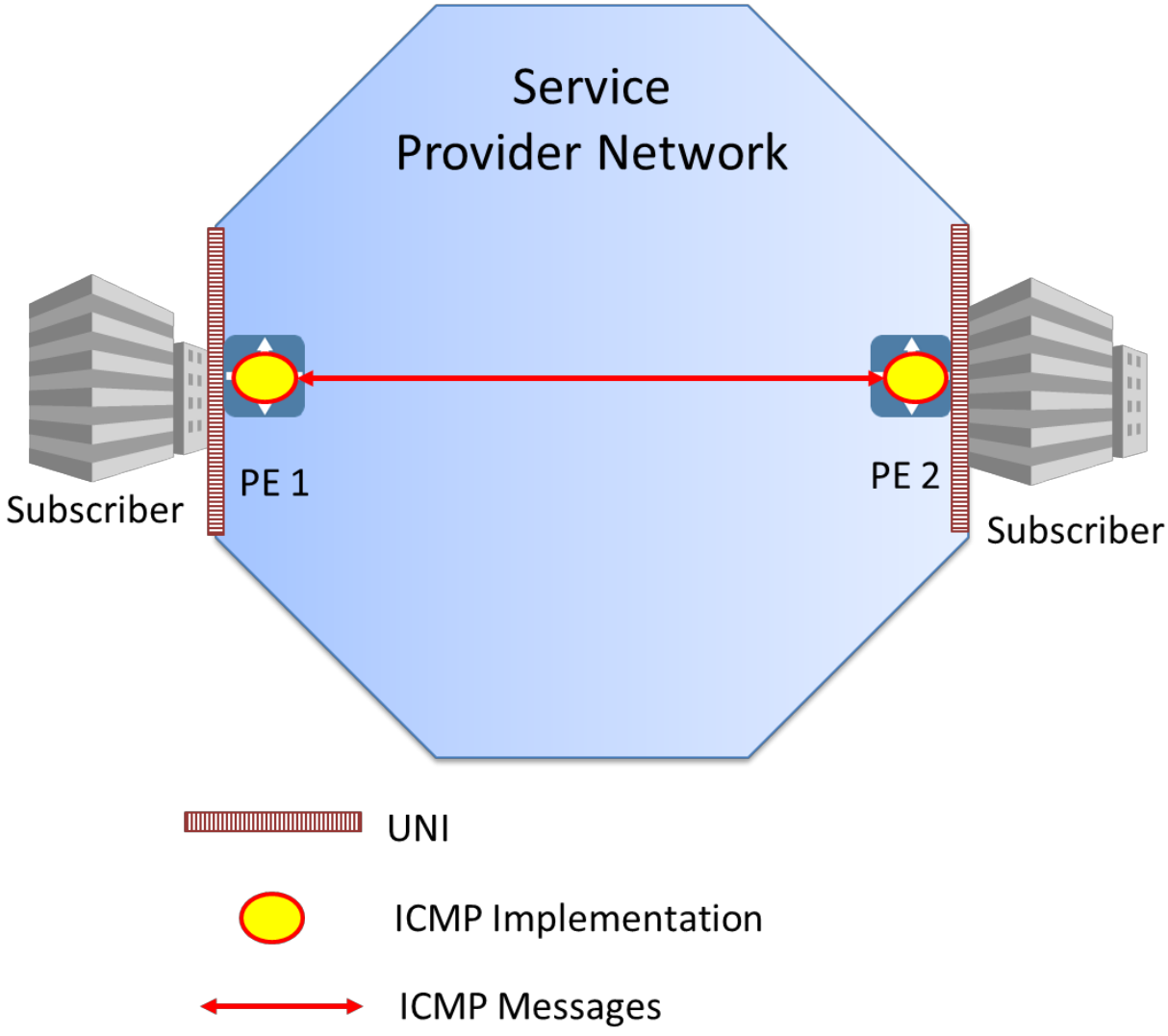

Figure 6 – ICMP Ping

Figure 6 shows an ICMP Ping between PEs within a SP's network. In the event of a BFD failure between two IPVC EPs, isolation of the fault may be required. Sending ICMP Pings between the PEs determines if continuity exists between them and enables the measurement of the approximate Two-way delay between them. Multiple ICMP Pings can be sent to attempt to determine of the problem is intermittent or is constant.

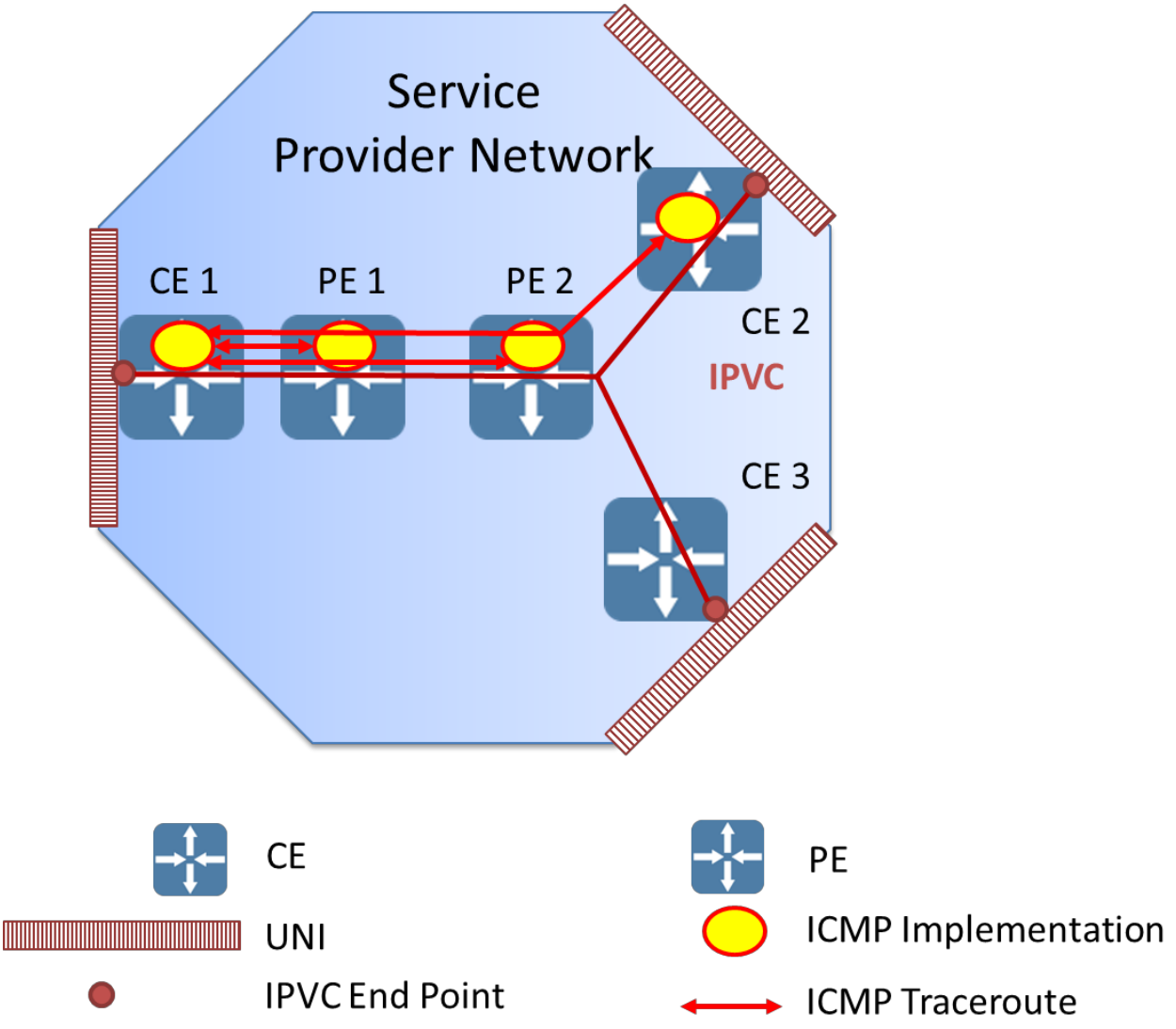

Figure 7 – ICMP Traceroute

Figure 7 shows an example of the use of ICMP Traceroute. It is desired to determine the path of a flow between CE 1 and CE 2. An ICMP Echo message with a Time to Live (TTL) of 1 is sent to the IP address of CE 2. PE 1 receives this message and responds by sending ICMP Time Exceeded message. A second ICMP Echo message is sent, this time with a TTL of 2. PE 2 responds to this message. A third ICMP Echo message is sent with a TTL of 3. This reaches CE 2. CE 2 responds to the message. The ICMP implementation in CE 1 is able to determine the path to CE 2 from these responses.

An ICMP Traceroute might be used when an ICMP Ping fails to reach the destination to determine the path of the flow between the end points or to determine the path of the flow to verify correct control protocol operation.

7.2 FM Tool Requirements

As stated previously, BFD is being specified as the primary Proactive FM tool. ICMP Ping and ICMP Traceroute are specified as On-demand tools. This section of the document specifies the requirements that must be supported for each of these tool sets.

[R1] An IP SOAM Implementation **MUST** support a mechanism to limit the number of IP SOAM FM packets processed per second.

This requirement is intended to limit the implementation's vulnerability to distributed denial-of-service attacks.

7.2.1 Proactive Monitoring

BFD is specified in IETF RFC 5880 [11]. Additional details on BFD intervals are specified in IETF RFC 7419 [14]. See RFC 5880 [11] for a detailed description of the BFD protocol and its operation. When proactively monitoring a single hop, BFD is implemented as described in RFC 5881 [12]. When proactively monitoring multihop services, BFD is implemented as described in RFC 5883 [13].

7.2.1.1 BFD Overview

BFD is intended to detect faults in the bidirectional path between two forwarding engines, including interfaces, data link(s), and to the extent possible the forwarding engines themselves, with potentially very low latency. BFD is a more efficient method to provide sub-second detection of the failure of a path between two systems than control protocol "hello" messages. BFD can be used to notify control protocols of a detected failure. This means individual control protocols "hello" timers need not be configured individually and aggressively. They can rely on BFD for failure notification.

BFD operates between a pair of systems that are exchanging BFD packets. If a system stops receiving BFD packets for some specified period of time, the path is declared failed. A path is only declared up when properly constructed BFD packets are received at each system in the pair.

The time interval between the transmissions of two consecutive BFD packets is negotiated between the two BFD systems. As specified in RFC 5880 [11], the average interval between BFD packets will be roughly 12.5% less than the negotiated value. RFC 7419 [14] provides recommendations on time intervals that are supported by all systems to make the negotiation process easier. Once the time interval is determined, RFC 5880 [11] defines two modes for BFD, Asynchronous and Demand. For FM Proactive monitoring, this document focuses on Asynchronous. Asynchronous mode provides a more proactive solution for monitoring for faults than Demand mode and can provide faster fault detection than a Demand session with the same transmission interval. The Echo function is an adjunct to both modes and allows one system to

transmit BFD packets and the other system to loop them back through its forwarding path. The Echo function cannot be used with mulithop BFD specified in RFC 5883 [13].

Authentication can be supported by BFD to limit the ability of false packets to impact the forwarding paths. Authentication methods range from a simple password to MD5 and SHA1 authentication.

7.2.1.2 BFD Support

This section details requirements for network elements supporting BFD. Where support for an RFC is mandated, unless otherwise stated, all required and recommended requirements apply as stated in the RFC.

[R2] A BFD Implementation **MUST** comply with RFC 5880 [11] if BFD is supported.

[R3] A BFD Implementation **MUST** comply with RFC 5881 [12] if single hop BFD is supported.

[R4] A BFD Implementation **MUST** comply with RFC 5883 [13] if multi-hop BFD is supported.

Support for Demand mode, as specified in RFC 5880 section 6.6 [11], is optional. RFC 5880 [11] section 6.8.15 describes how the BFD implementation responds to a forwarding plane reset.

RFC 7419 [14] describes issues with negotiating BFD transmission intervals. To resolve these issues, it specifies a minimum list of common intervals that are to be supported.

[R5] A BFD implementation **MUST** support the following common intervals, {100ms, 1s} as specified in RFC 7419 [14].

[D1] The intervals {3.3ms, 10ms, 20ms, 50ms, 10s}, specified in RFC 7419 [14], **SHOULD** be supported.

[R6] A BFD implementation **MUST** support a Detect multiplier of 3.

[D2] A BFD implementation **SHOULD** support a Detect multiplier range of 2-255

[R7] A BFD implementation that supports an interval in the list of {3.3ms, 10ms, 20ms, 50ms} **MUST** support all longer intervals in that list as specified in RFC 7419 [14].

A BFD implementation may support additional transmission intervals. The use of these intervals is subject to an agreement by the Subscriber and Service Provider.

Using BFD to monitor an IP Service might require that the IP SOAM FM packets containing the BFD packets be treated differently by the network devices in the SP Network. For this reason, the ability to set the DSCP value of the IP Data Service packets is required. The Service Provider

might want to match the value of a Subscriber's service and use a different value for their network. The following requirements support these features.

[R8] A BFD Implementation **MUST** support the ability to configure and set the DSCP value of IP SOAM FM packets containing BFD packets.

[R9] The default value for the DSCP value **MUST** be 48.

7.2.2 On-Demand Fault Management

On-demand Fault Management for IPv4 is done using the Echo/Echo Reply and Time Exceeded messages defined in IETF RFC 792 [2]. On-demand Fault Management for IPv6 is done using the Echo Request/Echo Reply and Time Exceeded messages defined in IETF RFC 4443 [8]. For ease of exposition, "Echo Request" is used in this document to refer to both the IPv4 "Echo" message and the IPv6 "Echo Request" message. ICMP Ping is a tool that sends a sequence of ICMP Echo Request messages to a given destination and expects to receive a corresponding sequence of ICMP Echo Response messages. The number of responses received can give an indication of whether there is a fault, and the approximate round trip time can also be measured. ICMP Traceroute is a tool that sends a sequence of ICMP Echo Request messages to a given destination, with incrementing TTL values (starting at 1). It expects to receive a corresponding sequence of ICMP Time Exceeded messages from successive nodes along the path, until the TTL value is large enough for the Echo Request message to reach the destination. This allows the path from the source to the destination to be determined.

[R10] An On-demand Fault Management implementation supporting IPv4 **MUST** comply with the requirements and message formats for Echo Request, Echo Reply, and Time Exceeded Messages as specified in RFC 792 [2].

[R11] An On-demand Fault Management implementation supporting IPv4 **MUST** support a unicast DA.

[R12] An IPv4 multicast address **MUST NOT** be used as the DA when performing On-demand IP SOAM FM.

[R13] An On-demand Fault Management implementation supporting IPv6 **MUST** comply with the requirements and message formats for Echo Request, Echo Reply and Time Exceeded Messages as specified in RFC 4443 [8].

[R14] An On-demand Fault Management implementation supporting IPv6 **MUST** support a unicast DA.

[R15] An IPv6 multicast address **MUST NOT** be used as the DA when performing On-demand IP SOAM FM.

[R16] An On-demand Fault Management implementation of ICMP Ping **MUST** support a time interval between the transmissions of Echo Request messages of 1 second.

[D3] An On-demand Fault Management implementation of ICMP Ping **SHOULD** support a time interval between the transmissions of Echo Request messages of 100ms.

[R17] An On-demand Fault Management implementation of ICMP Ping **MUST** allow the number of Echo Request messages to be transmitted to be selected by the user.

[R18] An On-demand Fault Management implementation of ICMP Ping **MUST** be capable of transmitting Echo Request messages indefinitely.

[R19] An On-demand Fault Management implementation of ICMP Ping **MUST** allow the user to stop the transmission of Echo Request messages.

[R20] An On-demand Fault Management implementation of ICMP Traceroute **MUST** support the reception of Time Exceeded messages from unicast addresses other than the target DA.

[R21] An On-demand Fault Management implementation of ICMP Traceroute **MUST** support reporting the IP addresses and TTL for each Time Exceeded message received.

[R22] An On-demand Fault Management implementation of ICMP Ping **MUST** allow the user to select the length of transmitted ICMP Echo Request messages.

[R23] An On-demand Fault Management implementation of ICMP Traceroute **MUST** allow the user to select the length of transmitted ICMP Echo Request messages.

[R24] An On-demand Fault Management implementation of ICMP Ping **MUST** allow for configuration of the packet length of the Echo Request message to any value in the range of 64-1500 Bytes.

[D4] An On-demand Fault Management implementation of ICMP Ping **SHOULD** allow for configuration of the packet length of the Echo Request message to any value in the range of 1501-10000 Bytes.

[D5] An On-demand Fault Management implementation of ICMP Ping **SHOULD** by default transmit 5 Echo Request messages.

[D6] An On-demand Fault Management implementation of ICMP Ping **SHOULD** by default transmit Echo Request messages at 1-second interval.

[D7] An On-demand Fault Management implementation of ICMP Ping **SHOULD** by default use 64-bytes long Echo Request messages.

[D8] An On-demand Fault Management implementation of ICMP Traceroute **SHOULD** by default transmit Echo Request messages at 1-second interval.

[D9] An On-demand Fault Management implementation of ICMP Traceroute **SHOULD** by default use 64-bytes long Echo Request messages.

SPs can use other on-demand tools such as TCP ping or HTTP ping in their networks. The use of these tools is outside the scope of the document.

7.3 FM Reporting

The requirements for reporting of faults detected by Fault Management for Proactive monitoring are described below.

[R25] FM implementations **MUST** support the ability to generate a notification to the SOF/ICM within 2 seconds of a fault being detected by an FM session.

Notification Attribute	Description
Date and Time	Date and Time of the fault state change in UTC with millisecond granularity
Local IP Address	IP address of the BFD implementation that is generating the notification
Peer IP Address	IP address of the peer for which a fault has been detected
FM Session ID	ID assigned by the SOF upon the creation of the BFD session. This ID is not transmitted within any measurement packets and is used only by the SOF to identify an FM session.
Notification Type	Either SET or CLEAR. A SET is sent with all severities of notifications. A CLEAR is not sent with Informational Notifications.
Notification Severity	Critical, Major, Minor, or Informational; used to indicate the severity of the notification.
Notification Description	Textual description of the fault.

Table 4 – Notification Attributes

[R26] A fault notification **MUST** contain the attributes listed in Table 4.

[D10] An FM implementation **SHOULD** support synchronization of the local time-of-day clock with UTC to within one second of accuracy.

[R27] An FM implementation **MUST** support the ability to enable or disable notification of faults on a per FM session basis.

[R28] An FM implementation **MUST** support the ability to define the severity of a fault report.

[R29] An FM implementation **MUST** support at least two fault report severities, Critical and Major.

[O1] An FM implementation **MAY** support additional fault report severities.

The requirements for reporting of On-demand tools are described below.

[R30] An FM implementation of an ICMP Ping **MUST** report the following:

- Number of TX packets
- Number of RX packets
- Minimum Round Trip Delay
- Average Round Trip Delay
- Maximum Round Trip Delay
- Count of lost packets
- Percentage of lost packets

[R31] An FM implementation of an ICMP Traceroute **MUST** report the following for each response received to an ICMP Echo Request:

- IP Source Address
- Time to Live
- Round Trip Delay

8 Performance Monitoring

Performance Monitoring (PM) provides the ability to measure the performance of IP Services. This section contains the Use Cases, Tool Requirements, and Deployment Guidelines for PM for IP Services.

8.1 PM Use Cases

Degradations in performance can have a greater impact on customer's perception of network quality than faults. Most networks have failover mechanisms that provide protection in the event of a fault. In many cases, degradations do not cause these mechanisms to engage. As a result, customer packets may continue to be transported over degraded facilities, leading to packet retransmissions or excessive packet delay.

MEF 61.1 [25] defines an IPVC Service Level Specification Attribute that allows objectives to be specified for a number of Performance Metrics such as One-way Mean Packet Delay and One-way Packet Loss Ratio. The performance objectives specified in the SLS are a commitment by the SP to the Subscriber of how the service is expected to perform and can result in the SP issuing rebates to Subscribers if SLS objectives are not met. Performance Measurement allows SPs to monitor the performance of their network to ensure they are meeting the performance objectives specified in the SLS. Appendix E describes how SLS objectives can be determined from the performance measurements specified in this document.

PM uses several terms that need to be understood.

- SLS Reference Point (SLS-RP). This is defined in MEF 61.1 [25] as a point from or to which performance objectives are specified as part of an SLS; either an IPVC EP or a location specified in the SLS Service Attribute.

- Measurement Point (MP). An MP is defined within this document as a point from or to which performance is measured. An MP can be at an IPVC EP or at a location specified by the SP. An MP is assigned an IP address and IP packets are routed between the IP addresses of two MPs. There are two types of MPs, Controller and Responder. A Controller MP is the MP that initiates SOAM PM Packets and receives responses from the Responder MP. A Responder MP is the MP that receives SOAM PM Packets from the Controller MP and transmits responses to the Controller MP. It should be noted that SLS-RP and MP of the same service and directionality, i.e., "from" or "to", may be co-located or placed in different points along the path of the service.

- MP Pair. An MP Pair is a set of a particular Controller MP and a particular Responder MP that are measuring performance. An example is two MPs each located at different IPVC EPs of the same IPVC that are measuring performance between them. This MP Pair reports the performance between these two MPs as a part of the performance for the entire IPVC. An MP is a part of one or more MP Pairs.

- PM Session. A PM Session is initiated on a Controller MP to take performance measurements for a given SOAM PM IP Traffic Class between the Controller MP and a given Responder MP.

- Measurement Interval. Measurement Intervals (MI) are discrete, non-overlapping periods of time during which the PM Session measurements are performed, and results are gathered.

- PM Tool. PM Tools are the functionalities or implementations that are used to perform the SOAM measurements. PM Tools specified in this document are limited to TWAMP Light, STAMP, and TWAMP.

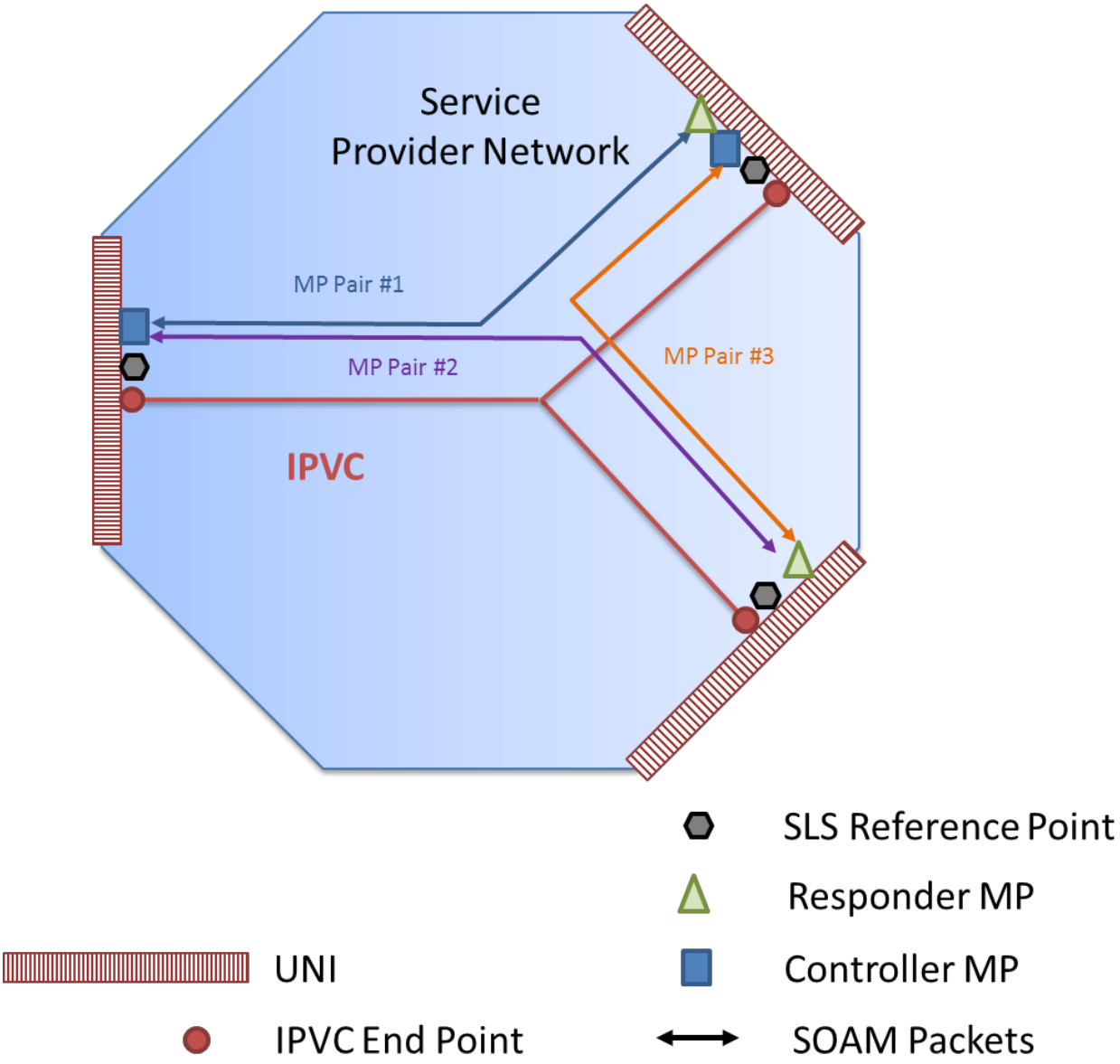

Figure 8 – SLS-RPs, MPs and MP Pairs

Figure 8 shows a single IPVC. The SLS-RPs and MPs are located at the UNIs. Three MP Pairs are shown in blue, purple and orange. SOAM PM packets are exchanged between the MPs in each MP Pair.

SPs normally approach monitoring the performance of their services and network in one of two methods. In the first method, they identify IPVC EPs as SLS-RPs and configure MPs at each IPVC EP including the entire path of the service in their SLS. In the second method, they designate SLS-RPs at some location, configure MPs at these locations, and measure performance between these MPs. Often with the second method there is an IPVC-like connection also known as an IP-PMVC (IP-Performance Monitoring Virtual Connection) dedicated to measuring the performance of connections between locations rather than monitoring specific Subscriber IPVCs. The difference between these is shown in Figure 9. Note that in both of these methods, MPs are created at the points in the network between which the SLS objectives are specified, i.e. in the same places as the SLS-RPs. This provides the most direct way of measuring performance so as to determine whether the objectives specified in the SLS have been met. However, it is not required that MPs and SLS-RPs are in the same places, and other arrangements are possible.

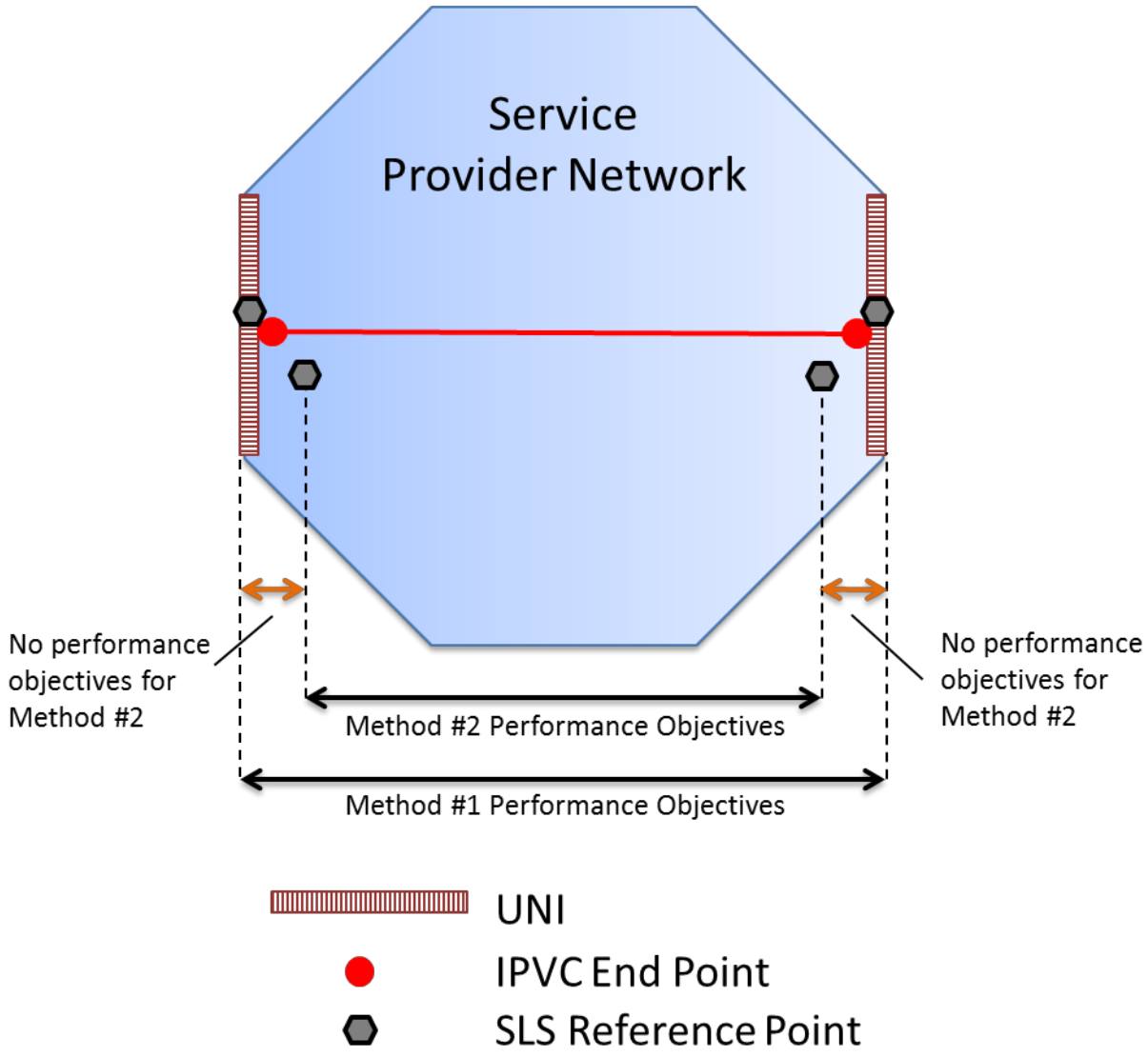

Figure 9 – SLS Method 1 and Method 2 Comparison

Examples of possible locations of the MPs are shown in Figure 10.

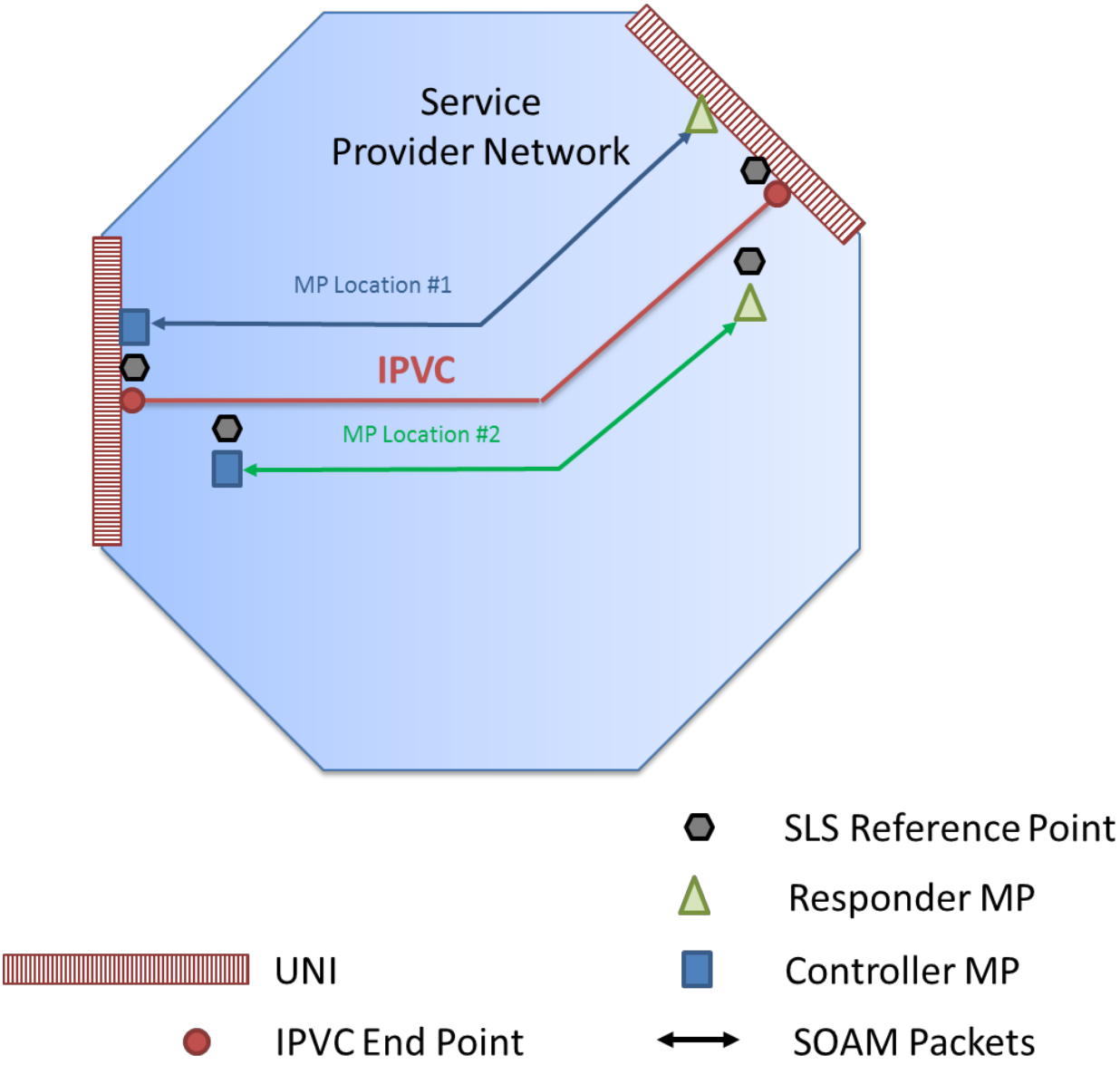

Figure 10 – Example MP Locations

PM can be performed using one of these three mechanisms:

- Active method where synthetic packets are generated, and measurements are performed on these packets.
- Passive method where counters reflecting customer traffic are retrieved from network elements.
- Hybrid method where customer traffic is modified to allow performance measurements to be performed using customer packets.

This document focuses on active PM measurement and discusses hybrid PM measurement. Passive PM measurement is outside the scope of the document. This is because the retrieval of network element counters is implementation specific. Future versions of this document might address passive PM measurement if the retrieval of these counters is standardized.

Within this document, Active Measurement is specified as using TWAMP Light/STAMP/TWAMP. These PM tools are defined in RFC 5357 [10] and IETF RFC 8762 [18]. They enable Single-Ended monitoring of packet delay and packet loss (detailed description in section 8.3). The protocol defined for each of these PM tools has a Session-Sender (Controller MP) and a Session-Reflector (Responder MP). The Controller MP generates measurement packets. The Responder MP responds to these packets. Time stamps in the packets allow accurate One-way Delay Measurements to be performed if Time of Day (ToD) clock synchronization is present at both MPs. If ToD synchronization is not present, it is not possible to make accurate One-way Delay Measurements. Two-way Delay Measurements are always possible. The ICM or SOF can divide the Two-way measurements in half in order to approximate the One-way delay, but in this case the results should be identified as derived when reporting to the user.

Hybrid Measurement is described using the AltM method. AltM is defined in RFC 8321 [17]. AltM enables Single-Ended monitoring for One-way Packet Delay and Packet Loss. See Section 9 for informational text on AltM.

PM Tools that measure Packet Delay (PD) and Packet Loss (PL) can be used to calculate additional metrics. PD measurements are used to calculate Mean Packet Delay, Inter-Packet Delay Variation, and Packet Delay Range. PL, measured as the difference between the number of transmitted packets and the number of packets received, is used to calculate the Packet Loss Ratio (PLR).

The following sections detail the use cases for PM including Location to Location monitoring and UNI to UNI monitoring. Location to Location monitoring provides a view of performance between locations using an IPVC-like connection but does not monitor a particular Subscriber IPVC in an SP's network. UNI to UNI monitoring provides a view of the performance of a Subscriber IPVC from UNI to UNI.

8.1.1 Location to Location Monitoring

One way of monitoring performance by SPs is to monitor network performance from Location to Location via a single PE at each Location. As such, individual IPVCs are not monitored. Locations are connected together using a Network Measurement IPVC-like connection called an IP-Performance Monitoring Virtual Connection (IP-PMVC). This monitoring via the IP-PMVC between Locations provides an indication of the performance of the SP's network between the Locations. Authentication might be used to provide secure communications in TWAMP and STAMP implementations. If Active Measurement is being used, the measurement packets are routed over the IP-PMVC that connects the Locations together. The measurement packets on the IP-PMVC are expected to be treated similar to Subscriber packets. Service Providers need to ensure that they take into account network techniques such as Traffic Engineering (TE) and Equal Cost Multi Path (ECMP) routing when designing the operation of IP-PMVCs. Packet loss

or delay that is measured between each location approximates the performance experienced by the Subscriber.

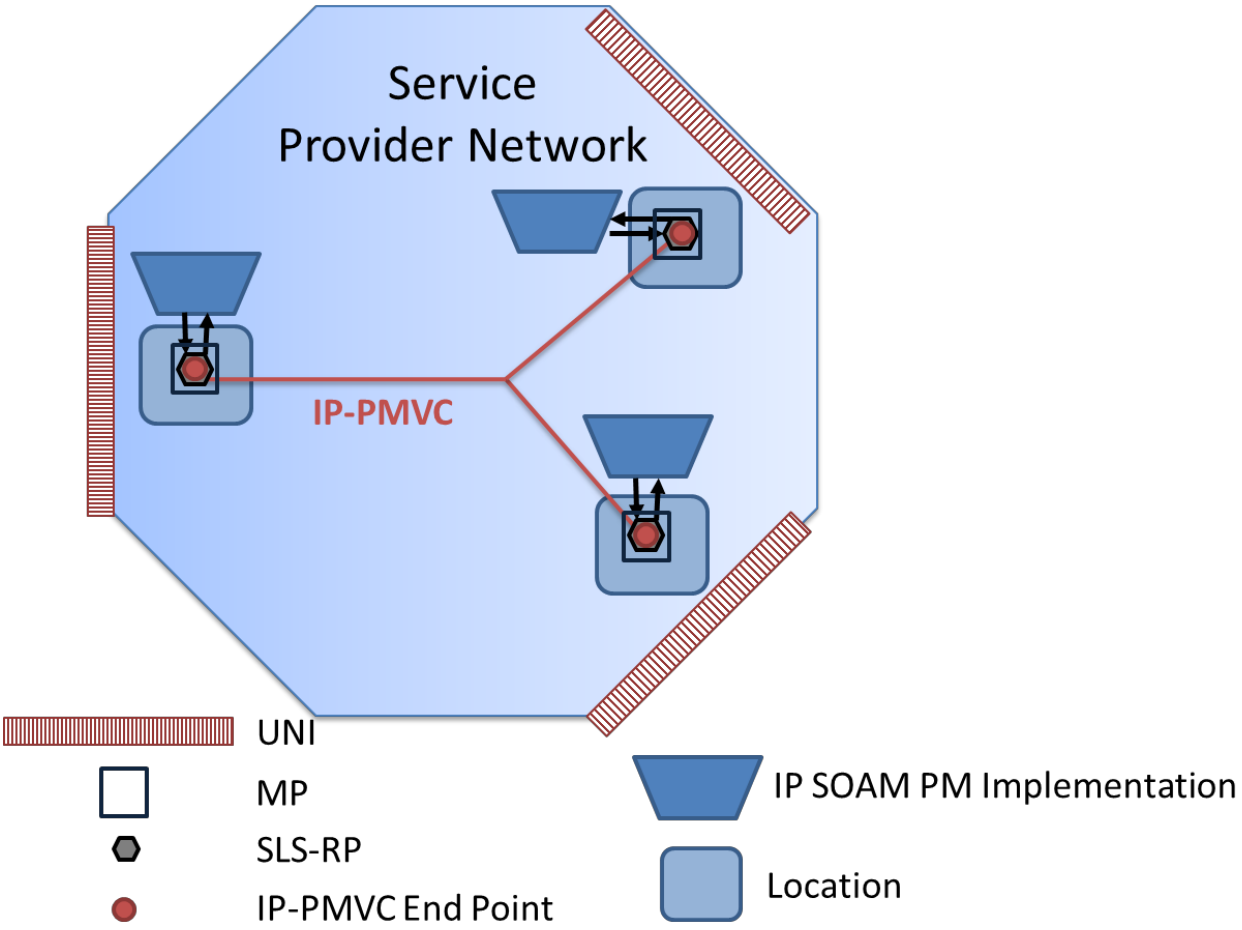

Figure 11 – Active PM Location to Location via IP-PMVC

Figure 11 is an example of a SP monitoring the performance of their network from Location to Location using an IP-PMVC dedicated to monitoring. The Locations are defined by the SP and interconnected using the IP-PMVC. An IP SOAM Implementation, either purpose built hardware, an application running in a Virtual Machine (VM) on external hardware, or an application running in the device at the location capable of generating measurement packets is connected to the SP network, sometimes via a UNI-like connection, and measurement packets are transmitted between all of the Locations via MPs that in this case are also IP-PMVC EPs. An MP can be at the same point as the SLS-RP, as shown in Figure 11, but does not have to be at the same point. Data collection is performed for some or all MP Pairs. A Location could represent a portion of a city, a city, a country, a region, or some other entity. An MP Pair might include PM reports for multiple CoS Names that are monitored between the Locations. Subscribers who have IPVCs that connect between those entities might use the PM reports as an indication if the performance of their IPVCs has met the SLS. Within the SLS some Location Pairs might have different performance objectives than others. The SLS performance objectives that apply to one MP Pair might be different than the SLS performance objectives that apply to another MP Pair. This is because the expected performance between some cities, countries, or regions differs.

Some Locations might offer higher performance SLS performance objectives while others offer lower performance SLS performance objectives.

When Location to Location monitoring is used, the SP needs to ensure that the IP-PMVC is configured such that performance degradations that impact Subscriber packets also impact the IP SOAM PM packets flowing over the IP-PMVC.

8.1.2 IPVC Monitoring

Another method of PM for an IP service is to monitor the IPVC. This method might include the entire path of the service or some portion of it. Examples are from UNI to UNI, for UNIs that have IPVC EPs in the same IPVC, or monitoring some portion of the IPVC. The SP is able to monitor degradations that occur at any point in the IPVCs between the two Measurement Points (MPs). This provides a more comprehensive view of the Subscriber's service performance. Using Active Measurement to perform IPVC monitoring requires that the PM packets be carried on the Subscriber's IPVC.

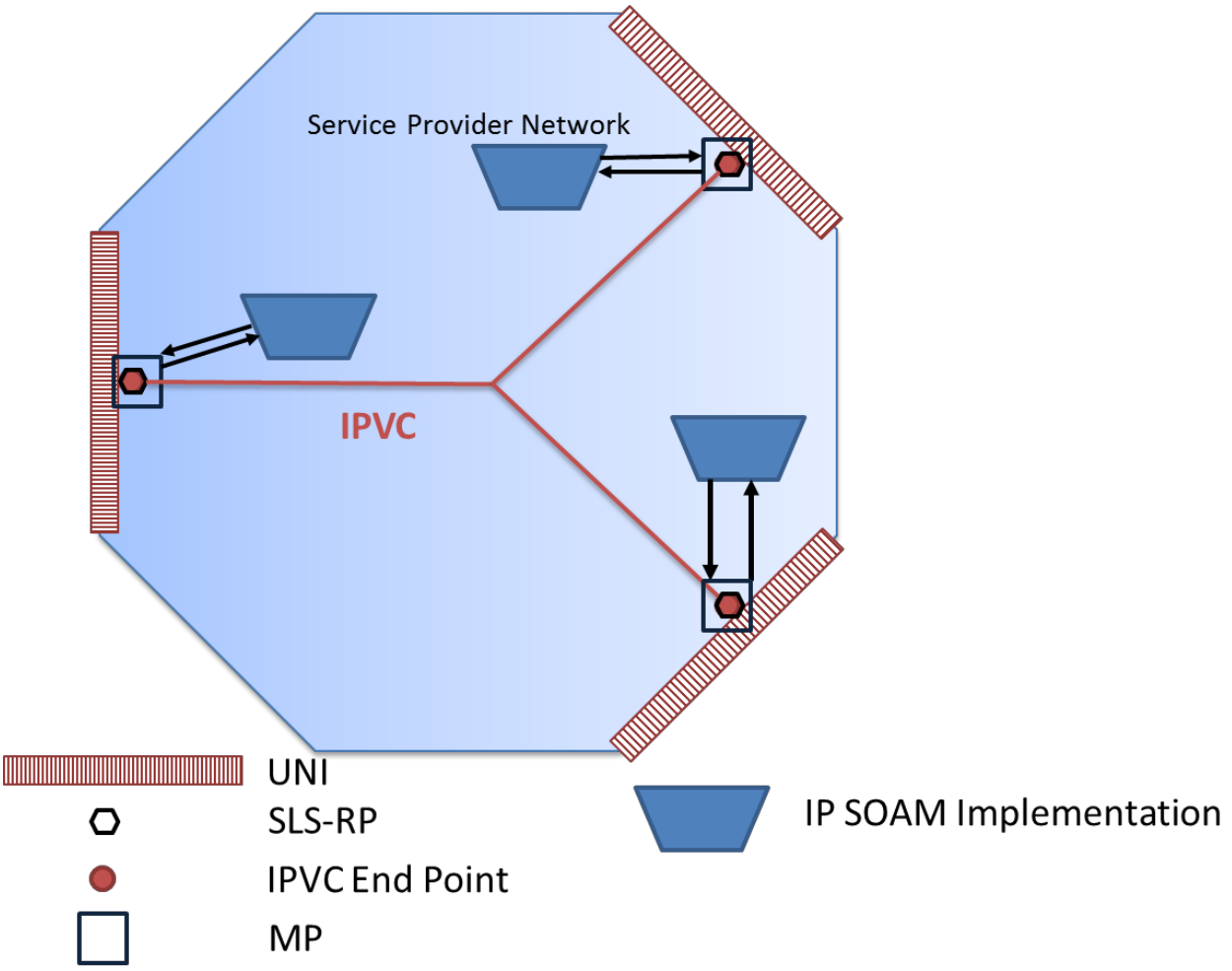

Figure 12 – IPVC EP to IPVC EP Active Measurement

Figure 12 is an example of Active Measurement on an IPVC from UNI to UNI, for UNIs that have IPVC EPs in the same IPVC. In this example, the IPVC EP, SLS-RP, and MP are all co-located. IP SOAM PM Implementations are deployed with the IPVC EPs. The IP SOAM PM Implementations are capable of generating monitoring packets. Packets are exchanged between the MPs active on the IPVC, and measurements between some or all MP Pairs are made and collected.

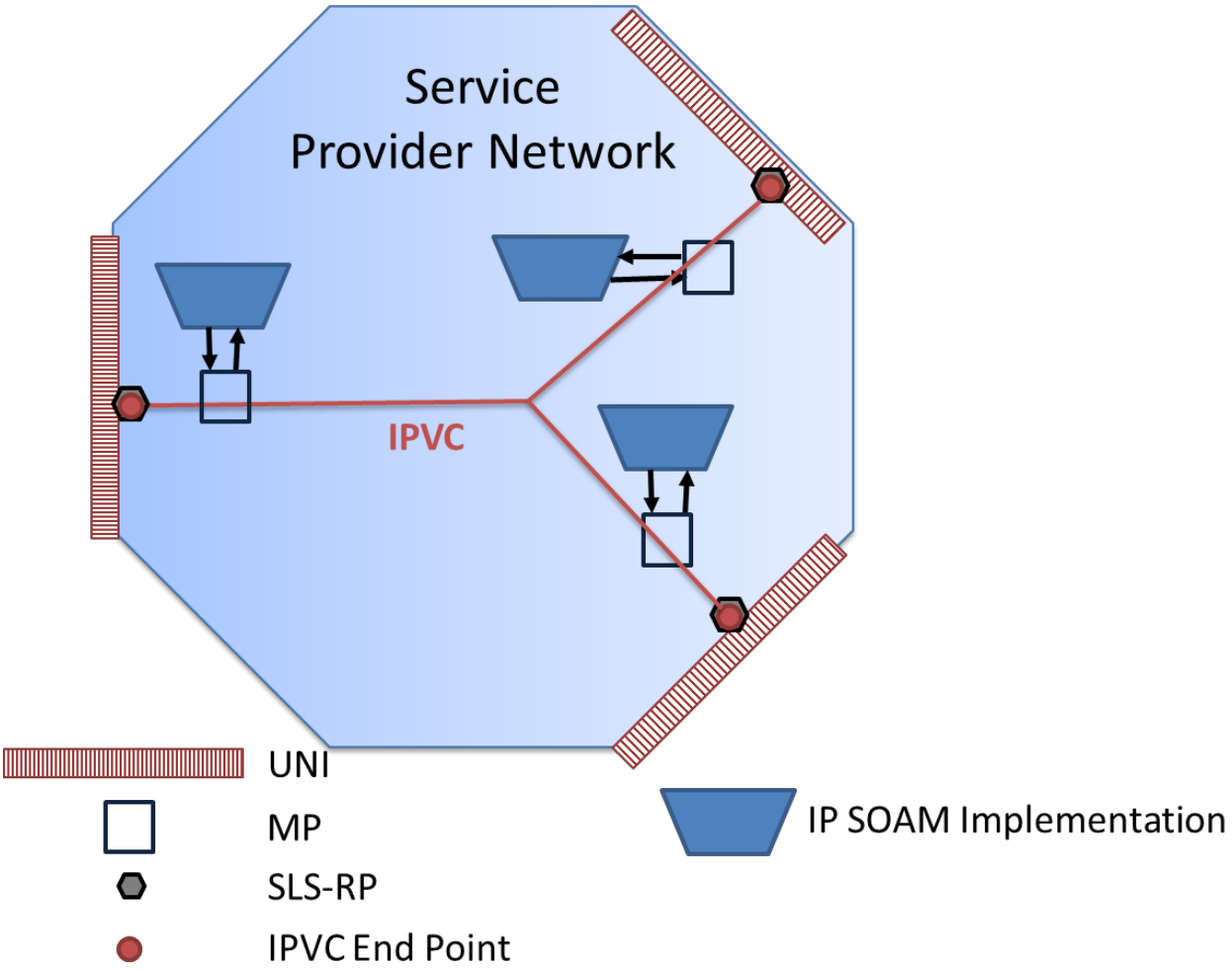

Figure 13 – Active Measurement when MPs are not at IPVC EPs

Figure 13 shows monitoring of an IPVC that places the MPs at some point other than the IPVC EP. This is similar to Location to Location monitoring as shown in section 8.1.1 but monitoring is per Subscriber IPVC versus an IP-PMVC dedicated to monitoring. This type of monitoring requires support for MPs and IP SOAM Implementations at some point within the Service Provider's network.

While monitoring each IPVC has some definite benefits, it also has some challenges. IPVC monitoring requires that either all IPVC EPs within an IPVC support both an MP and an IP SOAM PM Implementation, or that some points in the SP's network do so. This requires instantiation of many IP SOAM Implementations which can use processing capacity at each location.

This differs from Location to Location monitoring where only one or two IP-PMVC EPs per Location need to instantiate MPs and IP SOAM PM Implementations as shown in section 8.1.1. The limited number of MPs limits the processing capacity required to support IP SOAM.

An IP SOAM PM Implementation might be able to be supported as a part of a device supporting the CE, PE, or other function rather than be a separate device as shown in the figures. Monitoring

per IPVC EP increases the probe count compared to Location to Location monitoring and therefore increases the amount of data that must be processed.

A means to communicate between the ICM/ECM and the IP SOAM Implementation instantiated in the network is required. This can be harder if the IP SOAM Implementation is at the UNI, as bandwidth and other network resources may be more constrained compared to an IP SOAM Implementation located nearer the core of the network. There are impacts of either of these communication methods. These impacts are highlighted in Table 5.

UNI to UNI	Location to Location
MP required at all monitored UNI (or some point in the SP's network for each UNI)	MP located at one or two locations per city, etc. in SP's network
IP SOAM Implementation required at all monitored UNI (or some point in the SP's network for each UNI)	IP SOAM Implementations deployed at one or two locations per city, etc. in SP's network
Increased processing requirements at Provider-Managed CE to support IP SOAM Implementation	No impact to processing requirements at Provider-Managed CE
Enhanced communication path requiring additional bandwidth to Provider-Managed CE to allow for reporting performance measurements	Communication path to IP SOAM Implementations uses existing communication path to devices in the SP's network
Additional bandwidth and/or services needed for communications between a Provider-Managed CE and the ICM/ECM.	No additional bandwidth and/or services needed to a Provider-Managed CE.

Table 5 – Comparison of the Impact UNI-UNI and Location-Location Scope of IP SOAM Has on the SP's Network

The functionality described above allows monitoring the performance between all IPVC EPs of an IPVC, between some subset of IPVC EPs, between IPVC EPs and MPs that are not at the IPVC EPs, and between any combination of these. If Provider-Managed CEs are used, then examples of these include monitoring CE to PE, CE to CE or PE to PE.

8.2 PM Common Requirements

This section provides requirements that are applicable to PM. The requirements below provide for the life cycle of PM Sessions (starting, stopping, etc.) and storage of PM measurement data.

Many requirements apply to an "IP SOAM PM Implementation", which refers to the capabilities of a device or virtual function that are required to support IP SOAM Performance Monitoring.

8.2.1 Life Cycle

The requirements of this section apply to the life cycle of a PM Session, and to the scheduling of performance measurements conducted as part of a PM Session. Specifically, scheduling controls when, how long, and how often measurements will be taken for a PM Session.

8.2.1.1 General Overview of Parameters

The Performance Monitoring process is made up of a number of Performance Monitoring instances, known as PM Sessions. A PM Session is initiated on a Controller MP to take performance measurements for a given SOAM PM IP CoS Name and a given Responder MP. A PM Session is used for Loss Measurement and Delay Measurement.

The PM Session is specified by several direct and indirect parameters. A general description of these parameters is listed below, with more detailed requirements provided elsewhere in the document.

- The End Points are the Controller MP and a Responder MP.
- The DSCP used for the PM Session is chosen such that the performance of measurement packets is representative of the performance of the Qualified Packets being monitored.
- The PM Tool is any of the tools described in section 8.2 (TWAMP Light, STAMP, or TWAMP).
- The Message Period is the SOAM PM Packet transmission frequency (the time between SOAM PM Packet transmissions).
- The Start Time is the time that the PM Session begins.
- The Stop Time is the time that the PM Session ends.
- The Measurement Intervals are discrete, non-overlapping periods of time during which the PM Session measurements are performed, and results are gathered. SOAM PM packets for a PM Session are transmitted only during a Measurement Interval. Key characteristics of Measurement Intervals are the alignment to the clock and the duration of the Measurement Interval. Measurement Intervals can be aligned to either the PM Session Start Time or to a clock, such as the local time-of-day clock. The duration of a Measurement Interval is the length of time spanned by a non-truncated Measurement Interval.
- The Repetition Time is the time between the start times of the Measurement Intervals.

8.2.1.2 Proactive and On-Demand PM Sessions

A PM Session can be classified as either a Proactive or an On-demand session. A Proactive session is intended to continuously measure the performance between the MPs for the given SOAM PM IP CoS Name. An On-demand session is intended to monitor the performance between the MP Pair for the given SOAM IP PM CoS Name for a shorter period of time to check on performance, e.g., after a change has been made in the network.

A Proactive session runs all the time once it has been created and started. Since the intent is to provide continuous performance measurement, Proactive sessions use a Start Time of "immediate" and a Stop Time of "forever". Measurements are collected into multiple fixed

length Measurement Intervals covering different periods of time. Measurement Intervals for Proactive sessions are generally aligned to a clock, rather than the Session Start Time. Data is collected and a history of data is stored for a number of Measurement Intervals. Monitoring continues until the PM Session is deleted.

On-demand sessions are run when needed, and a report is provided at the end. Since On-demand sessions are intended to cover some finite period of time, absolute or relative Start and Stop Times may be used if those values are known. Alternatively, a Start Time of "immediate" and/or a Stop Time of "forever" may be used (with the intention of manually ending the session when no longer needed), especially if the monitoring period is of unknown duration (e.g., "until troubleshooting is completed".) Measurements may be gathered into one Measurement Interval spanning the entire session duration, or multiple Measurement Intervals covering different periods of time. When multiple Measurement Intervals are used, then historical data from past Measurement Intervals may or may not be stored on the device. In addition, Measurement Intervals may be aligned with the session Start Time or aligned with a clock.

8.2.1.3 Create

A PM Session has to be created before it can be started. This applies for both On-demand and Proactive PM Sessions. In order to create a PM Session, a PM Tool must be assigned to the PM Session.

[D11] An IP SOAM PM Implementation **SHOULD** support multiple concurrent PM Sessions to the same destination, regardless of the setting of other parameters for the PM Sessions, and regardless of whether the PM Sessions use the same or different PM Tools using the five tuple (destination and source IP addresses, transport type, and destination and source port numbers) to identify each PM Session.

Multiple PM Sessions using the same PM Tool could be used, for example, to monitor different SOAM PM IP CoS Name (and hence measure performance for different IP CoS Name packets), different packet lengths, or to support both Proactive and On-demand sessions.

[R32] An IP SOAM PM Implementation **MUST** provide a way to indicate to the ICM/SOF whether a PM Session is Proactive or On-demand.

8.2.1.4 Delete

The requirements of this section apply to the deletion of a PM Session.

[R33] An IP SOAM PM Implementation **MUST** support the capability to delete a PM Session.

[R34] After a PM Session is deleted, further IP SOAM PM Packets relating to the session **MUST NOT** be sent.

[R35] After a PM Session is deleted, further measurements associated with the deleted PM Session **MUST NOT** be made.

[O2] Before the data from a deleted PM Session is lost, an IP SOAM PM Implementation **MAY** issue a report (similar to the report that would happen when Stop Time is reached).

[R36] After a PM Session is deleted, all the stored measurement data relating to the deleted PM Session **MUST** be deleted.

Note: a PM Session may be deleted at any point in its lifecycle, including before it has started.

8.2.1.5 Start and Stop

When a PM Session is started, it can be specified to start immediately, or be scheduled to start in the future. Both start conditions, particularly "immediate", are conditional upon the local interface reaching the operational Up state and the address associated with the Responder being reachable.

[R37] For Proactive PM Sessions, the Start Time **MUST** be "immediate".

[R38] For On-demand PM Sessions, an IP SOAM PM Implementation **MUST** support a configurable Start Time per PM Session. The Start Time can be specified as "immediate", as an offset from the current time, or as a fixed absolute time in the future.

An offset from the current time (i.e., a "relative" time) could be specified as a given number of hours, minutes, and seconds from the current time. A fixed absolute time could be specified as a given UTC date and time.

[D12] For On-demand PM Sessions, the default Start Time **SHOULD** be "immediate".

The following requirements apply to stopping of a PM Session.

[R39] For Proactive PM Sessions, the Stop Time **MUST** be "forever".

[R40] For On-demand PM Sessions, an IP SOAM PM Implementation **MUST** support a configurable Stop Time per PM Session. The Stop Time can be specified as "forever" or as an offset from the Start Time.

An offset from the current time (i.e., a "relative" time) could be specified as a given number of hours, minutes, and seconds from the Start Time.

[R41] For On-demand PM Sessions, if the Stop Time is specified as an offset from the Start Time, then the Stop Time **MUST** be equal to or greater than the Message Period of the PM Session.

[D13] For On-demand PM Sessions, the default Stop Time **SHOULD** be "forever".

[R42] An IP SOAM PM Implementation **MUST** support stopping a PM Session by management action, prior to the Stop Time being reached.

[R43] After a PM Session is stopped, whether by reaching the scheduled Stop Time or by other means, further SOAM PM Packets relating to the session **MUST NOT** be sent.

[R44] After a PM Session is stopped, the stored measurements relating to the PM Session **MUST** remain available for retrieval**.**

Note: a PM Session cannot be restarted once it has been stopped, as this would make it difficult to interpret the results. Instead, a new PM Session can be started.

8.2.1.6 Measurement Intervals

For the duration of a PM Session, measurements are partitioned into fixed-length Measurement Intervals. The length of the period of time associated with a Measurement Interval is called the duration of the Measurement Interval. The results of the measurements are captured in a Measurement Interval Data Set. The results in a Measurement Interval Data Set are stored separately from the results of measurements performed during other Measurement Intervals. This section contains requirements pertaining to Measurement Intervals in the Life Cycle of the PM Session. Requirements pertaining to storage of Measurement Interval Data Sets are found in section 8.2.2.1.

[R45] A SOAM PM Implementation **MUST** support a configurable duration for Measurement Intervals.

[R46] A SOAM PM Implementation **MUST** support a Measurement Interval with duration of 15 minutes for Proactive PM Sessions.

[R47] A SOAM PM Implementation **MUST** support Measurement Intervals with a duration of between 1 minute and 15 minutes (in 1-minute increments) for On-Demand PM Sessions.

[D14] The default Measurement Interval duration for On-Demand PM Sessions **SHOULD** be 5 minutes.

8.2.1.7 Repetition Time

For each PM Session, a Repetition Time can be specified if it is not desirable to perform measurements continuously. If the Repetition Time is “none”, then a new Measurement Interval is started immediately after the previous one finishes, and hence performance measurements are made continuously. If a Repetition Time is specified, a new Measurement Interval is not started until after Repetition Time has passed since the previous Measurement Interval started. During the time between the end of the previous Measurement Interval and the start of the next one, no SOAM PM Packets are sent by the Controller MP relating to the PM Session, and no measurements are initiated. Note that Responder MPs may send SOAM Packets during the time between two Measurement Intervals in response to SOAM Packets that may have previously been sent by the Controller MP.

[R48] An IP SOAM PM Implementation **MUST** support a configurable Repetition Time per PM Session. The Repetition Time can be specified as "none" or as a repeating time interval.

A repeating time interval (i.e., a relative time) could be specified as every given number of hours, minutes, and seconds from the Start Time.

[D15] The default Repetition Time **SHOULD** be "none".

[R49] If the Repetition Time is a relative time, the time specified **MUST** be greater than the duration of the Measurement Interval.

[R50] During the time between two Measurement Intervals, SOAM PM Packets relating to the PM Session **MUST NOT** be sent by the Controller MP.

8.2.1.8 Alignment of Measurement Intervals

The following requirements pertain to the alignment of Measurement Intervals with time-of-day clock or PM Session Start Time.

[D16] An IP SOAM PM Implementation **SHOULD** by default align the start of each Measurement Interval, other than the first Measurement Interval, on a boundary of the local time-of-day clock that is divisible by the duration of the Measurement Interval (when Repetition Time is "none").

[D17] An IP SOAM PM Implementation **SHOULD** by default align the start of each Measurement Interval, other than the first Measurement Interval, on a boundary of the local time-of-day clock that is divisible by the Repetition Time (when Repetition Time is not "none").

When Measurement Intervals are aligned with the ToD clock, the Start Time of a PM Session might not correspond with the alignment boundary. In this case, the first Measurement Interval could be truncated.

[D18] An IP SOAM PM Implementation **SHOULD** allow for no alignment to the ToD clock.

[D19] An IP SOAM PM Implementation **SHOULD** support a configurable (in minutes) offset from ToD time for alignment of the start of Measurement Intervals other than the first Measurement Interval.

For example, if the Measurement Interval is 15 minutes and the Repetition Time is "none" and if ToD offset is 5 minutes, the Measurement Intervals would start at 5, 20, 35, 50 minutes past each hour.

8.2.1.9 Summary of Time Parameters

Possible values for the time parameters are summarized in the table below and are further explained in Appendix A:

Attribute	Possible Values	PM Session Type
Start Time	"Immediate" (default) Relative Time Fixed Time	Proactive or On-Demand Proactive or On-Demand On-Demand On-Demand
Stop Time	"Forever" (default) Relative Time	Proactive or On-Demand On-Demand
Repetition Time	"None" Relative Time	Proactive or On-Demand Proactive or On-Demand

Table 6 – Time Parameters

8.2.2 Storage

The requirements of this section apply to storage of performance measurement results taken during Measurement Intervals, using counters or Measurement Bins (for some delay-related parameters). Performance measurements are stored separately for each Measurement Interval. A Measurement Bin is a counter and records the number of performance measurements falling within a specified range.

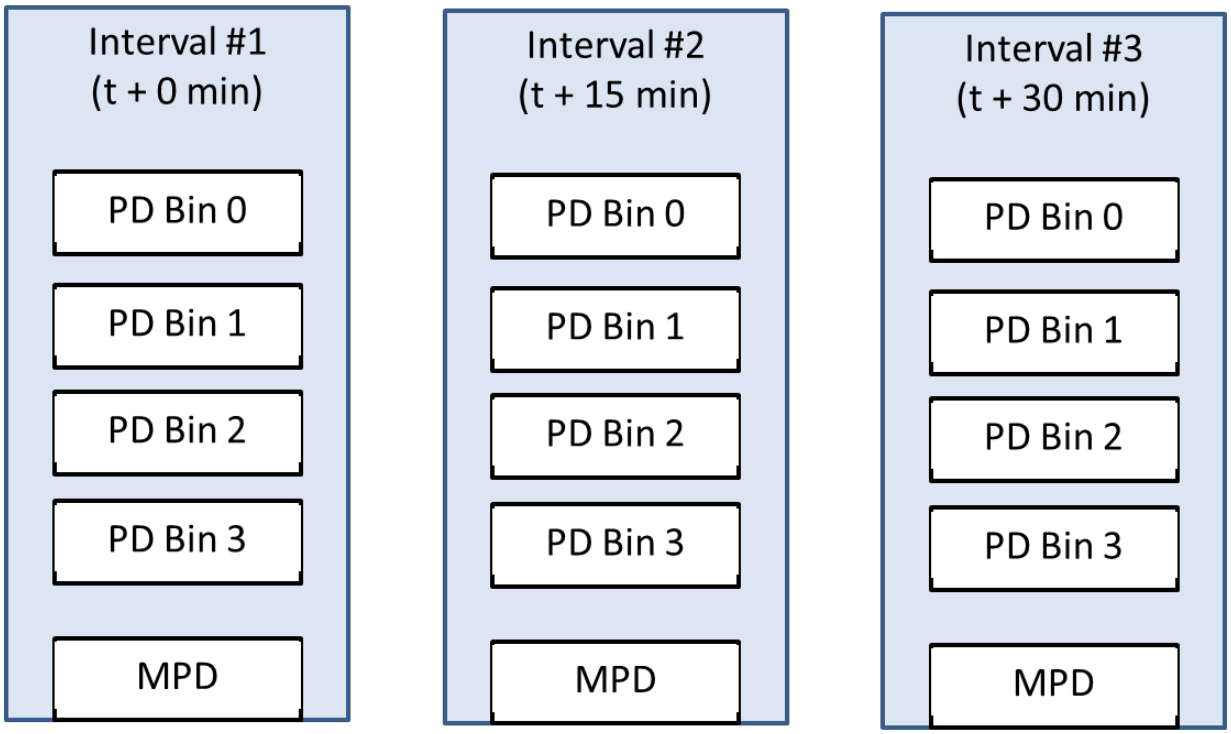

Figure 14 – Example of Measurement Bins and Intervals

Figure 14 shows the relationship between Measurement Bins and Measurement Intervals. Multiple Measurement Bins can be configured for a PM Session. Counts in these bins are incremented during each Measurement Interval.

Only Delay Measurements use bins; for Loss Measurements, bins are not used. Instead, each Measurement Interval contains counters that display Transmitted (TX) and Received (RX) packet counts. This is shown in Figure 15 below.

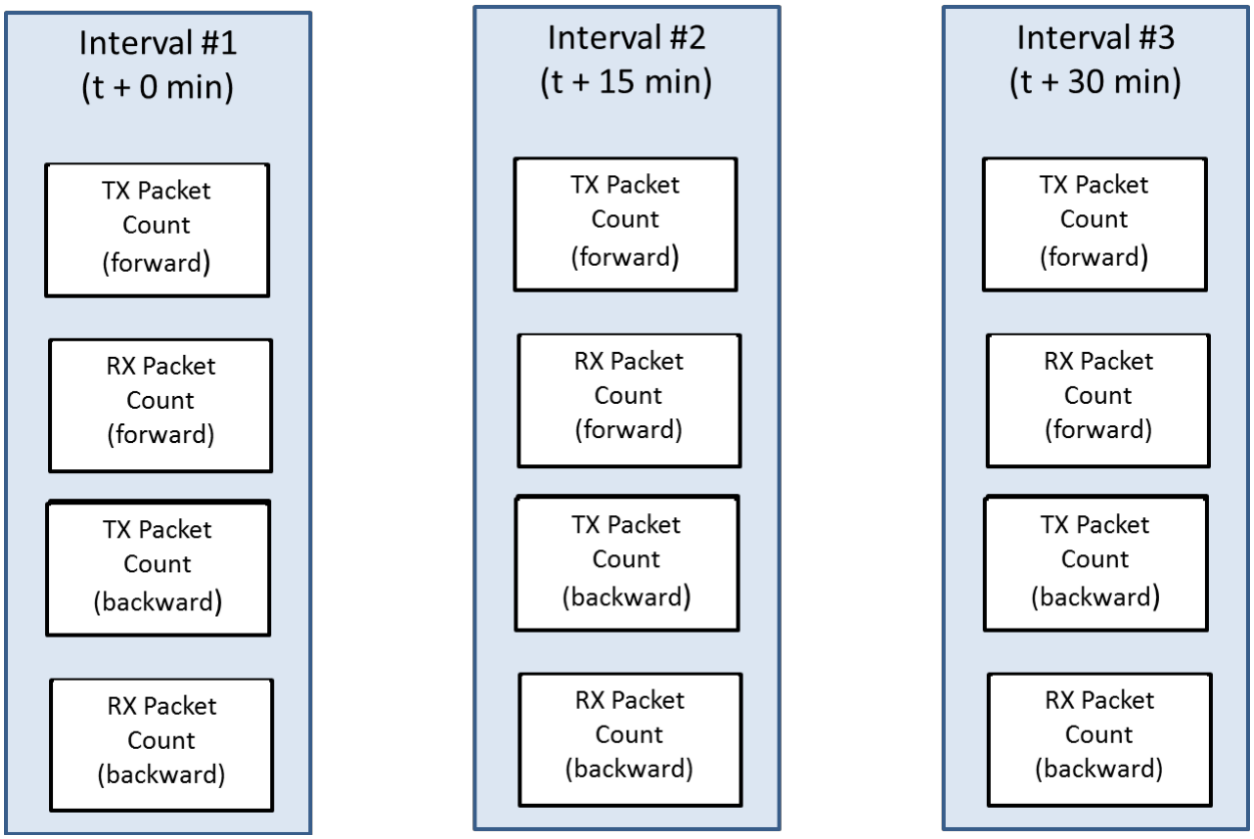

Figure 15 – Example of Packet Count Measurements

8.2.2.1 Measurement Interval Data Sets

The following requirements apply to the storage of the results of PD, PDR, MPD, IPDV, or PLR, performance measurements conducted between a given source and destination MP Pair, for a given PM Session during a given Measurement Interval.

[R51] An IP SOAM PM Implementation **MUST** store measurement data for a current Measurement Interval and at least 8 hours of historic measurement data (captured per Measurement Interval) for a given data set of a Proactive PM Session.

[D20] An IP SOAM PM Implementation **SHOULD** store measurement data for a current Measurement Interval and at least 24 hours of historic measurement data (captured per Measurement Interval) for a given data set of a Proactive PM Session.

[D21] An IP SOAM PM Implementation **SHOULD** store measurement data for a current Measurement Interval and at least 8 hours of historic measurement

data (captured per Measurement Interval) for a given data set of an On-demand PM Session.

[R52] An IP SOAM PM Implementation **MUST** record the value of the local ToD clock in UTC at the scheduled start of the Measurement Interval.

[R53] An IP SOAM PM Implementation **MUST** record the value of the local ToD clock in UTC at the scheduled end of the Measurement Interval.

[R54] An IP SOAM PM Implementation **MUST** support an elapsed time counter per Measurement Interval, which records the number of seconds that have elapsed since the Measurement Interval began.

[D22] An IP SOAM PM Implementation **SHOULD** support synchronization of the local time-of-day clock with UTC to within one second of accuracy.

[R55] An IP SOAM PM Implementation **MUST** record the results of a completed performance measurement as belonging to the Measurement Interval Data Set for the Measurement Interval in which the performance measurement was initiated.

IP SOAM PM response packets may get delayed and to ensure calculation of more comprehensive performance metrics, an implementation of the Controller MP needs to accept such late arriving packets. The period of time the Controller MP waits for IP SOAM PM packets is controlled by the timer referred to as “wait timer”.

[R56] An implementation of SOAM PM **MUST** support configurable wait timer, with the range of values from 1 second through to 5 seconds in one-second increments and the default value of 5 seconds, associated with the end of the Measurement Interval.

[R57] For Single-Ended Functions, a SOAM PM response packet received by the Controller MP after the expiration of the associated wait timer after the end of the Measurement Interval in which the corresponding SOAM PM request packet was transmitted **MUST** be discarded and considered lost.

8.2.2.2 Measurement Bins

The following requirements apply to the use of Measurement Bins for recording the results of delay performance measurements which can be used to determine conformance to PD, IPDV, and PDR objectives conducted between a given source and destination MP for a given PM Session during a Measurement Interval. Additional detail on Measurement Bins is provided in Appendix B.

When using Single-Ended Delay Measurement, PD, IPDV and PDR can be monitored using Two-way measurements, and/or using One-way measurements in the Forward and/or Backward direction. The particular measurements supported in an IP SOAM PM Implementation depend on the device capabilities (e.g., time-of-day clock synchronization between Controller MP and Responder MP).

The following requirements apply to each PD measurement supported in an IP SOAM PM Implementation.

[R58] An IP SOAM PM Implementation **MUST** support a configurable number of PD Measurement Bins per Measurement Interval.

[D23] For an IP SOAM PM Implementation, the default number of PD Measurement Bins per Measurement Interval **SHOULD** be 2.

[R59] An IP SOAM PM Implementation **MUST** support at least 2 PD Measurement Bins per Measurement Interval.

[D24] An IP SOAM PM Implementation **SHOULD** support at least 10 PD Measurement Bins per Measurement Interval.

The following requirements apply to each IPDV or PDR measurement supported in an IP SOAM PM Implementation.

[R60] An IP SOAM PM Implementation **MUST** support a configurable number of IPDV Measurement Bins per Measurement Interval.

[D25] For an IP SOAM PM Implementation, the default number of IPDV Measurement Bins per Measurement Interval supported **SHOULD** be 2.

[R61] An IP SOAM PM Implementation **MUST** support at least 2 IPDV Measurement Bins per Measurement Interval.

[D26] An IP SOAM PM Implementation **SHOULD** support at least 10 IPDV Measurement Bins per Measurement Interval.

[R62] An IP SOAM PM Implementation **MUST** support a configurable number of PDR Measurement Bins per Measurement Interval.

[D27] For an IP SOAM PM Implementation, the default number of PDR Measurement Bins per Measurement Interval supported **SHOULD** be 2.

[R63] An IP SOAM PM Implementation **MUST** support at least 2 PDR Measurement Bins per Measurement Interval.

[D28] An IP SOAM PM Implementation **SHOULD** support at least 10 PDR Measurement Bins per Measurement Interval.

Note: For PDR the minimum PD for the MI is subtracted before binning the results (see Appendix D for more details).

The following general Measurement Bin requirements apply to any IP SOAM PM Implementation. Each bin is associated with a specific range of observed delay, IPDV or PDR. Bins are defined to be contiguous, and each is configured with its lower bound. Because the bins are contiguous, it is only necessary to configure the lower bound of each bin. Furthermore, the

lowest bin is assumed to always have a lower bound of 0, and the highest bin is assumed to have an upper bound of ∞.

Note: All values for IPDV, PDR and Two-way PD are positive by definition. Values for One-way PD can be negative if there is no ToD synchronization, and such measurements would not match any Measurement Bin as defined above; however, in this case taking One-way PD measurements is not recommended except for the purpose of finding the minimum PD for normalization of PDR, and finding the minimum PD does not require Measurement Bins.

A Measurement Bin is associated with a single counter that can take on non-negative integer values. The counter records the number of measurements whose value falls within the range represented by that bin.

[R64] An IP SOAM PM Implementation **MUST** support a configurable lower bound for all but the first Measurement Bin.

[R65] The lower bound for each Measurement Bin **MUST** be larger than the lower bound of the preceding Measurement Bin.

[R66] The unit for a lower bound **MUST** be in microseconds (µs).

[R67] The lower bound of the first Measurement Bin **MUST** be fixed to 0µs.

[R68] Measured performance values that are greater than or equal to the lower bound of a given bin and strictly less than the lower bound of the next bin (if any), **MUST** be counted in that, and only that bin.

[D29] The default lower bound for a Measurement Bin **SHOULD** be an increment of 5000 µs larger than the lower bound of the preceding Measurement Bin.

For example, four Measurement Bins gives the following:

Bin	Lower Bound	Range
Bin 0	0 µs	0 µs ≤ measurement < 5,000 µs
Bin 1	5,000 µs	5,000 µs ≤ measurement < 10,000 µs
Bin 2	10,000 µs	10,000 µs ≤ measurement < 15,000 µs
Bin 3	15,000 µs	15,000 µs ≤ measurement < ∞

Table 7 – Example Measurement Bin Configuration

[R69] Each Measurement Bin counter **MUST** be initialized to 0 at the start of the Measurement Interval.

8.2.2.3 Volatility

The following requirement applies to the volatility of storage for Measurement Interval data.

[D30] An IP SOAM PM Implementation **SHOULD** store the data for each completed Measurement Interval in local non-volatile memory.

The set of completed Measurement Intervals whose data is stored represents a contiguous and moving window over time, where the data from the oldest historical Measurement Interval is aged out at the completion of the current Measurement Interval.

8.2.2.4 Measurement Interval Status

The following requirements apply to a discontinuity within a Measurement Interval. Conditions for discontinuity include, but are not limited to, the following:

- Loss of connectivity between the Controller MP and the Responder MP.
- Per section 10.1.6.1 of ITU-T G.7710/Y.1701 [20], the local time-of-day clock is adjusted by at least 10 seconds.
- The conducting of performance measurements is started part way through a Measurement Interval (in the case that Measurement Intervals are not aligned with the Start Time of the PM Session).
- The conducting of performance measurements is stopped before the current Measurement Interval is completed.
- A local test, failure, or reconfiguration disrupts service on the IPVC.

[R70] An IP SOAM PM Implementation **MUST** support a Suspect Flag per Measurement Interval.

[R71] The Suspect Flag **MUST** be set to false at the start of the current Measurement Interval.

[R72] An IP SOAM PM Implementation **MUST** set the Suspect Flag to true when there is a discontinuity in the performance measurements conducted during the Measurement Interval.

Note: Loss of measurement packets does not affect whether the Suspect Flag is set.

[D31] When the suspect flag is set to true for a Measurement Interval, an IP SOAM PM Implementation **SHOULD** record the reason for the discontinuity.

[R73] The value of the Suspect Flag for a Measurement Interval **MUST** always be stored along with the other results for that Measurement Interval when that Measurement Interval's data is moved to history.

8.3 PM Implementation Requirements

A PM Implementation uses PM Tools to perform the measurements. A PM Session is an instantiation of a particular PM Tool between a given MP Pair using a given IP CoS Name over a given (possibly indefinite) period of time. A PM Session can be given a unique identifier, known as the PM Session ID, by the SOF. This is used by the SOF to identify a specific PM Session.

Note: Only unicast packets are used to perform PM Measurements to avoid causing congestion in the network.

An explanation of Single-Ended is shown in Figure 16. This term is also defined in MEF 35.1 [23].

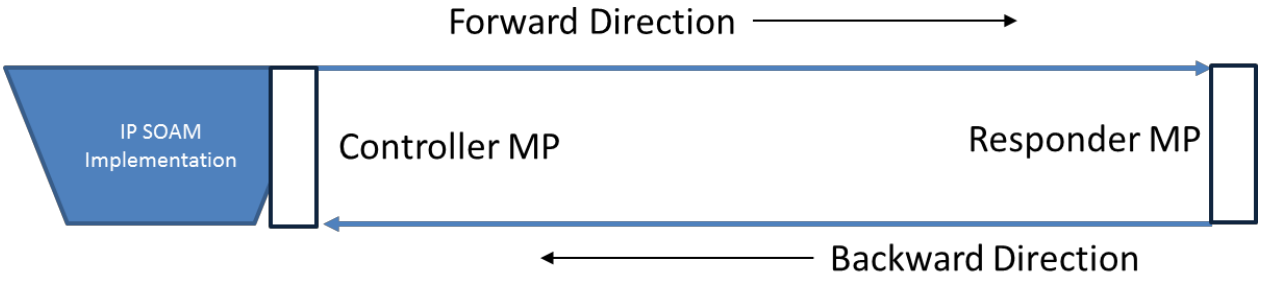

Figure 16 – Single-Ended Function

As seen in Figure 16, a Single-Ended Function places a Controller MP at one end of the service being monitored. The Controller MP transmits and receives measurement packets. The Single-Ended Function also places a Responder MP at the other end of the service being monitored. The Responder MP processes the packets received from the Controller MP and transmits packets to the Controller MP. Controller to Responder measurements and Responder to Controller measurements are also known as Forward and Backward measurements, respectively. Single-Ended Functions can be used to perform One-way measurement in the forward and backward directions, and to perform Two-way measurements. This is because the responder is not a simple loopback but processes the packets adding sequence numbers and timestamps including the time the packet was received, the timestamp quality estimate, and the time the packet was transmitted as described in section 8.3.1. Single-ended forward and backward measurements are included in the scope of this document.

With optional time-of-day (ToD) clock synchronization, accurate One-way Packet Delay (PD) and Mean Packet Delay (MPD) measurements can be taken. Two-way PD, MPD, Packet Delay Range (PDR), and Inter-Packet Delay Variation (IPDV) measurements and One-way PDR and IPDV measurements can always be taken and do not require ToD clock synchronization. For PD and MPD, if ToD synchronization is not sufficiently accurate for performance measurement purposes, the One-way performance metrics of MEF 61.1 [25] can be estimated by dividing the Two-way measurement by 2, although this introduces considerable statistical bias. Also note that when measuring One-way PDR, it is necessary to normalize measurements by subtracting the minimum delay. This allows One-way PDR to be measured even if ToD synchronization is not present. Examples of this are shown below (more details in Appendix D).

When the minimum delay between two MPs is a positive value, use the lowest positive value as the minimum delay. For example, if the minimum delay measured between two MPs is 7000ms then all One-way Delay Measurements have 7000ms subtracted from them and the result is the normalized measurement.

When the minimum delay between two MPs is a negative value, use the most negative value as the minimum delay. For example, if the minimum delay measured between two MPs is -7000ms then all One-way Delay Measurements have -7000ms subtracted from them and the result is the normalized measurement.

MEF 61.1 [25] defines that multiple Class of Service Names (CoS Names) can be supported by an IP Service. These CoS Names are used to identify which CoS to map the packet to and how the packet is treated by the network. Each of the CoS Names can be used to specify a different objective within an SLS. When measuring the performance of an IP service, it might be necessary to monitor the performance of different CoS Names between the same two MPs. This is done by creating a separate PM Session for each CoS Name to be monitored. When the IP SOAM Measurement packets use the Subscriber IPVC they are treated the same way as the Subscriber packets for each CoS Name being monitored. When the IP SOAM Measurement packets use the IP-PMVC, they are treated the same as Subscriber packets for each CoS Name being monitored, though the IP-PMVC packets might travel on a different path than when PM is performed on the IPVC itself.

The intention is for IP SOAM Measurement packets to be treated the same as Subscriber IP Data packets and to take the same network paths. The IP SOAM Measurement packets include the DA of the IP SOAM Implementation at the targeted IPVC EP, CoS markings matching the Subscriber packets within the Service Provider's network for that CoS Name, and are introduced into the network onto the same device as the Subscriber's IP Data packets and that serves the Subscriber's IPVC EP. The IP SOAM Measurement packets use the same queues, processors, and network facilities as the Subscriber's IP Data packets. The IP SOAM Measurement packets experience the Service Provider's network in a similar manner to the Subscriber's IP Data packets.

In the case of Location to Location monitoring, the IP-PMVCs are configured similar to Subscriber IPVCs on devices serving Subscriber IPVCs. The SP needs to ensure IP SOAM Measurement packets are processed similarly to Subscriber IP Data packets. Using the same queues, processors, and network facilities as Subscriber packets can ensure that the IP SOAM Measurement packets experience the Service Provider's network in a similar manner to the Subscriber's.

Note: The Dual-Ended Function (OWAMP) is not within the scope of this document. OWAMP requires coordination and communication between the two ends of the service. Because of the added complexity of OWAMP vs. TWAMP Light or STAMP, OWAMP is not addressed. One-way measurements are possible using a Single-Ended Function as discussed above.

8.3.1 PM Implementation Description

The PM Implementation provides Single-Ended Functions that measure Packet Delay (PD), and Packet Loss (PL). The implementation also provides calculations of Mean Packet Delay (MPD), Inter-Packet Delay Variation (IPDV), Packet Delay Range (PDR), and Packet Loss Ratio (PLR). The ability to use TWAMP Light to perform these measurements is mandatory, other tools can be used.

TWAMP Light, STAMP, or TWAMP are used for Single-Ended PD and MPD measurements. Two-way Delay Measurements are performed by the Session-Sender (Controller MP) using the timestamps in the Session-Reflector (Responder MP) response packet. These timestamps are shown in Figure 17. The Controller MP transmits an IP SOAM Measurement packet to the DA of the Responder MP. Timestamp T1 is added by the Controller MP when the IP SOAM Measurement packet is transmitted. Timestamp T2 is added by the Responder MP when the IP

SOAM Measurement packet is received. Timestamp T3 is added to the IP SOAM Measurement packet by the Responder MP when the packet is transmitted to the DA of the Controller MP. Timestamp T4 is added to the IP SOAM Measurement packet by the Controller MP when the packet is received from the Responder MP.

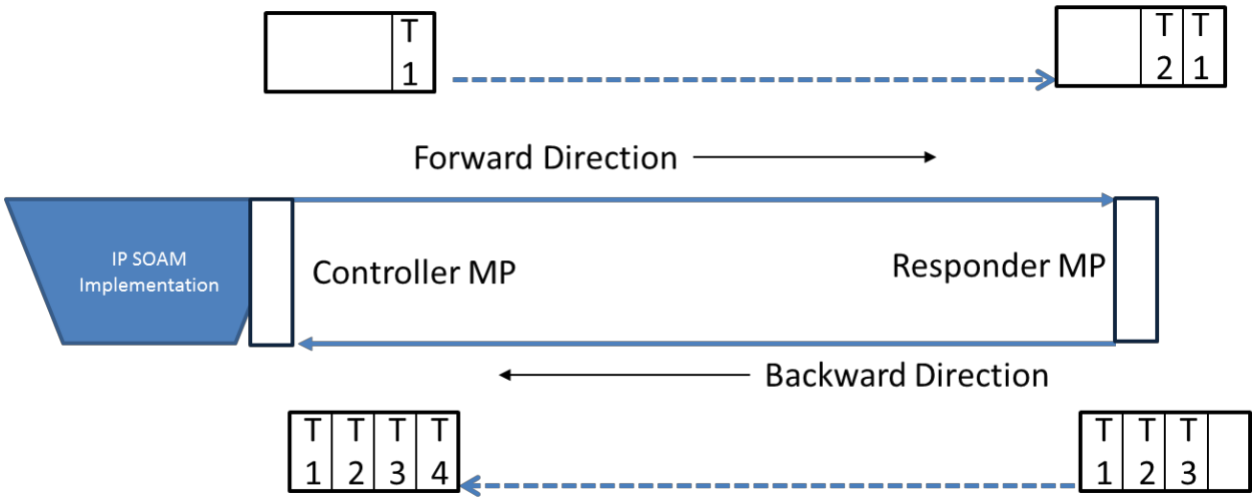

Figure 17 – Timestamp Locations

[R74] Two-way PD **MUST** be calculated as (T4-T1)-(T3-T2) where T1 = Session-Sender Timestamp at the Controller MP, T2 = Receive Timestamp at the Reflector MP, T3 = Timestamp of packet transmit at the Reflector MP, and T4 = time measurement packet is received by Session-Sender (Controller MP) from Session-Reflector.

Note: By subtracting the difference between T3 and T2 the processing time at the Session-Reflector is removed from the measurement.

One-way PD is always measured between the MPs even if ToD synchronization is not in place, as the values are used to calculate IPDV and PDR. If ToD synchronization is in place, these values can also be reported as the One-way PD and used to calculate One-way MPD.

[R75] One-way PD **MUST** be calculated as Forward PD (T2-T1) and Backward PD (T4-T3) where T1 = Session-Sender Timestamp at the Controller MP, T2 = Receive Timestamp at the Responder MP, T3 = Timestamp of packet transmit at the Responder MP, and T4 = time measurement packet is received by Session-Sender (Controller MP) from Session-Reflector.

If ToD synchronization does not exist between the MPs, One-way PD and MPD can be estimated by dividing the Two-way measured value in half.

[R76] When a SOAM PM Implementation estimates One-way PD and MPD from Two-way measurements it **MUST** indicate this.

As noted above, the PD measurements are used to calculate several other metrics. The methodologies for these calculations are detailed below.

To determine the Mean Packet Delay the following formula is used, where n is the number of packet delay measurements in the MI:

$$\frac{\sum^{n}(Packet\ delays\ of\ all\ Packet\ Delay\ measurements\ in\ an\ MI)}{n}$$

To determine Inter Packet Delay Variation the following is used:

A parameter, i, is the IP SOAM Measurement packet ordered pair selection offset as referred to in [D36]. Given a sequence of received periodic IP SOAM Measurement packets, the set of ordered pairs can be expressed as $\{ \{p_1, p_{1+i}\}, \{p_2, p_{2+i}\}, \{p_3, p_{3+i}\}, \ldots\}$.

The IPDV is the calculated difference in One-way packet delay between the packets in each ordered pair selection. Note that this can be calculated even when there is no ToD synchronization in place (so One-way PD values may be negative), since taking the difference between two measurements cancels out any inaccuracy.

Packet Delay Range is calculated by first determining the minimum PD measured during the current or previous MI. Once an estimate of the minimum is available, observed delays can be normalized by subtracting the minimum, and then the appropriate bin counters can be incremented as the normalized delay is processed from each received IP SOAM Measurement packet.

One suggested practical approach is to record the minimum delay of each Measurement Interval, and to use that value as the estimated minimum at the beginning of the following Measurement Interval. As each Delay Measurement is received, the estimated minimum can be set to the minimum of the current measured delay and the previous estimate. Then each received Delay Measurement is normalized by subtracting the estimated minimum. With this approach, there would never be a negative value for a normalized PDR measurement.

PL is measured using the same synthetic packets as are used to measure packet delay, transmitted to the same MPs. The number of packets transmitted by the Controller MP, the number of packets received at the Responder MP, the number of packets transmitted by the Responder MP, and the number of packets received by the Controller MP are collected. Calculations of One-way and Two-Way PLR are performed using these values. [R89] provides the formula used to calculate PLR based on the PL measurements (for more details see Appendix C).

Synthetic packets are inserted at a rate that provides statistically valid measurements. The synthetic packets have to be treated the same by the network as the Subscriber packets to obtain accurate results. In addition, the synthetic packets that are used for monitoring need to reflect the packet length of the CoS Name that is being monitored. As an example, a CoS Name that is intended for voice packets would use small packets while a CoS Name intended for file transfer might use longer packets.

[R77] An IP SOAM PM implementation **MUST** support TWAMP Light as a PM Tool.

[D32] An IP SOAM PM implementation **SHOULD** support STAMP as a PM Tool.

[O3] An IP SOAM PM implementation **MAY** support TWAMP as a PM Tool.

[R78] An implementation of a Controller MP in TWAMP Light mode **MUST** comply with all aspects of RFC 5357 [10], to the extent specified in Appendix I, that apply to the Session Sender.

[CR1]<[D32] An implementation of a Controller MP **MUST** comply with all aspects of IETF RFC 8762 [18] that apply to the Session Sender when STAMP is used.

[CR2]<[O3] An implementation of a Controller MP **MUST** comply with all aspects of RFC 5357 [10] that apply to the Control Client and Session Sender, when TWAMP is used.

[R79] An implementation of a Responder MP in TWAMP Light mode **MUST** comply with all aspects of RFC 5357 [10], to the extent specified in Appendix I, that apply to the Session Reflector.

[CR3]<[D32] An implementation of a Responder MP **MUST** comply with all aspects of IETF RFC 8762 [18] for a Session Reflector when STAMP is used.

[CR4]< [O3] An implementation of a Responder MP **MUST** comply with all aspects of RFC 5357 [10] for a Server and Session Reflector when TWAMP is used.

[R80] An IP SOAM PM Implementation **MUST** support a configurable transmission interval for measurement packets.

[R81] An implementation of a Controller MP **MUST** be able to transmit measurement packets at the following intervals: 100ms, 1second, 10seconds when TWAMP Light, STAMP, or TWAMP are being used.

[R82] An IP SOAM Implementation **MUST** support a mechanism to limit the number of IP SOAM PM packets processed per second.

[D33] An implementation of a Controller MP **SHOULD** be able to transmit measurement packets at the following interval: 10ms when TWAMP Light, STAMP, or TWAMP are being used.

[R83] An IP SOAM PM Implementation **MUST** support a configurable unicast destination IP address for measurement packets.

[R84] An IP SOAM PM Implementation **MUST** support the ability to set the value of the Differentiated Services field in the IP header for measurement packets.

[R85] An IP SOAM PM Implementation **MUST** support configurable IP packet length that includes the measurement PDU, further referred to as measurement packet lengths.

[R86] An IP SOAM PM Implementation **MUST** support measurement packet lengths in the range of 64-1500 Bytes.

[D34] An IP SOAM PM Implementation **SHOULD** support measurement packet lengths in the range of 1501-10000 Bytes.

[R87] When transmitting IPv4 measurement packets, the Do Not Fragment flag **MUST** be set to 1.

Avoiding fragmentation can be accomplished by ensuring that any generated packets are less than or equal to the MTU for the service.

[D35] An IP SOAM PM Implementation **SHOULD** support the configurable selection of pairs of measurement packets for IPDV measurement purposes.

[D36] The default selection offset for IPDV **SHOULD** be 1.

[R88] An IP SOAM PM Implementation **MUST** support, for PDR measurement purposes, normalizing delays by subtracting the estimated minimum delay of the interval.

[D37] An IP SOAM PM Implementation **SHOULD** use the observed minimum delay of the previous Measurement Interval as the estimated minimum delay to normalize PDR measurements at the beginning of a Measurement Interval.

[D38] During the Measurement Interval an IP SOAM PM Implementation **SHOULD** set the estimated minimum to the lower of the previous estimate or the minimum measured delay for the current Measurement Interval.

A shift of the minimum delay might be significant, or it might be minor. The NE relies on the SOF/ICM to determine whether the change in the minimum is such that the PDR measurements for the Measurement Interval should be invalidated. In the case where the minimum has increased, the PDR measurements for the previous Measurement Interval may also need to be invalidated (see Appendix D for the detailed discussion).

TWAMP Light, STAMP, or TWAMP are used to perform PL measurements. The PLR is the ratio of the number of packets lost to the number of packets transmitted by the Session-Sender.

[R89] The PLR **MUST** be determined using the following formula:

$$PLR = \frac{TX\ Packets - RX\ Packets}{TX\ Packets}$$

TWAMP Light, STAMP and TWAMP all support Stateful and Stateless responders although the terms are only used in the RFC 8762 STAMP [18]. The Stateful mode of a Session-Reflector is one in which it counts packets received in a test session. The Stateless mode of a Session-Reflector is one in which it does not count the number of packets received in a test session.

The definition of TWAMP Light as Stateful or Stateless is somewhat vague in RFC 5357 [10]. The TWAMP Light definition references section 4.2 of RFC 5357 [10] which defines the Session-Reflector as Stateful (e.g. adding timestamps and the sequence number to the response packet). For this reason, this document specifies that TWAMP light is required to support Stateful Packet Loss measurement.

[R90] An IP SOAM PM Implementation using TWAMP Light **MUST** use Stateful Packet Loss measurement as specified in section 4.2 of RFC 5357 [10].

[R91] An IP SOAM PM Implementation of STAMP **MUST** use Stateful Packet Loss measurements.

Stateful Packet Loss measurements require that the Session-Reflector (Responder MP) maintains test state for determining forward loss, by identifying gaps in the received sequence number. This implies that the Session-Reflector keeps a state for each PM session, uniquely identifying which SOAM PM Packets belong to one such PM session instance and enabling adding a sequence number in the test reply that is individually incremented on a per-session basis. The method used by the Session-Reflector to keep a state for each PM Session is beyond the scope of this document.

Stateless Packet Loss measurements do not require the Session-Reflector (Responder MP) to maintain test state and Session-Reflector will reflect back the received sequence number without modification.

Stateful Packet Loss measurement allows One-way Packet Loss (Forward and Backward) to be measured. Stateless Packet Loss measurement allows only Two-way Packet Loss to be measured.

A TWAMP implementation can only be Stateful, and STAMP and TWAMP-Light implementations are required by this document to use the Stateful mode.

[R92] The Session-Controller (Controller MP) **MUST** identify the SOAM PM Packets belonging to each PM Session active at the Controller MP using the 5-tuple of (Source IP Address, Destination IP Address, Protocol, Source Port, Destination Port).

[R93] The Session-Reflector (Responder MP) **MUST** identify the SOAM PM Packets belonging to each PM Session active at the Responder MP using the 5-tuple of (Source IP Address, Destination IP Address, Protocol, Source Port, Destination Port).

[R94] Two-way PLR **MUST** be calculated using the number of packets transmitted by the Session-Sender (Controller MP) and the number of packets received by the Session-Sender (Controller MP).

[R95] One-way PLR in the Forward direction **MUST** be calculated using the Sender Sequence Number of packets transmitted by the Controller MP, the Sequence Number of packets received by the Responder MP.

[R96] One-way PLR in the Backward direction **MUST** be calculated using the Sequence Number of the packets transmitted by the Responder MP and the total packets received at the Session-Sender (Controller MP).

The following requirements specify the ***output data set*** that is recorded by the Controller MP per Measurement Interval.

[R97] An IP SOAM PM implementation **MUST** provide the ability of the implementation to deliver PM reports to specified applications or user or the application or user to retrieve PM reports for each PM Session at the end of each PM Measurement Interval.

[R98] A PM report **MUST** contain the following in addition to the data shown in Table 8 and Table 9:

- Controller IP Address
- Responder IP Address

The Controller and Responder IP Addresses might be changed to other identifiers within the LSO architecture.

[R99] The ability to retrieve all PM reports for a given PM Session **MUST** be provided.

[R100] A PM report **MUST** be available to be retrieved or delivered within two minutes of completion of the Measurement Interval x.

There may be packets in-flight between the Controller and Responder when the MI completes. This two-minute period allows those packets to reach their destination and allows for processing of the PM data into the report format within the IP PM Implementation.

[R101] The ability to retrieve the current Measurement Interval **MUST** be provided. This displays the same information as the PM report up to the time of the query.

[R102] An IP SOAM PM Implementation **MUST** support the following data at the Controller MP per Measurement Interval per PM Session:

Data	Description
Start Time-of-day timestamp	A timestamp of the time-of-day in UTC at the scheduled start time of the Measurement Interval.
End Time-of-day timestamp	A timestamp of the time-of-day in UTC at the scheduled end time of the Measurement Interval.
Measurement Interval elapsed time	A counter of the number of seconds of the Measurement Interval as calculated by the NE. Note: this may differ from the difference between the start and end times if measurements started or stopped part way through the Measurement Interval, or if there was a shift in the time-of-day clock. Some of these conditions will result in the Suspect Flag being set.
Two-way PD counter per configured PD Measurement Bin	A counter per Measurement Bin that counts the number of PD measurements that fall within the configured range.
Mean Two-way PD	An integer reflecting the average (arithmetic mean) Two-way PD measurement.
Minimum Two-way PD	An integer reflecting the minimum Two-way PD measurement.
Maximum Two-way PD	An integer reflecting the maximum Two-way PD measurement.
One-way IPDV counter in the Forward direction per configured IPDV Measurement Bin	A counter per Measurement Bin that counts the number of IPDV measurements (i.e., each instance of $\|D_i - D_j\|$ in the Forward direction) that fall within a configured bin.
Mean One-way IPDV in the Forward direction	An integer reflecting the average (arithmetic mean) One-way IPDV measurement in the Forward direction.
Maximum One-way IPDV in the Forward direction	A 32-bit integer reflecting the maximum One-way IPDV measurement in the Forward direction in microseconds.
One-way IPDV counter in the Backward direction per configured IPDV Measurement Bin	A counter per Measurement Bin that counts the number of IPDV measurements in the Backward direction that fall within a configured bin.
Mean One-way IPDV in the Backward direction	An integer reflecting the average (arithmetic mean) One-way IPDV measurement in the Backward direction.
Maximum One-way IPDV in the Backward direction	An integer reflecting the maximum One-way IPDV measurement in the Backward direction.
One-way PDR counter in the Forward direction per configured PDR Measurement Bin	A counter per Measurement Bin that counts the number of PDR measurements in the Forward direction that fall within a configured bin.
Mean One-way PDR in the Forward direction	An integer reflecting the average (arithmetic mean) One-way PDR measurement in the Forward direction.
Maximum One-way PDR in the Forward direction	An integer reflecting the maximum One-way PDR measurement in the Forward direction.

Data	Description
One-way PDR counter in the Backward direction per configured PDR Measurement Bin	A counter per Measurement Bin that counts the number of PDR measurements in the Backward direction that fall within a configured bin.
Mean One-way PDR in the Backward direction	An integer reflecting the average (arithmetic mean) One-way PDR measurement in the Backward direction.
Maximum One-way PDR in the Backward direction	An integer reflecting the maximum One-way PDR measurement in the Backward direction.
Minimum One-way PD in the Forward direction	An integer reflecting the minimum One-way PD measurement in the Forward direction.
Minimum One-way PD in the Backward direction	A 32-bit integer reflecting the minimum One-way PD measurement in the Backward direction in microseconds.
Tx Packet count in the Forward direction	A counter reflecting the number of SOAM PM Packets transmitted in the Forward direction.
Rx Packet count in the Forward direction	A counter reflecting the number of SOAM PM Packets received in the Forward direction.
Tx Packet count in the Backward direction	A 32-bit counter reflecting the number of SOAM PM Packets transmitted in the Backward direction.
Rx Packet count in the Backward direction	A counter reflecting the number of SOAM PM Packets received in the Backward direction.
Suspect Flag	A bit that indicates that the Suspect Flag has been set as specified in section 8.2.2.4.

Table 8 – Mandatory Stateful Single-Ended Data Set

[R103] Measured and calculated Delay attributes **MUST** provide at least microsecond granularity.

There are several issues that can impact the granularity of PD measurements. These include if time stamps are added via hardware or software and the precision of the clock within the device or application adding time stamps. In many cases adding time stamps via a software implementation does not allow sub-microsecond accuracy where timestamps added via hardware clocking does. A “white box” server may not have sufficient precision within the clock that it uses to provide sub-microsecond accuracy. This is because the clocking within the device that an application is running on is not thought to require an extremely precise clock. These are implementation issues and are beyond the scope of this document.

The minimum One-way PD measurements do not provide intrinsic information about the Packet Delay when time-of-day clock synchronization is not in effect but are needed to detect changes in the minimum that may invalidate PDR measurements.

Note that when time-of-day clock synchronization is not in effect, measurements of One-way PD may result in a negative value for the minimum. This does not impact the ability to monitor changes in the minimum for the purpose of invalidating PDR measurements.

[R104] If time-of-day clock synchronization is in effect for both MPs in the MP Pair, an IP SOAM PM Implementation **MUST** support the following additional data at the Controller MP per Measurement Interval per PM Session:

Data	Description
One-way PD counter in the Forward direction per configured PD Measurement Bin	A counter per Measurement Bin that counts the number of One-way PD measurements in the Forward direction that fall within the configured bin.
Mean One-way PD in the Forward direction	An integer reflecting the average (arithmetic mean) One-way PD measurement in the Forward direction.
Maximum One-way PD in the Forward direction	An integer reflecting the maximum One-way PD measurement in the Forward direction.
One-way PD counter in the Backward direction per configured PD Measurement Bin	A counter per Measurement Bin that counts the number of One-way PD measurements in the Backward direction that fall within the configured bin.
Mean One-way PD in the Backward direction	An integer reflecting the average (arithmetic mean) One-way PD measurement in the Backward direction.
Maximum One-way PD in the Backward direction	An integer reflecting the maximum One-way PD measurement in the Backward direction.

Table 9 – Mandatory Single-Ended Data Set with Clock Synchronization

8.4 PM Tool Requirements

The requirements for PM tools are detailed in this section. These requirements are currently limited to Active Measurement.

8.4.1 Active Measurement

The requirements for Active Measurement tools are defined in the following sections.

8.4.1.1 TWAMP Light

TWAMP Light is described in RFC 5357 [10] Appendix I. This is informative text in the RFC. Within the scope of this document, the support of TWAMP Light is required and therefore the text in the RFC is treated as if it was normative text. The method used as the Control-Client responder protocol is beyond the scope of this document.

TWAMP Light supports the same measurements as TWAMP but does not include the TWAMP-Control that TWAMP requires. This makes TWAMP Light easier to implement and to deploy in a network. It does require that the two MPs in the MP Pair be configured so that the appropriate measurement packets are generated and collected. TWAMP Light test session may be performed in Unauthenticated, Authenticated or Encrypted mode. In Unauthenticated mode, no additional configuration is required. In Authenticated or Encrypted mode, additional configuration of the

Controller and Responder MPs is required to ensure that keys are correctly configured at both MPs. The method used for this configuration is beyond the scope of this document.

The TWAMP Light session is a Stateful session.

[R105] A TWAMP Light implementation of a Controller MP **MUST** support a configurable UDP Destination port number.

[R106] A TWAMP Light implementation of a Responder MP **MUST** support a configurable UDP port that the Responder MP listens on.

[D39] A TWAMP Light implementation of a Controller MP **SHOULD** support a default UDP Destination port number of 862.

[D40] A TWAMP Light implementation of a Responder MP **SHOULD** support a default UDP port that the Responder MP listens on of 862.

[D41] A TWAMP Light implementation of a Controller MP **SHOULD** support a configurable UDP Source port.

[D42] A TWAMP implementation of a Responder MP **SHOULD** support a configurable UDP Source port.

[CR5]<[D41] The configurable UDP Source port of a Controller MP **MUST** come from the dynamic range of IANA's Service Name and Transport Protocol Port Number registry, as documented in RFC 6335 [27].

[CR6]<[D42] The configurable UDP Source port of a Responder MP **MUST** come from the dynamic range of IANA's Service Name and Transport Protocol Port Number registry, as documented in RFC 6335 [27].

8.4.1.2 STAMP

STAMP is an Active Measurement protocol for IP networks defined in RFC 8762 [18]. It uses UDP encapsulation. Configuration and management of the STAMP Session-Sender, Session-Reflector, and the test session between the two is outside the scope of this document.

STAMP test session may be performed in Unauthenticated or Authenticated mode. In the Unauthenticated mode STAMP is backward compatible with existing implementations of TWAMP Light (see more discussion on TWAMP Light in section 8.4.1.1).

8.4.1.2.1 Session-Sender Behavior

There are three modes of operation, Unauthenticated, Authenticated, and Encrypted, described for Session-Sender in RFC 8762 [18].

[CR7]<[D32] A STAMP implementation **MUST** support the Session-Sender Unauthenticated Mode as specified in section 4.1.1 of RFC 8762 [18].

[CD1]<[D32] A STAMP implementation **SHOULD** support the Session-Sender Authenticated Mode as specified in section 4.1.2 of RFC 8762 [18].

[CR8]<[D32] A STAMP implementation **MUST** support a configurable UDP Destination port that the Controller MP transmits on.

[CR9]<[D32] A STAMP implementation **MUST** support a configurable UDP port that the Responder MP listens on.

[CR10]<[D32] A STAMP implementation **MUST** support a default UDP Destination port that the Controller MP transmits on of 862.

[CR11]<[D32] A STAMP implementation **MUST** support a default UDP port that the Responder MP listens on of 862.

[CD2]<[D32] A STAMP implementation of a Controller MP **SHOULD** support a configurable UDP Source port.

[CD3]<[D32] A STAMP implementation of a Responder MP **SHOULD** support a configurable UDP Source port.

[CR12]<[CD2],[D32] The configurable UDP Source port of a Controller MP **MUST** come from the dynamic range of IANA's Service Name and Transport Protocol Port Number registry, as documented in RFC 6335 [27].

[CR13]<[CD3],[D32] The configurable UDP Source port of a Responder MP **MUST** come from the dynamic range of IANA's Service Name and Transport Protocol Port Number registry, as documented in RFC 6335 [27].

8.4.1.2.2 Session-Reflector Behavior

There are three modes of operation, Unauthenticated, Authenticated, and Encrypted, described for Session-Reflector in RFC 8762 [18]. In addition, the Session-Reflector can be either Stateless (does not maintain test state) or Stateful (maintains test state), which the mandatory mode based on [R91]. A Stateful Session-Reflector can be used to measure One-way packet loss. A Stateless Session-Reflector can be used to measure Two-way packet loss only.

[CR14]<[D32] A STAMP implementation **MUST** support the Session-Reflector Unauthenticated Mode as specified in section 4.2.1 of RFC 8762 [18].

[CD4]<[D32] A STAMP implementation **SHOULD** support the Session-Reflector Authenticated Mode as specified in section 4.2.2 of RFC 8762 [18].

8.4.1.2.3 Interoperability with TWAMP Light

In Unauthenticated mode, a STAMP implementation can be interoperable with a TWAMP Light implementation. The Session-Reflector can support either TWAMP Light or STAMP and

process packets correctly. The use of NTP timestamps by STAMP implementations make them interoperable with TWAMP Light implementations.

[CR15]<[D32] A STAMP implementation interoperating with TWAMP Light **MUST** use NTP timestamps.

8.4.1.3 TWAMP

TWAMP is defined in RFC 5357 [10]. TWAMP includes a control protocol and a test packet definition. The TCP control protocol allows for the configuration of a test between a Session-Sender and a Session-Reflector. It defines a Control Server and a Control Client. The test packet defines the packets exchanged between the Session-Sender and the Session-Reflector.

The security requirements listed are Desirable in Section 6 of RFC 5357 [10] and are Mandatory in this document.

[CR16]<[O3] If a TWAMP implementation supports Authenticated mode or Encrypted mode, then it **MUST** comply with security recommendations in Section 6 of RFC 5357 [10].

8.4.1.3.1 Session-Sender Behavior

There are three modes of operation, Unauthenticated, Authenticated, and Encrypted, described for Session-Sender in RFC 5357 [10].

[CR17]<[O3] A TWAMP implementation **MUST** support the Session-Sender Unauthenticated Mode as specified in section 4 of RFC 5357 [10].

[CD5]<[O3] A TWAMP implementation **SHOULD** support the Session-Sender Authenticated Mode as specified in section 4 of RFC 5357 [10].

[CD6]<[O3] A TWAMP implementation **SHOULD** support the Session-Sender Encrypted Mode as specified in section 4 of RFC 5357 [10].

[CR18]<[O3] A TWAMP implementation **MUST** support a configurable UDP Destination port that the Controller MP transmits on.

[CR19]<[O3] A TWAMP implementation **MUST** support a default UDP Destination port that the Controller MP transmits on of 862.

8.4.1.3.2 Session-Reflector Behavior

There are three modes of operation, Unauthenticated, Authenticated, and Encrypted, described for Session-Reflector in RFC 5357 [10].

[CR20]<[O3] A TWAMP implementation **MUST** support the Session-Reflector Unauthenticated Mode as specified in section 4 of RFC 5357 [10].

[CD7]<[O3] A TWAMP implementation **SHOULD** support the Session-Reflector Authenticated Mode as specified in section 4 of RFC 5357 [10] .

[CD8]<[O3] A TWAMP implementation **SHOULD** support the Session-Reflector Encrypted Mode as specified in section 4 of RFC 5357 [10].

[CR21]<[O3] A TWAMP implementation **MUST** support a configurable UDP port that the Responder MP listens on.

[CR22]<[O3] A STAMP implementation **MUST** support a default UDP port that the Responder MP listens on of 862.

8.5 Threshold Crossing Alerts (TCAs)

Performance thresholds, and corresponding Threshold Crossing Alerts (TCAs), can be configured for certain performance metrics, and used to detect when service performance is degraded beyond a given pre-configured level. Thresholds are always specific to a particular performance metric and a particular PM Session. When the measured performance in a Measurement Interval for that session reaches or exceeds the configured threshold level, a TCA can be generated and sent to an ICM or SOF.

In normal operation, performance data is collected from a device or network function by the ICM/SOF either periodically (e.g. once an hour) or On-demand. TCAs can be used as warning notifications to the ICM/SOF of possible service degradation, thus allowing more timely action to further investigate or address the problem. For example, if the maximum One-way PD threshold was set to 10ms, and a One-way PD value was measured at more than 10ms, a TCA would be generated.

[O4] An IP SOAM PM Implementation **MAY** support Threshold Crossing Alert functionality as described in sections 8.5.1, 8.5.2, and 8.5.3.

The requirements in the following subsections only apply if TCA functionality is supported.

8.5.1 TCA Reporting

Thresholds and associated TCAs are specific to a particular performance metric in a given PM Session. There are two types of TCA reporting: stateless and stateful. With stateless reporting, a TCA is generated in each Measurement Interval in which the threshold is crossed. With stateful reporting, a SET TCA is generated in the first Measurement Interval in which the threshold is crossed, and a CLEAR TCA is subsequently generated at the end of the first Measurement Interval in which the threshold is not crossed. Note that the use of 'stateful' and 'stateless' to describe TCA reporting is unrelated to the use of 'stateful' and 'stateless' to describe the behavior of a Responder MP with respect to loss measurement, as described in section 8.3.1.

Note: In ITU-T G.7710 [20] terminology, stateless TCA reporting corresponds to a transient condition, and stateful TCA reporting corresponds to a standing condition.

Regardless of the type of TCA reporting (stateless or stateful), it is not desirable to generate more than one TCA for a given threshold during each Measurement Interval, as to do otherwise could cause unnecessary load both on the NE and on the ICM/SOF receiving the TCAs.

Thresholds and TCAs are only defined for certain performance metrics, as described in section 8.5.2. Note that all of these performance metrics have the property that the value cannot decrease during a given Measurement Interval.

The process that takes a given threshold configuration for a given performance metric in a given PM Session and generates corresponding TCAs is termed a TCA Function. Multiple TCA Functions with different threshold values can be configured for the same PM Session and performance metric, so that TCAs can be generated for different degrees of service degradation. Where multiple TCA Functions are configured, corresponding TCAs are generated independently for each TCA Function.

8.5.1.1 Stateless TCA Reporting

The stateless TCA reporting treats each Measurement Interval separately. When using stateless TCA reporting, each TCA Function has a single configured threshold. As soon as the threshold is reached or crossed in a Measurement Interval for a given performance metric, a TCA is generated.

The following figure illustrates the behavior of stateless TCA reporting.

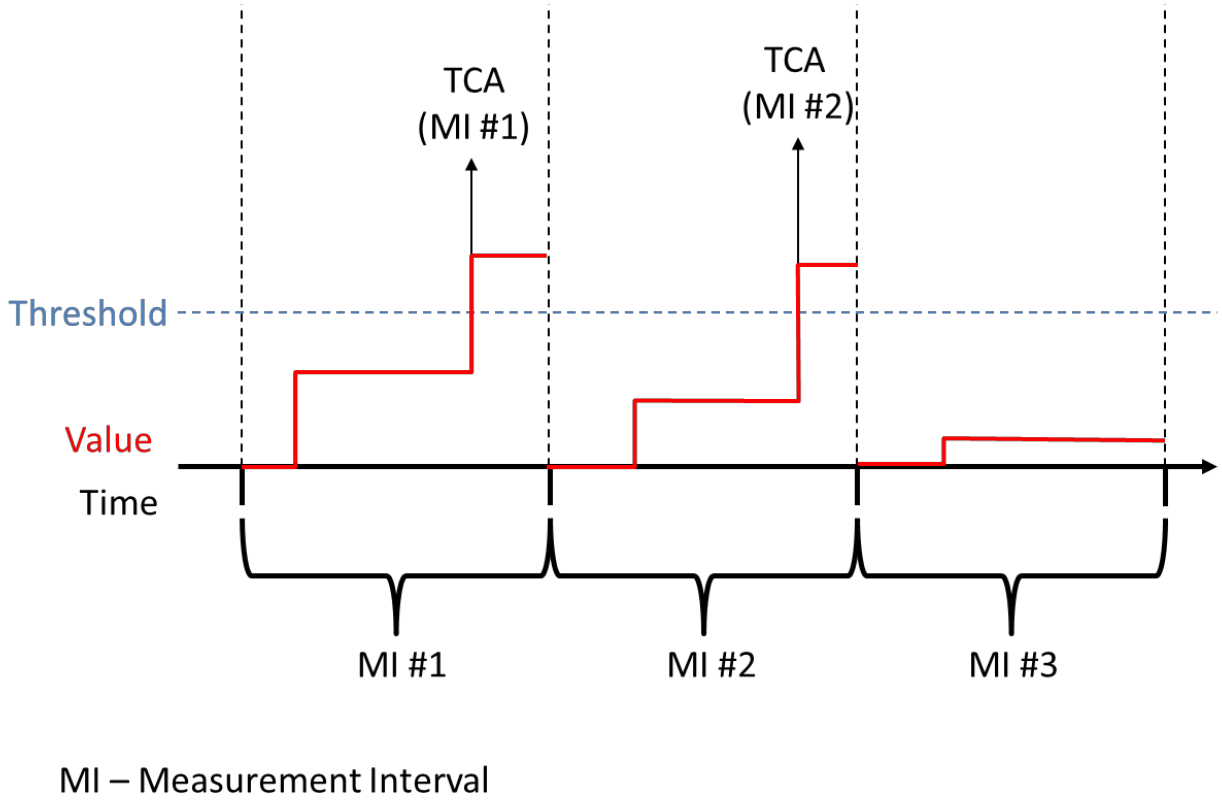

Figure 18 – Stateless TCA Reporting Example

As shown in the example in Figure 18, in MI #1, the measured performance value (e.g., Maximum Packet Delay) crosses the corresponding threshold. Therefore, a TCA is generated for MI #1. In MI #2, this threshold is crossed again. Another TCA is generated for MI #2. In MI #3, the measured performance value doesn't reach the threshold. There is no TCA for that performance metric for MI #3.

8.5.1.2 Stateful TCA Reporting

Stateful TCA reporting is another option for how TCAs are generated, that can reduce the total number of TCAs. The intent is to provide a notification when a degradation is first encountered, followed by another when the problem is resolved. This contrasts with stateless TCA reporting, in which TCAs are generated continuously for as long as the degradation lasts.

When using stateful TCA reporting, each TCA Function has two configured thresholds: a SET threshold and a CLEAR threshold. These may be the same, or the CLEAR threshold may be lower than the SET threshold. The TCA Function also has an internal state, which may be 'set' or 'clear'.

The TCA Function begins in the 'clear' state. A SET TCA is generated in the first Measurement Interval as soon as the SET threshold is reached or exceeded. The TCA Function is then considered to be in a 'set' state, and no further SET TCAs are generated in this state. In each subsequent Measurement Interval in which the CLEAR threshold is reached or exceeded, no TCA is generated.

At the end of the first Measurement Interval in which the CLEAR threshold is not reached or exceeded, a CLEAR TCA is generated, and the TCA Function returns to the 'clear' state. Thus, each SET TCA is followed by a single CLEAR TCA.

The following figure shows an example of stateful TCA reporting. In this example, the CLEAR threshold is equal to the SET threshold.

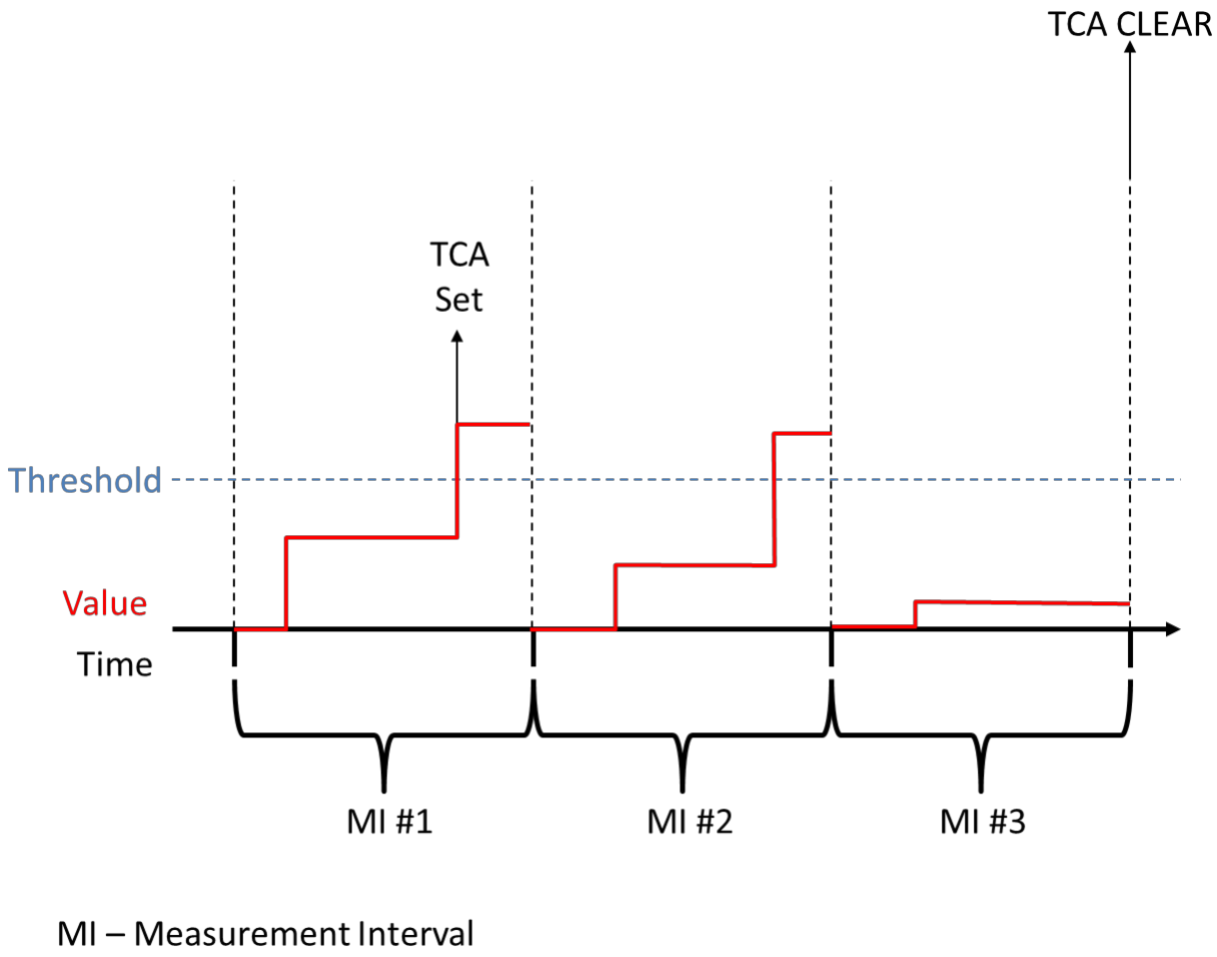

Figure 19 – Stateful TCA Reporting Example

In the example in Figure 19, a SET TCA is generated in MI #1. In MI #2, the threshold is crossed again but no SET TCA is generated because a SET TCA had been generated in MI #1. MI #3 is the first subsequent Measurement Interval that the measured performance value is below the CLEAR threshold. A CLEAR TCA is generated at the end of MI #3.

8.5.2 SOAM PM Thresholds for TCAs

TCAs are useful for some performance metrics but may not be meaningful for others. This section describes which performance metrics are required and how to support TCAs.

For performance metrics that use Measurement Bins, thresholds are defined in terms of an Upper Bin Count (UBC). The Upper Bin Count of bin k is the total of the counts for bins k and above, i.e. UBC(k) = count of bin (k) + count of bin (k+1) + ... + count of bin (n), where n is the last bin.

To configure a threshold, both the bin number, k, and the total count, N, need to be specified – this is represented as (N, k). A threshold (N, k) is considered to have been crossed when UBC(k) >= N. Figure 20 illustrates how a threshold is configured using bins.

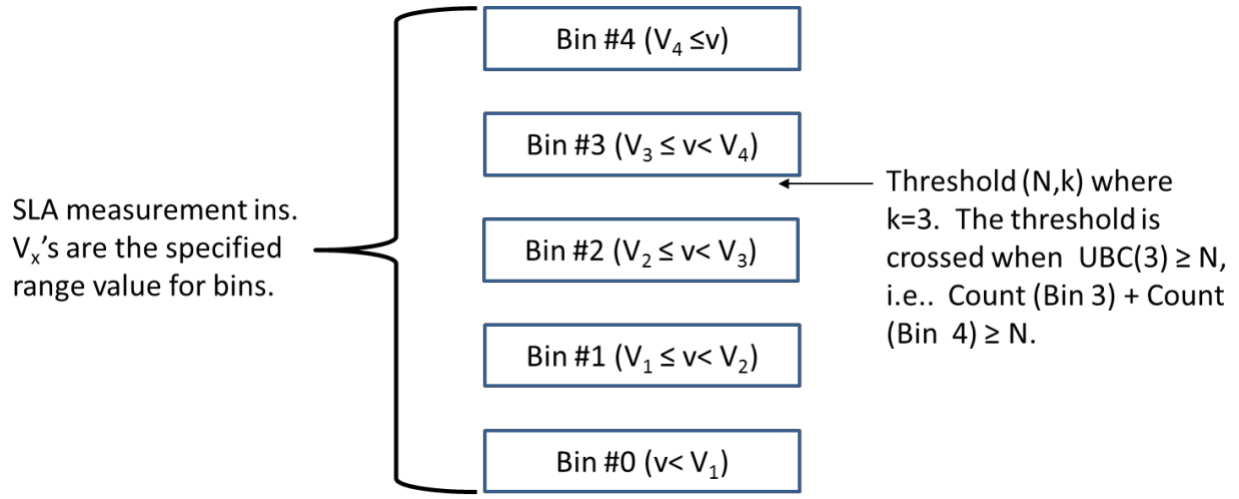

Figure 20 – Upper Bin Count for Threshold Crossing

The following table lists the applicable performance metrics that support TCAs. In each case, both One-way, and where applicable, Two-way performance metrics can be used. The table describes in each case the parameters that must be configured for the threshold, and the definition of when the threshold is crossed. For stateful TCA reporting, the "SET" thresholds and "CLEAR" thresholds are defined in the same way (although the configured values may be different).

Performance Metric	Configured Threshold	Threshold Crossing Detection	Notes
One-way IPDV in the Forward direction	Forward One-way (N_{IPDV}, k)	UBC(k) ≥ Forward One-way N_{IPDV}	Using Measurement Bins
One-way Maximum IPDV in the Forward direction	Forward One-way ($V_{maxIPDV}$)	Max IPDV ≥ Forward One-way $V_{maxIPDV}$	
One-way IPDV in the Backward direction	Backward One-way (N_{IPDV}, k)	UBC(k) ≥ Backward One-way N_{IPDV}	Using Measurement Bins
One-way Maximum IPDV in the Backward direction	Backward One-way ($V_{maxIPDV}$)	Max IPDV ≥ Backward One-way $V_{maxIPDV}$	

Performance Metric	Configured Threshold	Threshold Crossing Detection	Notes
One-way PD in the Forward direction	Forward One-way (N_{PD}, k)	UBC(k) ≥ Forward One-way N_{PD}	Using Measurement Bins. Requires ToD Synchronization
One-way Maximum PD in the Forward direction	Forward One-way (V_{maxPD})	Max PD ≥ Forward One-way V_{maxPD}	Requires ToD Synchronization
One-way PD in the Backward direction	Backward One-way (N_{PD}, k)	UBC(k) ≥ Backward One-way N_{PD}	Using Measurement Bins. Requires ToD Synchronization
One-way Maximum PD in the Backward direction	Backward One-way (V_{maxPD})	Max PD ≥ Backward One-way V_{maxPD}	Requires ToD Synchronization
Two-way PD	Two-way (N_{PD}, k)	UBC(k) ≥ Two-way N_{PD}	Using Measurement Bins
Two-way Maximum PD	Two-way V_{maxPD}	Max PD ≥ Two-way V_{maxPD}	
One-way PDR in the Forward direction	Forward One-way (N_{PDR}, k)	UBC(k) ≥ Forward One-way N_{PDR}	Using Measurement Bins
One-way Maximum PDR in the Forward direction	Forward One-way (V_{maxPDR})	Max PDR ≥ Forward One-way V_{maxPDR}	
One-way PDR in the Backward direction	Backward One-way (N_{PDR}, k)	UBC(k) ≥ Backward One-way N_{PDR}	Using Measurement Bins
One-way Maximum PDR in the Backward direction	Backward One-way (V_{maxPDR})	Max PDR ≥ Backward One-way V_{maxPDR}	
One-way Lost Packets (LP) in the Forward direction	Forward One-way (N_{LP})	LP ≥ Forward One-way N_{LP}	The count of Lost Packets is determined the following formula: TX packet count Forward direction – RX packet count Forward direction = Lost Packet count Forward direction
One-way Lost Packets (LP) in the Backward direction	Backward One-way (N_{LP})	LP ≥ Backward One-way N_{LP}	The count of Lost Packets is determined the following formula: TX packet count Backward direction – RX packet count Backward direction = Lost Packet count Backward direction

Performance Metric	Configured Threshold	Threshold Crossing Detection	Notes
Two-way Lost Packets (LP)	Two-way (N_{LP})	LP ≥ Two-way N_{LP}	The count of Lost Packets is determined the following formula: TX packet count Forward direction – RX packet count Backward direction = Lost Packet count Two-way

Table 10 – SOAM Performance Metrics TCA

Note that not all performance metrics are listed in Table 10. They are either not suitable or not necessary. For example, MPD is a performance metric measuring an average and thus a poor metric for immediate attention, compared to PD, PDR and IPDV.

If TCA functionality is supported, the following requirements are applicable for an IP SOAM PM Implementation:

[CR23]<[O4] An IP SOAM PM Implementation **MUST** support per performance metric, per PM Session configuration of TCA Functions and associated thresholds, using the parameters described in Table 10, for the following performance metrics:

- One-way IPDV in the Forward Direction
- One-way Maximum IPDV in the Forward Direction
- One-way IPDV in the Backward Direction
- One-way Maximum IPDV in the Backward Direction
- Two-way PD
- Two-way Maximum PD
- One-way PDR in the Forward Direction
- One-way Maximum PDR in the Forward Direction
- One-way PDR in the Backward Direction
- One-way Maximum PDR in the Backward Direction
- One-way PL in the Forward Direction
- One-way PL in the Backward Direction
- Two-way PL

[CR24]<[O4] If time-of-day synchronization is supported, an IP SOAM PM Implementation **MUST** support per performance metric, per PM Session configuration of TCA Functions and associated thresholds, using the parameters described in Table 10, for the following performance metrics:

- One-way PD in the Forward Direction
- One-way Maximum PD in the Forward Direction
- One-way PD in the Backward Direction

- One-way Maximum PD in the Backward direction

[CR25]<[O4] An IP SOAM PM Implementation **MUST** support stateless TCA reporting.

[CD9]<[O4] An IP SOAM PM Implementation **SHOULD** support stateful TCA reporting.

[CR26]<[CD9],[O4] If an IP SOAM PM Implementation supports stateful TCA reporting, it **MUST** support a configurable parameter per TCA Function to indicate whether the TCA Function uses stateful or stateless TCA reporting.

[CR27]<[O4] An IP SOAM PM implementation **MUST** support a single configurable parameter for the threshold value for each TCA Function that uses stateless TCA reporting.

[CR28]<[CD9],[O4] If an IP SOAM PM Implementation supports stateful TCA reporting, it **MUST** support the CLEAR threshold being equal to the SET threshold.

[CD10]<[CD9],[O4] If an IP SOAM PM Implementation supports stateful TCA reporting, it **SHOULD** support the CLEAR threshold being different to the SET threshold.

For thresholds defined using bins, a CLEAR threshold (N_C, k_C) is defined to be less than or equal to a SET threshold (N_S, k_S) if $k_C = k_S$ and $N_C <= N_S$.

[CR29]<[CD10],[CD9],[O4] If an IP SOAM PM Implementation supports stateful TCA reporting with different SET and CLEAR thresholds, the CLEAR threshold **MUST** be less than or equal to the SET threshold.

[CR30]<[CD9],[O4] If an IP SOAM PM Implementation supports stateful TCA reporting, it **MUST** support a configurable parameter for the SET threshold for each TCA Function that uses stateful TCA reporting.

[CR31]<[CD10],[CD9],[O4] If an IP SOAM PM Implementation supports stateful TCA reporting with different SET and CLEAR thresholds, it **MUST** support a configurable parameter for the CLEAR threshold for each TCA Function that uses stateful TCA reporting.

If different SET and CLEAR thresholds are not used, the value configured for the SET threshold is also used for the CLEAR threshold.

[CR32]< [O4] If a TCA Function is configured to use stateless TCA reporting, a TCA **MUST** be generated for each Measurement Interval in which the threshold is crossed as defined in Table 10.

[CD11]<[O4] If a TCA Function is configured to use stateless TCA reporting, the TCA for a given Measurement Interval **SHOULD** be generated as soon as the threshold is crossed.

[CR33]<[O4] If a TCA Function is configured to use stateless TCA reporting, the TCA for a given Measurement Interval **MUST** be generated within 1 minute of the end of the Measurement Interval.

[CR34]<[CD9],[O4] If a TCA Function is configured to use stateful TCA reporting, in the 'clear' state a SET TCA **MUST** be generated for a given Measurement Interval if the SET threshold is crossed as defined in Table 10 during that Measurement Interval.

[CR35]<[CD9],[O4] If a TCA Function is configured to use stateful TCA reporting, in the 'clear' state, if the SET threshold is crossed during a given Measurement Interval, the state **MUST** be changed to 'set' by the end of that Measurement Interval.

[CD12]<[CD9],[O4] If a TCA Function is configured to use stateful TCA reporting, the SET TCA for a given Measurement Interval **SHOULD** be generated as soon as the SET threshold is crossed.

[CR36]<[CD9],[O4] If a TCA Function is configured to use stateful TCA reporting, the SET TCA for a given Measurement Interval **MUST** be generated within 1 minute of the end of the Measurement Interval.

[CR37]<[CD9],[O4] If a TCA Function is configured to use stateful TCA reporting, SET TCAs **MUST NOT** be generated when in the 'set' state.

[CR38]<[CD9],[O4] If a TCA Function is configured to use stateful TCA reporting, in the 'set' state a CLEAR TCA **MUST** be generated for a given Measurement Interval if the CLEAR threshold is not crossed as defined in Table 10 during that Measurement Interval.

[CR39]<[CD9],[O4] If a TCA Function is configured to use stateful TCA reporting, in the 'set' state, if the CLEAR threshold is not crossed during a given Measurement Interval, the state **MUST** be changed to 'clear' at the end of that Measurement Interval.

[CD13]<[CD9],[O4] If a TCA Function is configured to use stateful TCA reporting, the CLEAR TCA for a given Measurement Interval **SHOULD** be generated immediately at the end of the Measurement Interval.

[CR40]<[CD9],[O4] If a TCA Function is configured to use stateful TCA reporting, the CLEAR TCA for a given Measurement Interval **MUST** be generated within 1 minute of the end of the Measurement Interval.

[CR41]<[CD9],[O4] If a TCA Function is configured to use stateful TCA reporting, CLEAR TCAs **MUST NOT** be generated when in the 'clear' state.

[CR42]<[O4] For a given TCA Function applying to a given performance metric and a given PM Session, an IP SOAM PM Implementation **MUST NOT** generate more than one TCA for each Measurement Interval.

[CR43]<[O4] An IP SOAM PM Implementation **MUST** support the configuration of at least one TCA Function for each performance metric listed in Table 6, for each PM Session.

Note: this does not require that an IP SOAM PM Implementation is able to support configuration of a TCA Function for every performance metric for every PM Session simultaneously.

[CO1]<[O4] An IP SOAM PM Implementation **MAY** support the configuration of more than one TCA Function for a performance metric, for each PM Session.

8.5.3 SOAM PM TCA Notification Messages

Table 11 lists the SOAM PM TCA Notification message attributes used when sending a TCA to an ICM/SOF.

Field Name	Field Description
Date and Time	Time of the event, in UTC. For stateless TCAs, and stateful SET TCAs, this is the time the threshold was crossed; for stateful CLEAR TCAs, it is the time at the end of the Measurement Interval for which the CLEAR TCA is being generated.
PM Session	Identification of the PM Session for which the TCA Function was configured. The specific parameters needed to uniquely identify a PM Session are implementation specific.
Measurement Interval	The time, in UTC, at the start of the Measurement Interval for which the TCA was generated.
Performance Metric Name	Performance Metric for which the TCA Function was configured, i.e., one of those listed in Table 10.
Configured Threshold	The configured threshold parameters. For bin-based thresholds, this includes the bin number and the total count, i.e., (N, k).
Measured Performance Metric	Measured value that caused the TCA to be generated. For bin-based thresholds configured as (N, k), this is always equal to N for stateless TCAs and stateful SET TCAs; for stateful CLEAR TCAs, it is the value of UBC(k) at the end of the Measurement Interval. For "maximum" performance metrics, for stateless TCAs and stateful SET TCAs, this is the first value in the Measurement Interval that reaches or exceeds the configured threshold; for stateful CLEAR TCAs it is the maximum value at the end of the Measurement Interval.
Suspect Flag	Value of the Suspect Flag for the Measurement Interval for which the TCA was generated. Suspect Flag is true when there is a discontinuity in the performance measurements conducted during the Measurement Interval.
TCA Type	The type of TCA, i.e. one of STATELESS (if stateless TCA reporting was configured for the TCA Function), STATEFUL-SET (if stateful TCA reporting was configured and this is a SET TCA) or STATEFUL-CLEAR (if stateful TCA reporting was configured and this is a CLEAR TCA).
Severity	WARNING (for STATELESS or STATEFUL-SET) or INFO (for STATEFUL-CLEAR)

Table 11 – TCA Notification Message Fields

[CR44]<[O4] An IP SOAM PM Implementation **MUST** include the fields in the TCA notification messages listed in Table 11.

Table 12 shows the correlation between the general alarm and event notification parameters described in ITU-T X.733 [21] and X.734 [22], and the notification attributes considered in this document.

ITU-T X.733, X.734	IP Services SOAM
Event time	Date and time
Managed Obj Class	PM Session
Managed Obj Instance	Included in PM Session
Monitored Attribute	Performance Metric Name, Measurement Interval
Threshold Info	Configured Threshold, Measured Performance Metric
No Equivalent	Suspect Flag
Event Type (service degraded)	TCA Type
Severity	Severity
Probable Cause	Not applicable

Table 12 – Comparison of TCA Fields in X.73x and MEF 61

9 Hybrid Measurement

Hybrid measurement modifies the Subscriber packet in some way and uses the Subscriber packet to monitor the service rather than using synthetic packets. There are two expected benefits of using Hybrid measurement. The first is that there is no need for additional synthetic packets to be generated and carried across the network. This impacts the possibility of congestion occurring due to the addition of synthetic packets. The second is that measurement packets take the same path as Subscriber packets since the measurement packets are Subscriber packets. This is true but unless every Subscriber packet is modified all possible paths that the Subscriber packets traverse might not be measured. A general disadvantage of Hybrid Measurement methods is that measurements are only possible between a given ordered MP Pair when there are Subscriber packets flowing between that MP Pair, so there may be periods of time when no measurements can be made, if there is no Subscriber traffic during that time.

The type of Hybrid Measurement discussed in this document is Alternate marking (AltM).

9.1 Alternate Marking Explanation

RFC 8321 [17] describes a method to perform packet loss, delay, and jitter measurements on live traffic. This method is based on an AltM (coloring) technique. This technology can be applied in various situations, and could be considered Passive or Hybrid depending on the application.

Taking into consideration RFC 7799 [15] definitions, the AltM Method could be considered Hybrid or Passive, depending on the case. In the case where the marking method is obtained by changing existing field values of the packets (e.g., the Differentiated Services Code Point (DSCP) field), the technique is Hybrid. In the case where the marking field is dedicated, reserved, and included in the protocol specification, the AltM technique can be considered as Passive.

Note: At this time the use of AltM in an IP network has not been standardized.

The basic idea of AltM is to virtually split traffic flows into consecutive blocks: each block represents a measurable entity unambiguously recognizable by all network devices along the path. By counting the number of packets in each block and comparing the values measured by different network devices along the path, it is possible to measure packet loss occurred in any single block between any two points. The simplest way to create the blocks is to "color" the traffic e.g. setting proper values for one or two bits (two colors are sufficient), so that packets belonging to different consecutive blocks will have different colors. Whenever the color changes, the previous block terminates and the new one begins. Hence, all the packets belonging to the same block will have the same color and packets of different consecutive blocks will have different colors. Figure 21 shows a representation of the AltM methodology.

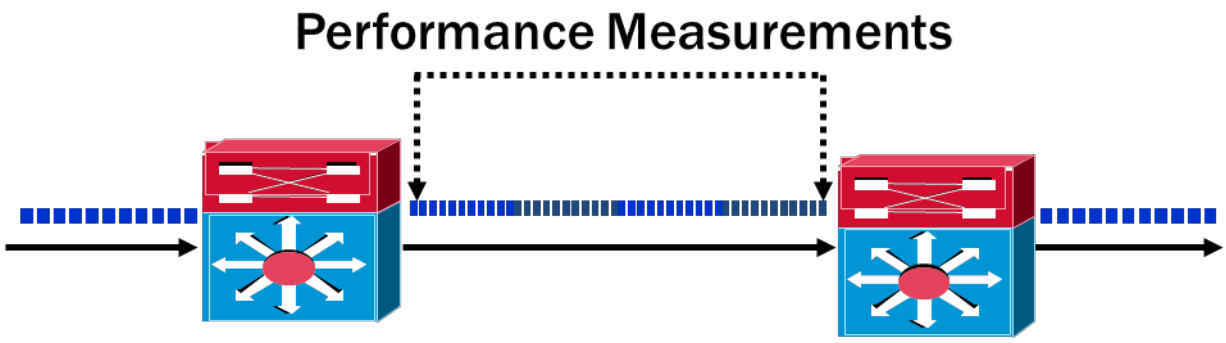

Figure 21 – AltM description

Since the traffic is colored, each block can be identified within the network.

There are two alternatives for color switching: using a fixed number of packets or a fixed timer. However, using a fixed timer for color switching offers better control over the method. The time length of the blocks can be chosen large enough to simplify the collection and the comparison of measurements taken by different network devices.

In addition, two different strategies can be used when implementing the method: link-based and flow-based. The end-to-end measurement can be split into Hop-by-Hop measurements (for each Link and/or each Router).

The flow-based strategy is used when only a part of all the traffic flows in the operational network need to be monitored. According to this strategy, only a subset of the flows is colored. Counters for packet Loss Measurements can be instantiated for each single flow, or for the set as a whole, depending on the desired granularity. Router1, Router2,… RouterN are configured to have dedicated counters for the different flows under monitoring.

The link-based measurement is performed on all the traffic on a point to point link-by-link basis. The link could be a physical link or a logical link. Counters could be instantiated for the traffic as a whole without distinction of the flow. Router1, Router2,… RouterN are not configured to filter any flow.

So, in order to perform the desired performance measurement for Subscriber's IP Service from PE to PE, the flow-based strategy can be used, and the interested flows can be selected based on Subscriber's IP addresses. Both End-to-End and Hop by Hop measurements can be applied depending on the necessity.

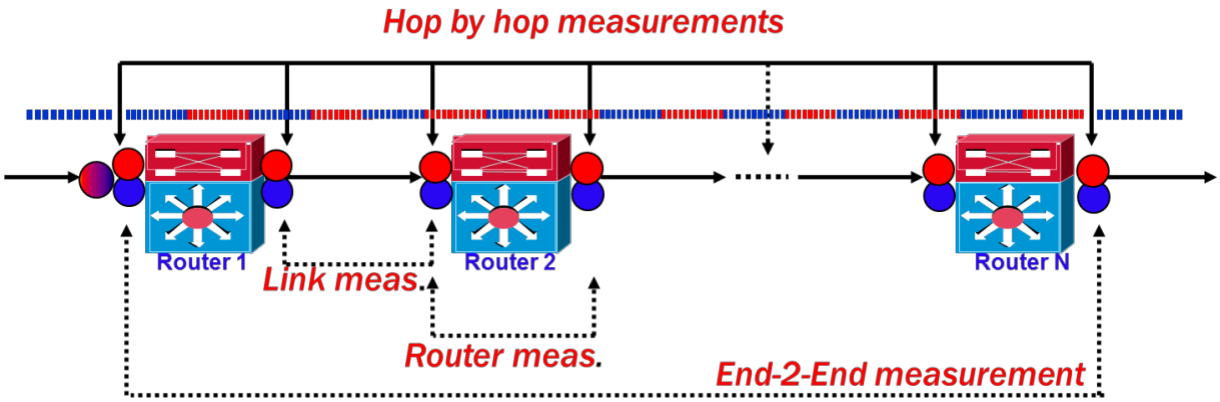

Figure 22 – AltM measurement strategies

It is possible to have Hop by hop measurements (Link meas. and Router meas.) or only End-to-End measurement depending on the case. If the IP service from PE to PE is MPLS based, Hop by hop measurements cannot be performed while End-to-End measurement is possible.

Since a Service Provider application is described here, the method can be applied to End-to-End services supplied to Subscribers and the method should be transparent outside the PM domain. So, the source node (e.g. Router 1 that can be a PE) marks the packets while the destination node (e.g. Router N that can be another PE) could restore the marking value to the initial value depending on the implementation.

The principle of coloring packets can also be used to make One-way delay measurements, as described in the following subsections. As with any One-way delay measurement technique, accurate measurements can only be achieved when ToD synchronization is in place. Note that, for all the One-way delay alternatives described, by summing the One-way delays of the two directions of a path, it is always possible to measure the Two-way delay (round-trip "virtual" delay). The limitation with measuring Two-way delay is that the One-way measurements are based on Subscriber packets. It is very likely that a Subscriber will send more packets in one direction than in the other which means that there will be more One-way Delay Measurements in one direction than the other. The Two-way Delay Measurement would be an approximation at best.

9.1.1 Single-Marking Methodology

The alternation of colors can be used as a time reference to calculate the delay. A measurement is valid only if no packet loss occurs and if packet misordering can be avoided.

9.1.2 Mean Delay

A different approach can be considered in order to overcome the sensitivity to out-of-order: it is based on the concept of mean delay. The mean delay is calculated by considering the average arrival time of the packets within a single block. The network device locally stores a timestamp for each packet received within a single block: summing all the timestamps and dividing by the total number of packets received, the average arrival time for that block of packets can be calculated. By subtracting the average arrival times of two adjacent devices, it is possible to

calculate the mean delay between those nodes. This method is more robust to out-of-order or lost packets, in the sense that provided the number of out-of-order or lost packets is small compared to the number of packets in the block, the error in the calculated mean delay is also small.

9.1.3 Double-Marking Methodology

The limitation of mean delay is that it doesn't give information about the delay value's distribution for the duration of the block. Additionally, it may be useful to have not only the mean delay but also the minimum, maximum, and median delay values and, in wider terms, to know more about the statistic distribution of delay values. Furthermore, calculation of IPDV and PDR requires individual delay measurements, not just measurement of the mean delay. So, in order to have more information about the delay and to overcome out-of-order issues, a different approach can be introduced; it is based on a Double-Marking methodology.

Basically, the idea is to use the first marking to create the alternate flow and, within this colored flow, a second marking to select the packets for measuring delay/jitter. The first marking is needed for packet loss and mean delay measurement. The second marking creates a new set of marked packets that are fully identified over the network, so that a network device can store the timestamps of these packets; these timestamps can be compared with the timestamps of the same packets on a second router (the double marked packets in the same order) to compute packet delay values for each packet. The number of measurements can be easily increased by changing the frequency of the second marking. The frequency of the second marking must not be too high in order to avoid out-of-order issues. For example, if the time length of the blocks is short (e.g. 100ms) only one double marked packet should be inserted. If the time length of the blocks is longer (e.g. 10 s) more double marked packets in a single block could be inserted, with a gap time between two of them big enough to avoid out of order packets. With the right gap time between consecutive double marked packets, the order of these packets will remain the same.

One-way delay measurements taken using this method can also be used to calculate IPDV and PDR..

The latest developments of RFC 8321 [17] generalize AltM technology to multipoint-to-multipoint scenario. The idea is to expand Performance Monitoring methodologies to measure any kind of unicast flows, also multipoint-to-multipoint, where a lot of flows and nodes have to be monitored. This is very useful for a Performance Monitoring SDN Controller Application.

9.2 Alternate Marking for FM

The main target for AltM is PM. The use of AltM for Proactive and On-demand Fault Management has been proposed but not standardized. It might be possible to trace the path of a given flow through the network.

9.3 Alternate Marking for PM

AltM [17] can provide the ability to measure the performance of a service through the use of its coloring techniques. Measurements such as PD and PL are possible using AltM.

10 References

[1] IETF RFC 791, *Internet Protocol, DARPA Internet Program Protocol Specification*, September 1981

[2] IETF RFC 792, *Internet Control Message Protocol*, September 1981

[3] IETF RFC 1321, *The MD5 Message Digest Algorithm*, April 1992

[4] IETF RFC 2119, *Key words for use in RFCs to Indicate Requirement Levels,* March 1997

[5] IETF RFC 3031, *Multiprotocol Label Switching Architecture*, January 2001

[6] IETF RFC 3174, *US Secure Hash Algorithm 1 (SHA1)*, September 2001

[7] IETF RFC 4364, *BGP/MPLS IP Virtual Private Networks (VPNs)*, February 2006

[8] IETF RFC 4443, *Internet Control Message Protocol (IPv6) for the Internet Protocol Version 6 (IPv6) Specification*, March 2006

[9] IETF RFC 4656, *A One-way Active Measurement Protocol (OWAMP)*, September 2006

[10] IETF RFC 5357, *Two-Way Active Measurement Protocol (TWAMP)*, October 2008

[11] IETF RFC 5880, *Bidirectional Forwarding Detection*, June 2010

[12] IETF RFC 5881, *Bidirectional Forwarding Detection for IPv4 and IPv6 (Single Hop)*, June 2010

[13] IETF RFC 5883, *Bidirectional Forwarding Detection (BFD) for Multihop Paths*, June 2010

[14] IETF RFC 7419, *Common Interval Support in Bidirectional Forwarding Detection*, December 2014

[15] IETF RFC 7799, *Active and Passive Metrics and Methods (with Hybrid Types In-Between)*, May 2016

[16] IETF RFC 8174, *Ambiguity of Uppercase vs Lowercase in RFC 2119 Key Words*, May 2017

[17] IETF RFC 8321, *Alternate Marking Method for Passive and Hybrid Performance Monitoring*, January 2018

[18] IETF RFC 8762, *Simple Two-way Active Measurement Protocol (STAMP)*, 03/21/2018

[19] ISO 8601, *Data elements and interchange formats –Information interchange -- Representation of dates and times*, 2004

[20] ITU-T Recommendation G.7710/Y.1701, *Common Equipment Management Function Requirements*, February 2012, November 2016

[21] ITU-T Recommendation X.733, *Information Technology – Open Systems Interconnection – Systems Management: Alarm Reporting Function*, February 1992, February 1994, April 1995, October 1996, March 1999

[22] ITU-T Recommendation X.734, *Information Technology – Open Systems Interconnection – Systems Management: Event Report Management Function*, September 1992, February 1994, April 1995, October 1996, March 1999

[23] MEF 35.1, *Service OAM Performance Monitoring Implementation Agreement*, May 2015

[24] MEF 55, *Lifecycle Service Orchestration (LSO): Reference Architecture and Framework*, March 2016

[25] MEF 61.1, *IP Service Attributes*, May 2019

[26] Telcordia GR-253-CORE, *SONET Transport Systems: Common Criteria*, September 2000

[27] IETF RFC 6335, Internet Assigned Numbers Authority (IANA) Procedures for the Management of the Service Name and Transport Protocol Number Registry, August 2011

Appendix A Life Cycle Terminology (Informative)

The following diagrams show how the life cycle terminology (see section 8.2.1) for a PM Session is used in this document. While measurements are being taken for a PM Session, the Message Period specifies the time interval between IP SOAM Measurement packets, and therefore how often the IP SOAM Measurement packets are being sent. The Measurement Interval is the amount of time over which the statistics are collected and stored separately from statistics of other time intervals.

Each PM Session supports Single-ended Delay and Single-ended PL measurements for a specific IP CoS Name on a specific MP Pair.

A PM Session can be Proactive or On-Demand. While there are similarities, there are important differences and different attributes for each. Each is discussed below in turn.

A.1 Proactive PM Sessions

For a Proactive PM Session, there is a time at which the session is created, and the session may be deleted later. Other attributes include the Message Period, Measurement Interval, Repetition Period, Start Time (which is always ‘immediate’ for Proactive PM Sessions), and Stop Time (which is always ‘forever’ for Proactive PM Sessions).

The IP SOAM Measurement packets associated with the PM Session are transmitted every “Message Period”. Data in the form of counters is collected during a Measurement Interval (nominally 15 minutes) and stored in a Current data set. When time progresses past the Measurement Interval, the former Current data set is identified as a History data set. There are multiple History data sets, and the oldest is overwritten.

The SOF/ICM will combine the counters retrieved from devices or virtual applications to calculate estimates over the SLS period T.

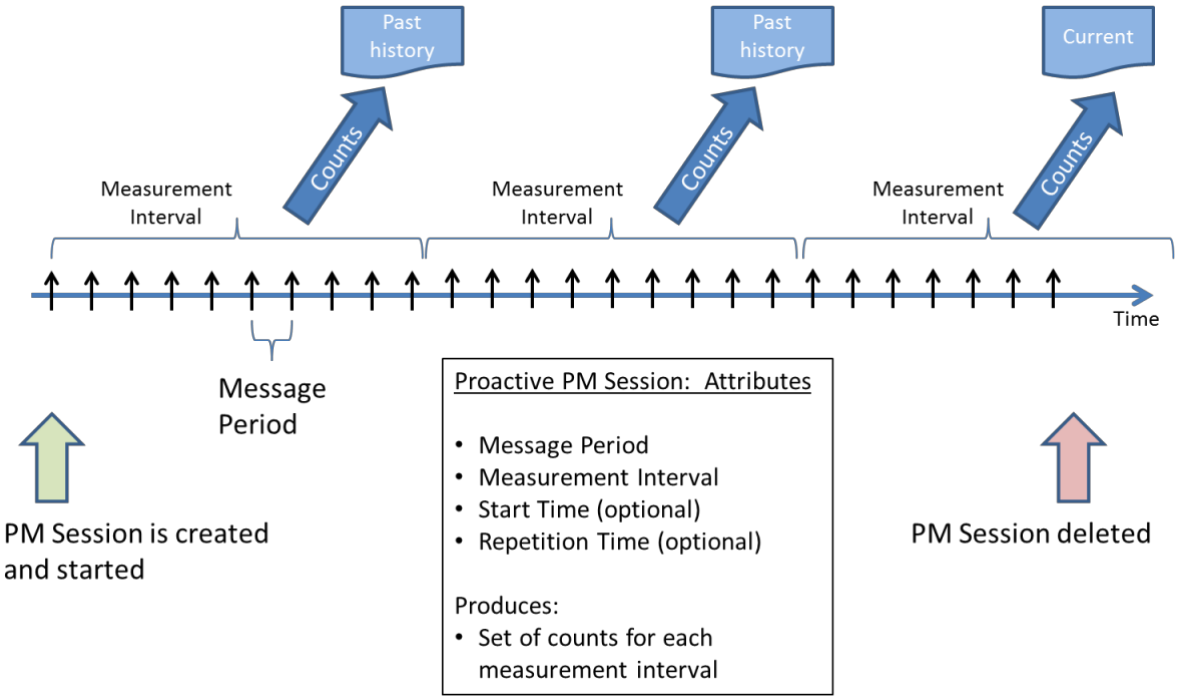

Figure 23 – Measurement Interval Terminology

A.2 On-Demand PM Sessions

For On-Demand PM Sessions, there is a Start Time and a Stop Time. Other attributes can include Message Period, Measurement Interval, and Repetition Time, depending on the type of session that is requested. Different examples are shown in the subsequent diagrams.

Note, in all examples it is assumed that during the interval data is being collected for a report, the counters of the report do not wrap. This is affected by the frequency IP SOAM Measurement packets are sent, the length of time they are sent, and the size of the report counters; the details are not addressed in this specification. At least one report is assumed to be saved after the Measurement Interval is complete.

In the first example, the On-Demand session is run, and one set of data is collected. That is, in this example, multiple Measurement Intervals are not used.

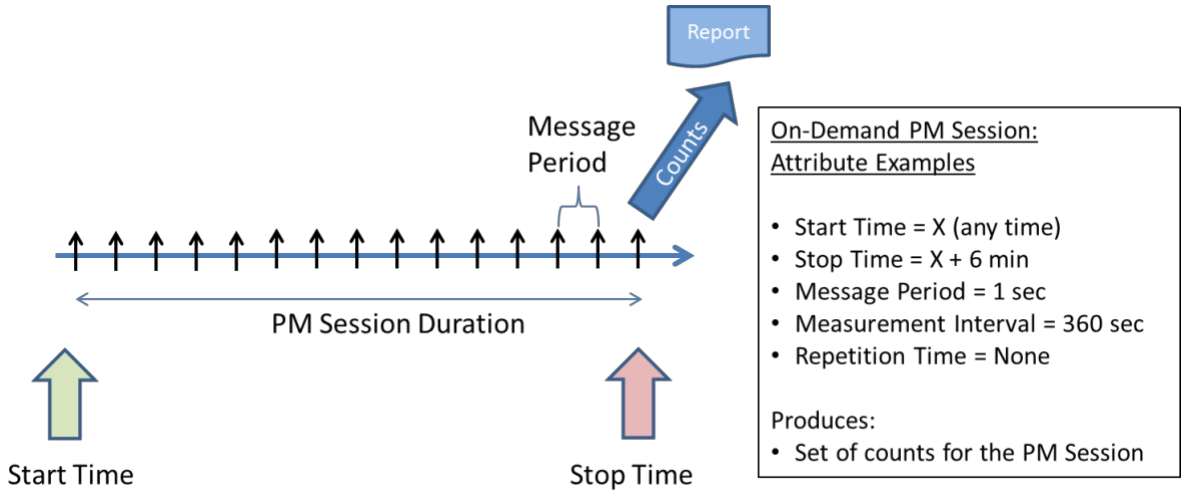

Figure 24 – Illustration of non-Repetitive, On-Demand PM Session

On-Demand PM Sessions can be specified so that Repetitions are specified. This is shown below. Note that a report is created at the end of each Measurement Interval (or Stop Time, if that occurs before the end of the Measurement Interval).

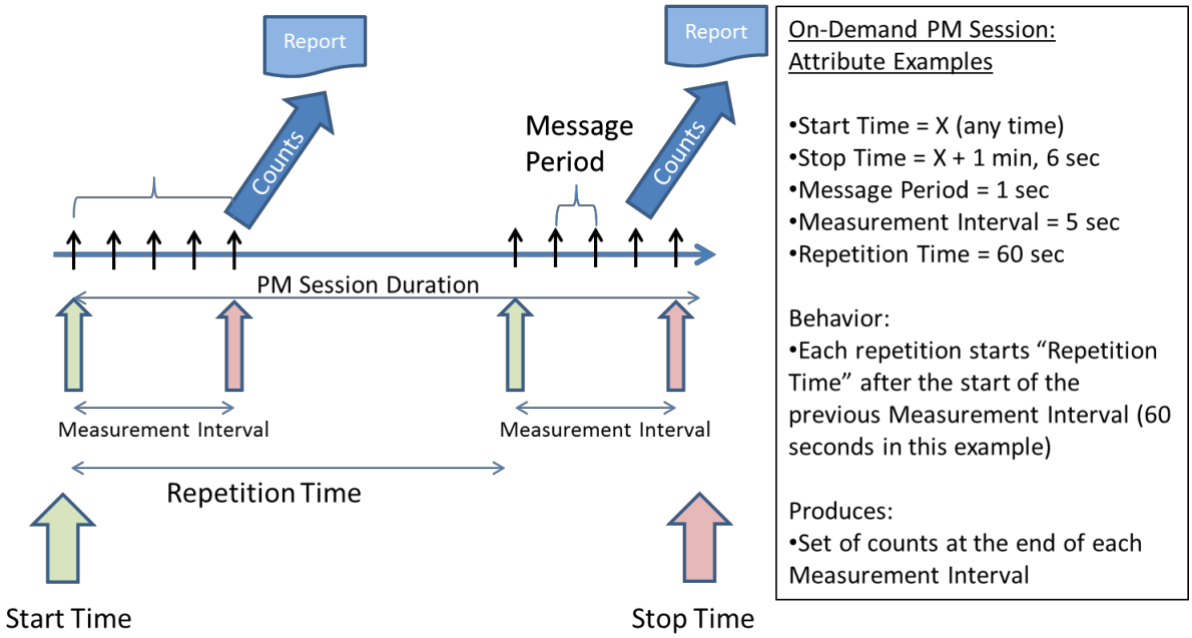

Figure 25 – Example of Repetitive On-Demand PM Session

A.3 PM Sessions With Clock-Aligned Measurement Intervals and Repetition Time of "None"

In all of the previous examples, Measurement Intervals were aligned with the PM Session, so that a PM Session Start Time always occurred at the beginning of a Measurement Interval. Measurement Intervals can instead be aligned to a clock, such as a local time-of-day clock.

When Measurement Intervals are aligned to a clock, then in general the PM Session Start Time will not coincide with the beginning of a Measurement Interval.

When the Repetition Time is "none", then the PM Session Start Time will always fall inside a Measurement Interval, so measurements will begin to be taken at the Start Time. As Figure 26 illustrates, when Measurement Intervals are aligned with a clock rather than aligned with the PM Session, then the first Measurement Interval could be truncated. The first, truncated Measurement Interval ends when the clock-aligned Measurement Interval boundary is reached. If the PM Session is Proactive, then a report is generated as usual, except that this report will have the Suspect Flag set to indicate the Measurement Interval's truncated status. Figure 26 depicts a Proactive PM Session, but the same principles apply to On-Demand PM Sessions with Repetition Times of "none".

Subsequent Measurement Intervals in the PM Session will be of full length, with Measurement Interval boundaries occurring at regular fixed-length periods, aligned to the clock. The exception may be the last Measurement Interval of the PM Session. When a PM Session is Stopped or Deleted, then the final Measurement Interval could be truncated, and so again the Suspect Flag would be set for this final, truncated Measurement Interval.

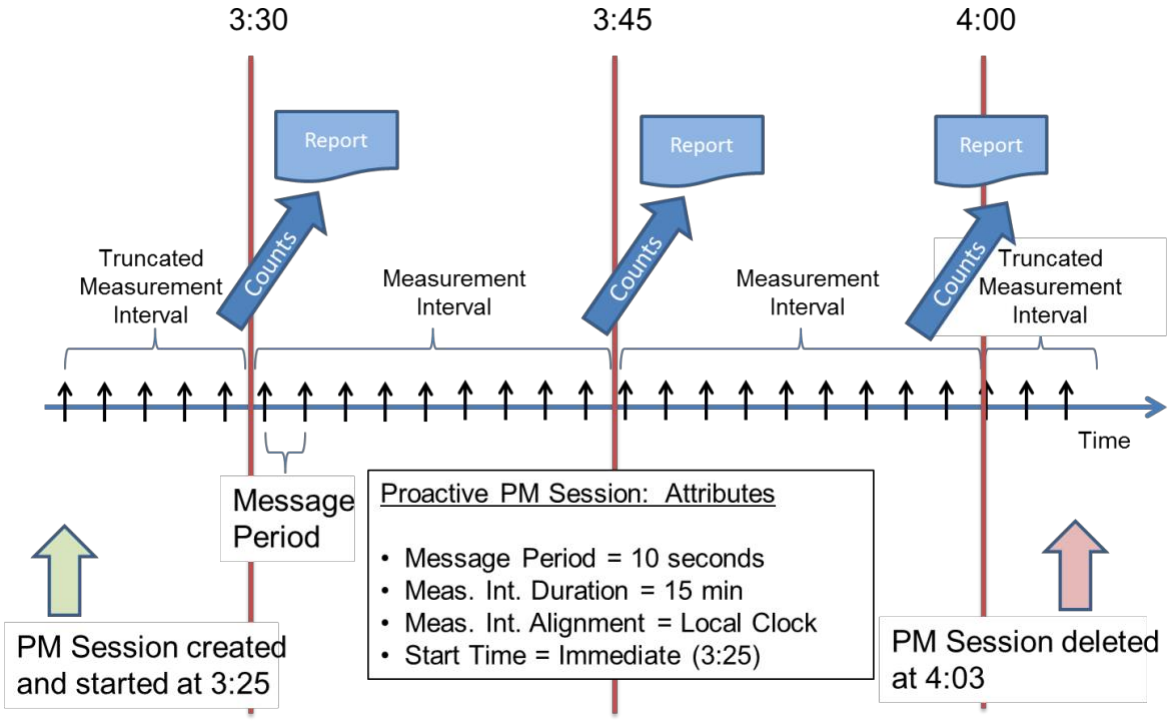

Figure 26 – Example Proactive PM Session with Clock-Aligned Measurement Interval

A.4 PM Sessions With Clock-Aligned Measurement Intervals and Repetition Times Not Equal To "None"

When Measurement Intervals are aligned with a clock and the Repetition Time is not equal to "none", then there are two possibilities for the PM Session Start Time. The first possibility is that the PM Session Start Time is at a time that would fall inside a clock-aligned Measurement

Interval. The second possibility when Repetition Times are not equal to "none" is that the PM Session Start Time could fall outside of a clock-aligned Measurement Interval.

If the PM Session Start Time would fall inside a clock-aligned Measurement Interval, then measurements would begin immediately at the PM Session Start Time. In this case, the first Measurement Interval might be truncated (unless PM Session Start Time is also chosen to align with local clock), and thus have its data flagged with a Suspect Flag. An example is illustrated in Figure 27. Figure 27 depicts an On-Demand PM Session, but the same principles apply to a Proactive PM Session whose Repetition Time is not equal to "none".

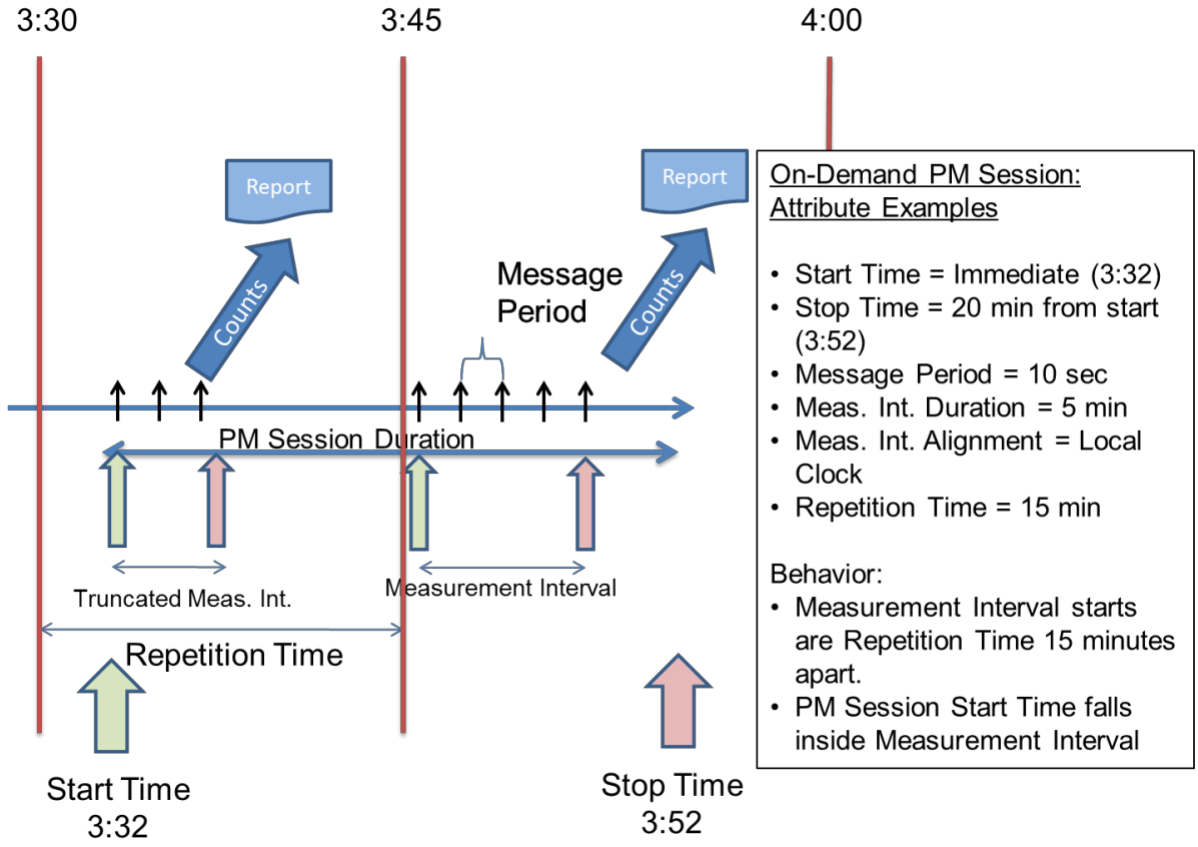

Figure 27 – Example On-Demand PM Session with Clock-Aligned Measurement Interval

In Figure 27, the PM Session starts at 3:32 and has a Stop Time at 3:52. Note that the PM Session might not have been given these explicit times; the PM Session could have had a Start Time of "immediate" and a Stop Time of "20 minutes from start". The Measurement Interval boundary is aligned to the local clock at quadrants of the hour. The next Measurement Interval boundary after the PM Session Start Time is at 3:45. Since the Repetition Time is 15 minutes and the Measurement Interval duration is 5 minutes, the PM Start Time of 3:32 falls inside a Measurement Interval, therefore measurements are begun at the PM Start Time. The first Measurement Interval ends at 3:35 due to its alignment with the local clock. Therefore, the first Measurement Interval is a truncated Measurement Interval (3 minutes long rather than the normal 5 minutes) and its data will be flagged with the Suspect Flag.

The next Measurement Interval begins at 3:45 and runs for its full 5-minute duration, so measurements cease at 3:50. In this example, the PM Session reaches its Stop Time before any more Measurement Intervals can begin. Note that the PM Session Stop Time could fall inside a Measurement Interval, in which case the final Measurement Interval would be truncated; or the PM Session could fall outside a Measurement Interval, in which case the final Measurement Interval would not be truncated. In Figure 28, the data from the second Measurement Interval would not be flagged as suspect.

Figure 27 covered the case where the PM Session Start Time falls inside a clock-aligned Measurement Interval. The second possibility when Repetition Times are not equal to "none" is that the PM Session Start Time could fall outside of a clock-aligned Measurement Interval. In such a case, measurements would not begin immediately at the PM Session Start Time, but rather would be delayed until the next Measurement Interval begins. An example is illustrated in Figure 28. Again, while Figure 28 depicts an On-Demand PM Session, similar principles apply to a Proactive PM Session whose Repetition Time is not equal to "none".

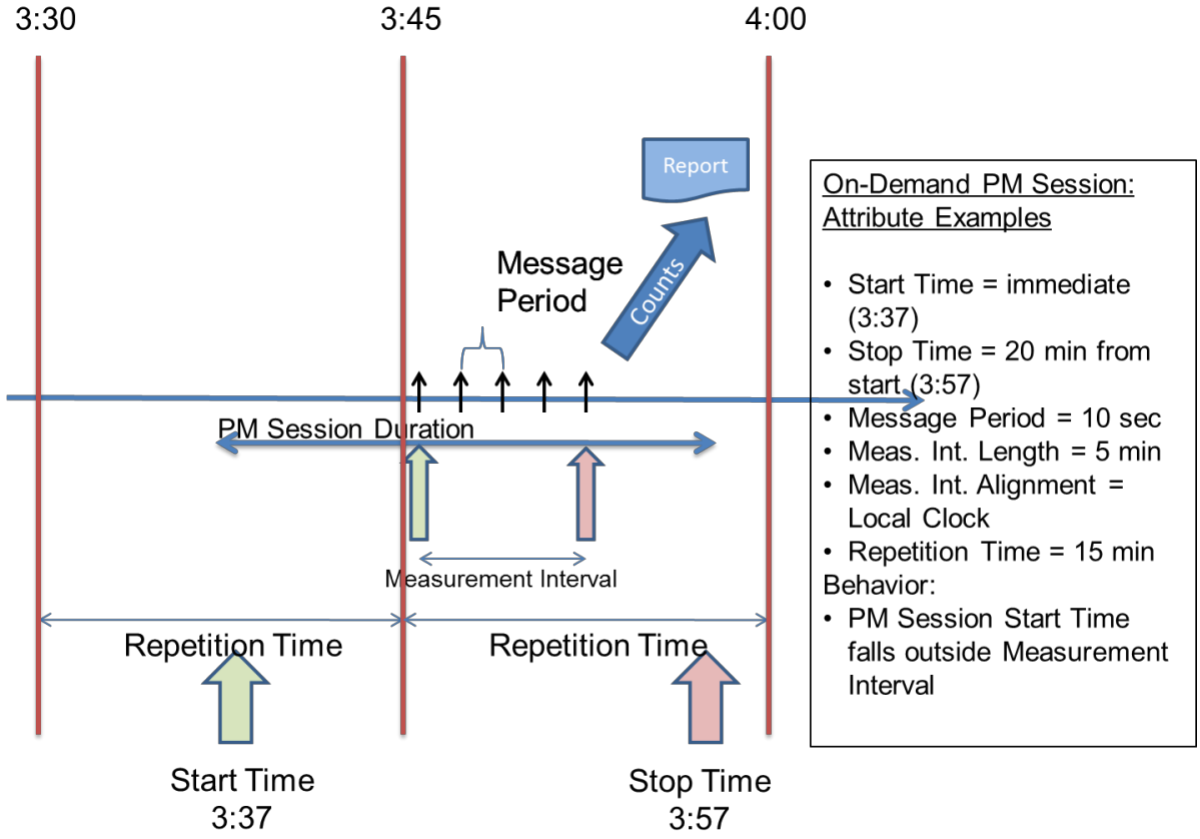

Figure 28 – Second Example of On-Demand PM Session with Clock-Aligned Measurement Interval

In Figure 28, the PM Session starts at 3:37 and has a Stop Time at 3:57. Note that the PM Session might not have been given these explicit times; the PM Session could have had a Start Time of "immediate" and a Stop Time of "20 minutes from start". Note also that in such a case,

the parameters given in Figure 28 might be identical to the parameters given in Figure 27, with the only difference being that the “Start button” is pressed 5 minutes later.

The Measurement Interval boundary is aligned to the local clock at quadrants of the hour. The next Measurement Interval boundary after the PM Session Start Time is at 3:45. Since the Repetition Time is 15 minutes and the Measurement Interval duration is 5 minutes, the PM Start Time of 3:37 falls outside a Measurement Interval. Therefore, measurements do not begin at the PM Session Start Time but instead are delayed until the next Measurement Interval boundary.

The first Measurement Interval for this example begins at 3:45, 8 minutes after the PM Session is started. This first Measurement Interval runs for its full 5 minutes, so its data will not have the Suspect Flag set. Measurements cease at 3:50 due to the 5-minute Measurement Interval duration. In this example, the PM Session reaches its Stop Time before any more Measurement Intervals can begin.

Note that, as in the previous case, the PM Session Stop Time could fall either inside or outside a Measurement Interval, and so the final Measurement Interval might or might not be truncated. In general, all Measurement Intervals other than the first and last Measurement Intervals should be full-length.

Appendix B Measurement Bins (Informative)

MEF 61.1 [25] performance metrics of One-way Packet Delay Percentile, One-way Packet Delay Range, and Inter-Packet Delay Variation are all defined in terms of the p-Percentile of packet delay or inter-packet delay variation. Direct computation of percentiles would be resource intensive, requiring significant storage and computation. This informative appendix describes a method for determining whether performance objectives are met using bins for packet delay, inter-packet delay variation, and packet delay range.

B.1 Description of Measurement Bins

As described in section 8.5.1.2, each packet delay bin is one of n counters, B_1, … B_n, each of which counts the number of packet delay measurements whose measured delay, x, falls into a range. The range for n+1 bins (there are n bins, plus Bin 0, so n+1) is determined by n delay thresholds, D_1, D_2, … D_n such that $0 < D_1 < D_2 < .. < D_n$. Then a packet whose delay is x falls into one of the following delay bins:

- Bin *0*, if $x < D_1$
- Bin i, if $D_i \leq x < D_{i+1}$
- Bin n, if $D_n \leq x$

Note: A Bin 0 (B_0) counter does not need to be implemented, because, B_0 can be determined from R, the total number of IP SOAM Measurement packets received using the following formula:

$$B_0 = R - \sum_{i=1}^{n} B_i$$

Similarly, each inter-packet delay variation (IPDV) bin is one of m counters, B_1, … , B_m, each of which counts the number of IPDV measurements whose measured delay, v falls into a range. The range for m+1 bins is determined by m IPDV thresholds, V_1, V_2, … V_m such that $0 < V_1 < V_2 < .. < V_m$. Then a packet whose IPDV v falls into one of the following IPDV bin:

- Bin 0, if $v < V_1$
- Bin i, if $V_i \leq v < V_{i+1}$
- Bin m, if $V_m \leq x$

Note: A Bin 0 (B_0) counter does not need to be implemented, because B_0 can be determined from R_y, the total number of IPDV measurement packet pairs received using the following formula:

$$B_0 = R_y - \sum_{i=1}^{m} B_i$$

B.2 One-way Packet Delay Percentile

As defined in MEF 61.1 [25], the One-way Packet Delay Percentile is met for an MP Pair if $Pp(x) < D$ where $Pp(x)$ is the p_{th} percentile of One-Way packet delay, x; and D is the One-Way packet delay percentile objective set for that MP Pair. To determine if this objective is met, assume that of the n delay bins defined for the MP Pair bin j is defined such that $D_j = D$.

Then we can conclude:

$$Pp(x) < D \text{ if and only if } \sum_{i=j}^{n} B_i < (1-p)R$$

For example, consider an objective for a MP Pair that the 95th percentile of One-way delay must be less than 2 milliseconds. If fewer than 5 out of 100 of the received packets have delay greater than 2 milliseconds, then the 95th percentile of delay must be less than 2 milliseconds.

B.3 One-way Inter Packet Delay

As defined in MEF 61.1 [25], the One-way Inter-Packet Delay Variation is met for an MP Pair if $Pp(v) < V$ where $Pp(v)$ is the p_{th} percentile of One-way IPDV, v; and V is the One-way IPDV objective set for that MP Pair. To determine if this objective is met, assume that of the m IPDV bins defined for the MP Pair, bin j is defined such that $V_j = V$

Then we can conclude:

$$Pp(v) < V \text{ if and only if } \sum_{i=j}^{m} B_i < (1-p)R_y$$

B.4 One-way Packet Delay Range

As defined in MEF 61.1 [25], the One-way Packet Delay Range is met for an MP Pair if $Q_h(x) = P_h(x) - P_0(x) < Q$ where x is the One-way packet delay, h is a high percentile such that $0 < h \leq 1$, $P_0(x)$ is the 0_{th} percentile (i.e., the minimum) of One-way packet delay and the lower bound of the range, $P_h(x)$ is the h_{th} percentile of One-way packet delay and the higher bound of the range, and Q is the One-way packet delay range objective for that MP Pair. When $h = 1$ then $P_h(x) =$ maximum(x). To determine if this objective is met, assume that of the m PDR bins defined for the MP Pair, bin j is defined such that $Q_j = Q$.

Then we can conclude:

$$Q_h(x) < Q \text{ if and only if } \sum_{i=j}^{m} B_i < (1-h)R$$

Note that requirements for measurements of minimum and maximum One-way delay are found in section 8.2. Also note that the minimum delay is lower bounded by c, the propagation delay of

the shortest path connecting the MP Pair. The constant *c* could be known when the IPVC is designed.

Appendix C Statistical Considerations for Loss Measurement (Informative)

This appendix provides considerations on how to configure the Measurement Interval and Measurement Period of the Loss Measurement capability. Measurement of Packet Loss is performed using IP SOAM PM Data packets. These are not Subscriber data packets but instead they are Synthetic data packets used specifically to measure the performance of an IP service. In the sections below, where the term Synthetic packets is used, this refers to IP SOAM Data packets.

C.1 Synthetic Packets and Statistical Methods

One of the first questions of statistical analysis is, “what is the required confidence interval?” This is a central question when one is comparing a null hypothesis against an alternate hypothesis, but for this problem, it is not immediately clear what the null hypothesis is.

The assumption is that if we are promising a loss rate of alpha% to a customer, we have to build the network to a slightly smaller loss rate (otherwise, any measurement, no matter how large and accurate the sample size, would yield violations half of the time). As an example, suppose a carrier promises a network with better than 1% loss, and builds a network to .7% loss. The carrier can then choose a one-tailed confidence interval (say 95%), and then it becomes straightforward to calculate the number of samples that are needed to get the variability of measurements to be as small as needed. This is shown below.

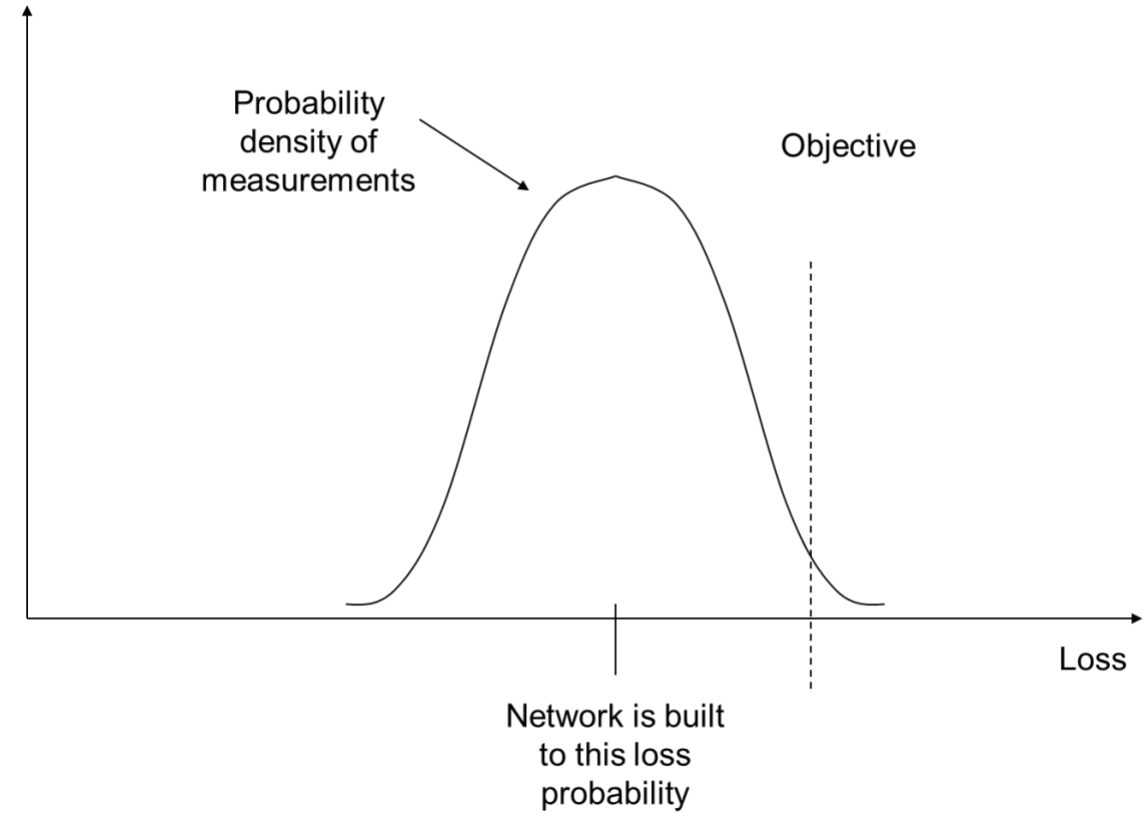

Figure 29 – Hypothesis Test for Synthetic Packet Loss Measurements

Before we specify confidence intervals or decide how much "better" the network should be built than promised, we can study how the sampling rate and sampling interval relate to the variability of measurements. A useful measure is the Coefficient of Variation (CoV), i.e. the ratio of a probability density's standard deviation to its mean. In the hypothetical diagram above, the value would be roughly 0.2. It should be clear that the smaller the CoV, the more accurate the measurements will be.

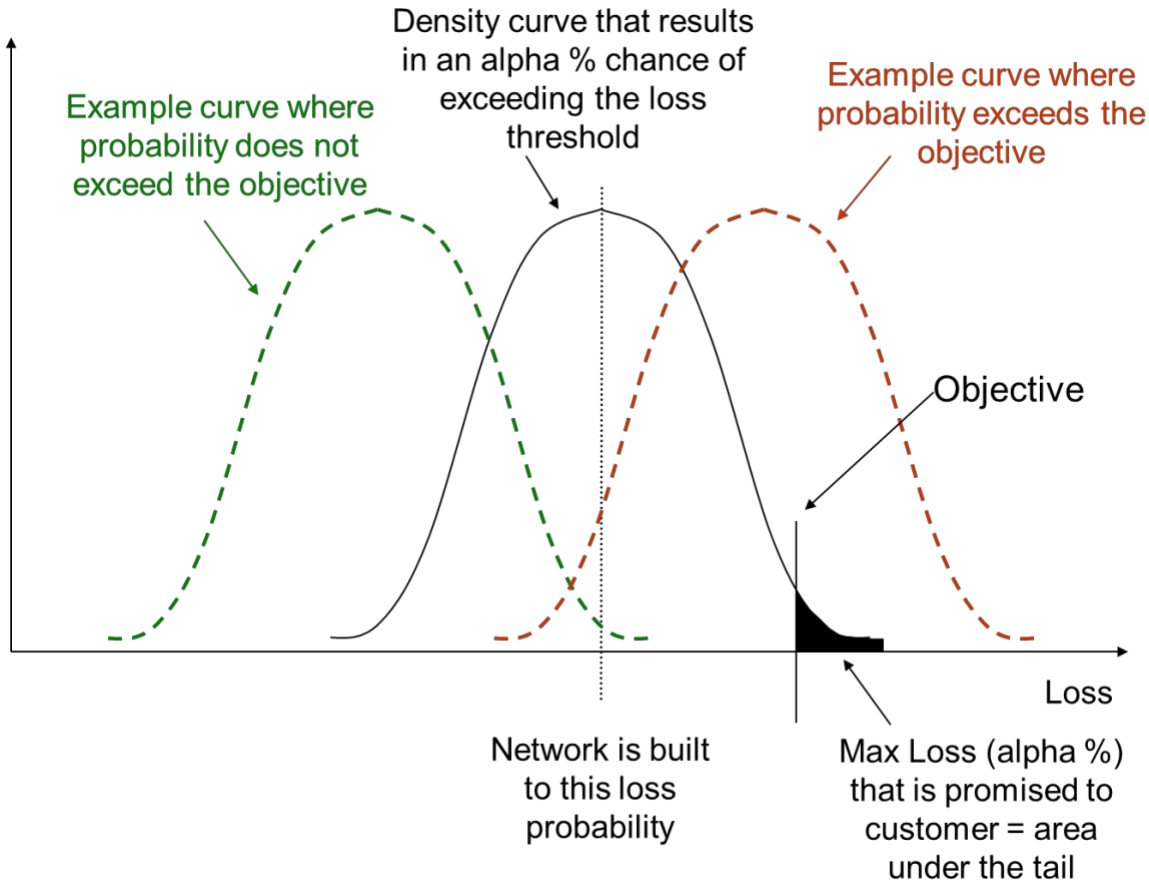

Figure 30 – Density Curve and Probability of Exceeding the Objective

Before getting into the simple equations that are relevant to the analysis, consider what the graphs look like for the Synthetic Packet approach, with specific examples of different Synthetic Packet Message Periods, Measurement Intervals, and probabilities of loss (i.e., the true Packet Loss Ratio of the network). These graphs are not hypothetical; they use exact values from the binomial probability density function. The assumption here is that the network is performing at exactly the PLR listed in the title of each graph, and the Y axis shows the probability that a specific percentage of Synthetic Packets would be lost in practice, i.e., that the measured PLR has the value shown on the X axis. Note that for some combinations of variables, the distribution is quite asymmetric with a long tail to the right, but for many others the distribution is an extremely close approximation to the normal. This, of course, is a well-known property of the binomial density function.

In each example, the number of samples (i.e., the number of Synthetic Packets) is shown - this is a function of the Message Period and the interval over which the PLR is calculated. For instance, sending one Synthetic Packet per second for 1 hour yields 3600 samples.

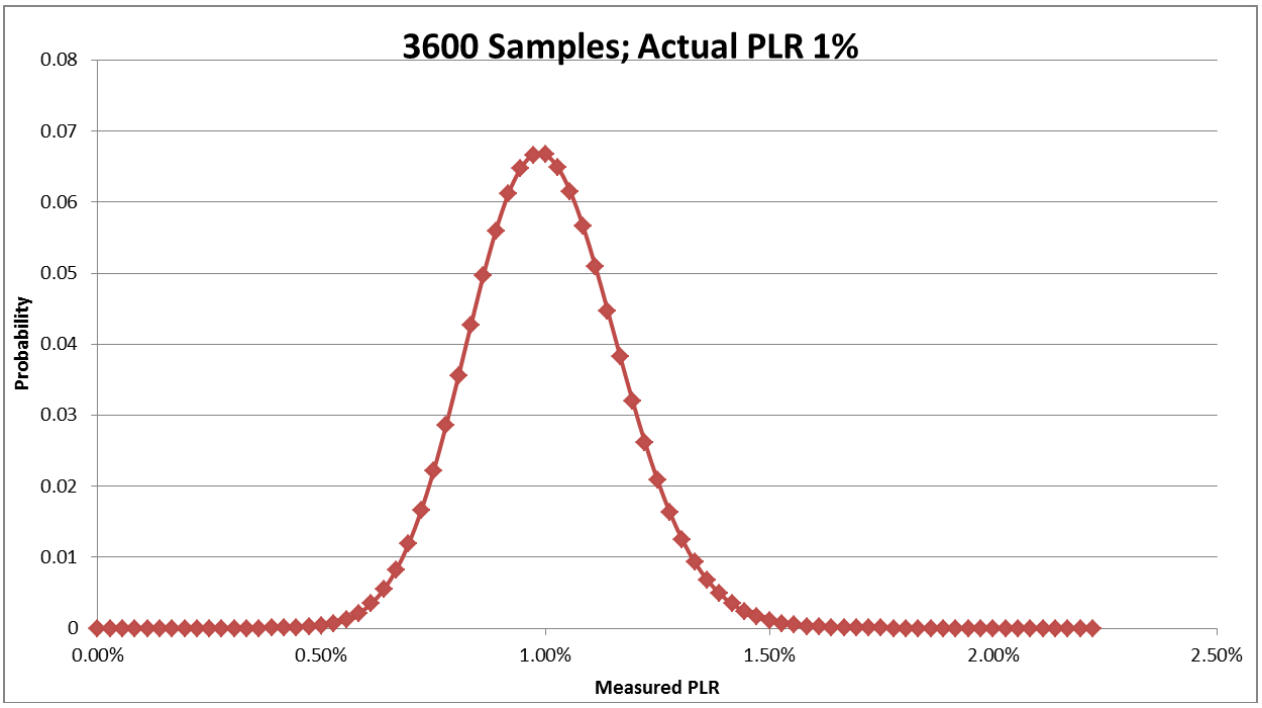

Figure 31 – Synthetic Loss Performance Example 1

The above has a CoV of 0.17. Note how it looks like a normal density.

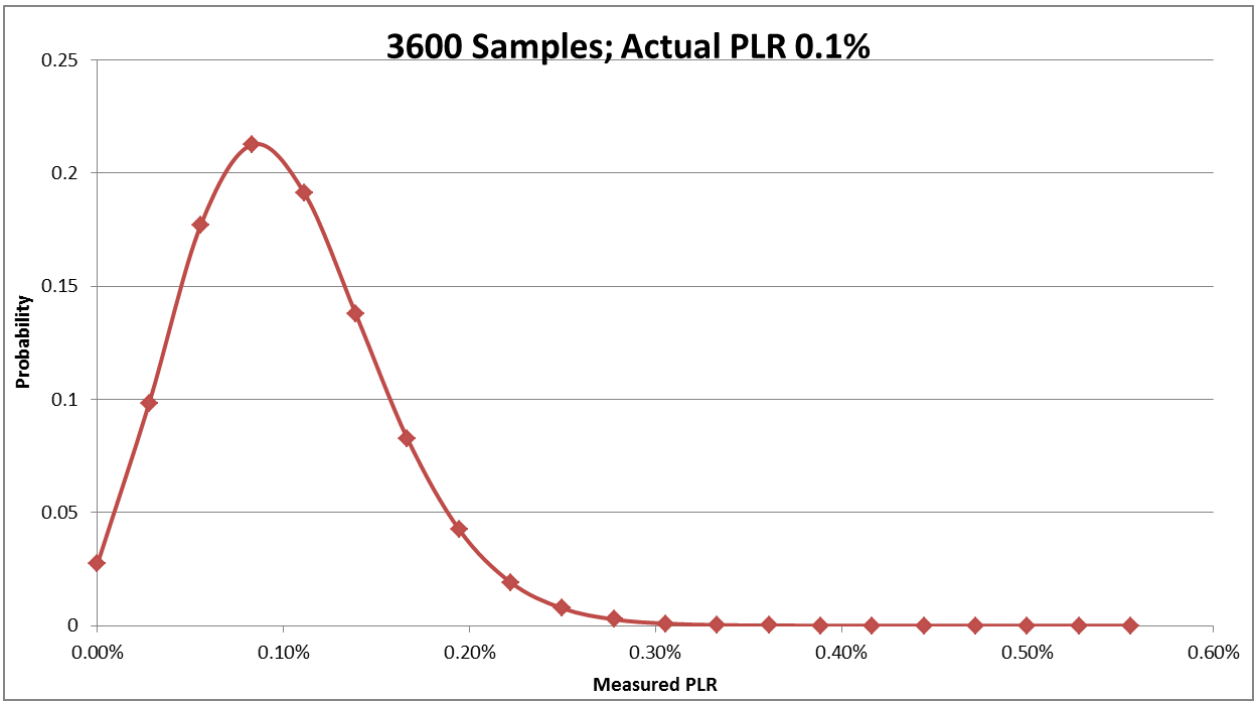

Figure 32 – Synthetic Loss Performance Example 2

In Example 2, the loss rate is smaller, and the CoV is 0.53. This is asymmetric, and variability seems too large for our use.

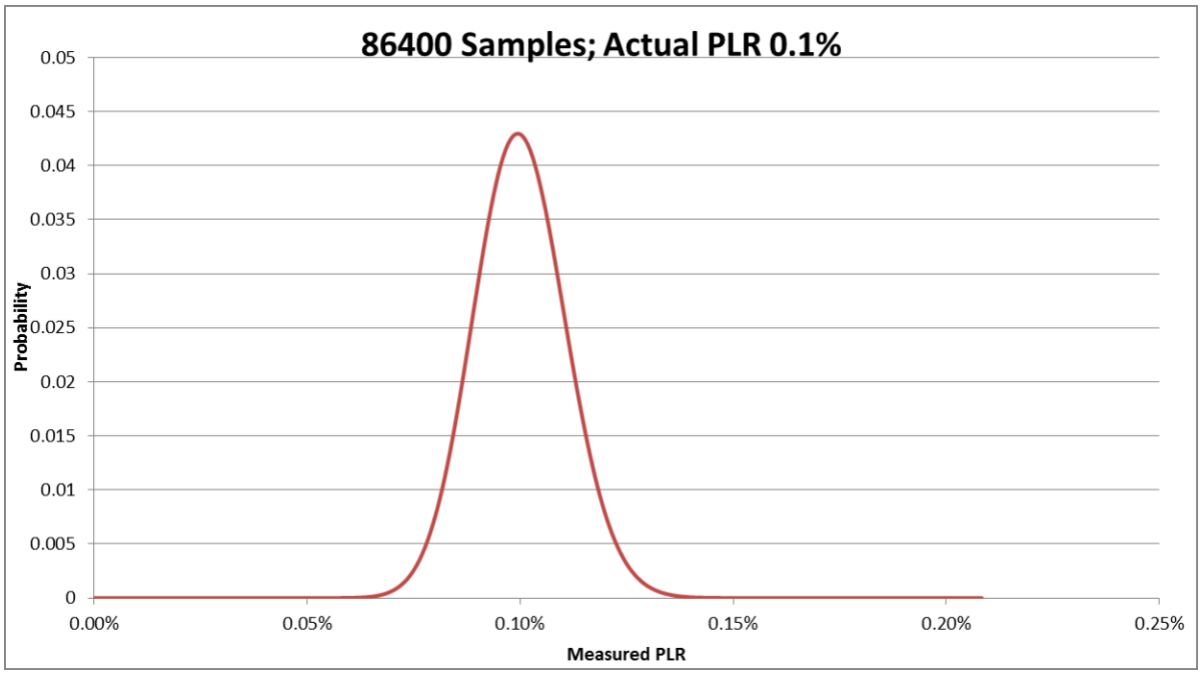

Figure 33 – Synthetic Loss Performance Example 3

Example 3 is the same as Example 2, but with a larger Measurement Interval and hence a higher number of samples. It has a CoV of 0.11 and appears to be precise enough for use.

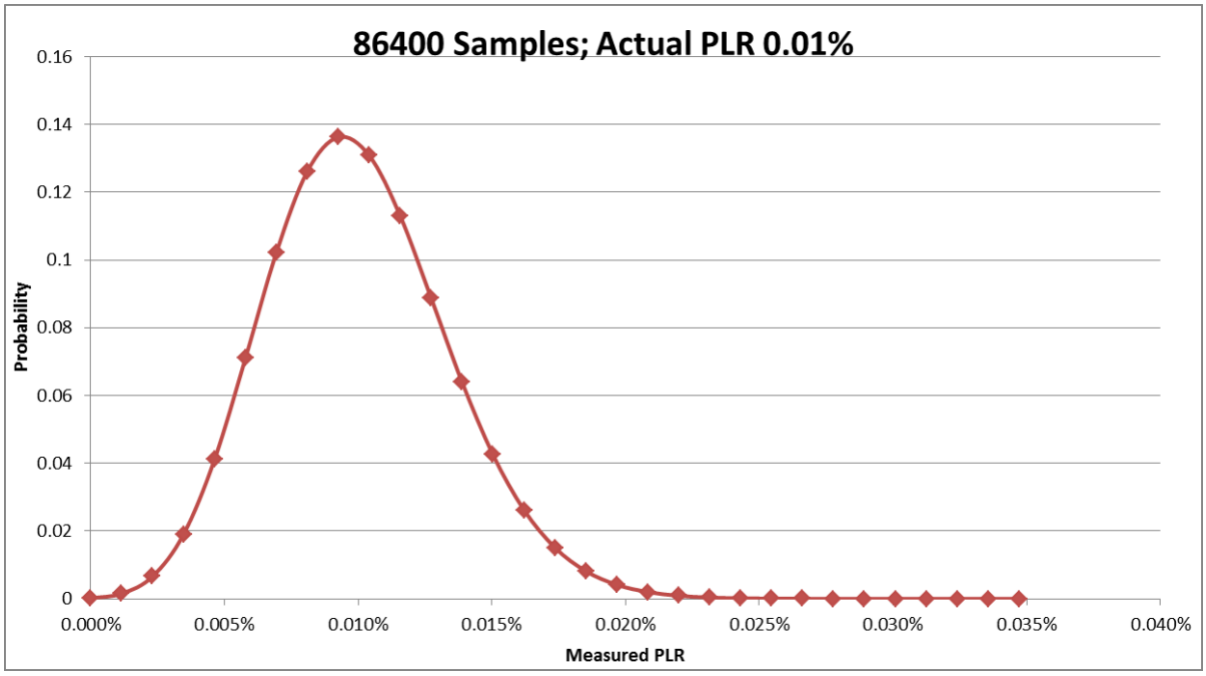

Figure 34 – Synthetic Loss Performance Example 4

In Example 4, the loss rate is even smaller. It has a CoV of 0.34 and may be too variable. Some similarities in patterns are clear; for example, as the probability of packet loss (p) gets smaller, the effects can be mitigated by having a larger number of synthetic loss packets (n). This is

predicted by fundamental properties of the density function. The binomial approximates the normal distribution for most of the types of numbers of concern. The exceptions are when the CoV is poor as shown in Examples 2 and 4.

The statistical properties are such that the following equations apply, where *p*=probability that a packet is lost, *q=1-p* is the probability that a packet is not lost, and *n* is the sample size:

Expected number of packets lost (i.e., mean) $= \mu n = np$

Standard deviation of number of packets lost $= \sigma n = \sqrt{npq}$

These can be easily converted into PLRs:

Expected measured PLR (i.e., mean)= $\mu PLR = \frac{\mu n}{n} =$ p

Standard deviation of measured PLR = $\sigma PLR = \frac{\sigma n}{n} = \sqrt{\frac{pq}{n}}$

Note that the expected value of the measured PLR (μ_{PLR}) is always equal to the probability of loss (p), i.e., the actual PLR of the network.

As introduced above, the coefficient of variation, of the sample statistic is the standard deviation as a fraction of the mean:

$$\frac{\sigma}{\mu} = \frac{\sqrt{npq}}{np} = \sqrt{\frac{q}{np}} = \sqrt{\frac{q}{p}} * \frac{1}{\sqrt{n}}$$

This is the key result. The smaller CoV is, the better. For a given CoV, we can state the following:

- As *n* goes up by a factor of 10, the CoV gets smaller (improves) by a factor of $\frac{1}{\sqrt{10}}$, or about 1/3.
- As *n* goes down by a factor of 10, the CoV gets larger (gets worse) by a factor of $\sqrt{10}$, or about 3.

Furthermore, if p goes down by a certain factor, then n needs to go up by the same factor. That is, if we need to support a loss probability that is 1/100th of what we comfortably support today, we have to either increase the rate of Synthetic Packets by 100 if we sample over the same interval, increase the interval by a factor of 100, or some combination of the two such as increasing both the rate and the interval by a factor of 10.

Below are example calculations of the Coefficient of Variation. Values are highlighted where the CoV is less than 0.2. This value is proposed as a reasonable bound.

1 hour	n	p	μ_{PLR}	σ_{PLR}	CoV
	3600	0.01	1.000%	0.1658%	0.1658
	3600	0.001	0.100%	0.0527%	0.5268
	3600	0.0001	0.010%	0.0167%	1.6666
	3600	0.00001	0.001%	0.0053%	5.2704
24 hour	86400	0.01	1.000%	0.0339%	0.0339
	86400	0.001	0.100%	0.0108%	0.1075
	86400	0.0001	0.010%	0.0034%	0.3402
	86400	0.00001	0.001%	0.0011%	1.0758
1 month	2592000	0.01	1.000%	0.0062%	0.0062
	2592000	0.001	0.100%	0.0020%	0.0196
	2592000	0.0001	0.010%	0.0006%	0.0621
	2592000	0.00001	0.001%	0.0002%	0.1964

Table 13 – CoV Calculations with Message Period 1s

1 hour	n	p	μ_{PLR}	σ_{PLR}	CoV
	36000	0.01	1.000%	0.0524%	0.0524
	36000	0.001	0.100%	0.0167%	0.1666
	36000	0.0001	0.010%	0.0053%	0.5270
	36000	0.00001	0.001%	0.0017%	1.6667
24 hour	864000	0.01	1.000%	0.0107%	0.0107
	864000	0.001	0.100%	0.0034%	0.0340
	864000	0.0001	0.010%	0.0011%	0.1076
	864000	0.00001	0.001%	0.0003%	0.3402
1 month	25920000	0.01	1.000%	0.0020%	0.0020
	25920000	0.001	0.100%	0.0006%	0.0062
	25920000	0.0001	0.010%	0.0002%	0.0196
	25920000	0.00001	0.001%	0.0001%	0.0621

Table 14 – CoV Calculations with Message Period 100ms

Appendix D Normalizing Measurements for PDR (Informative)

This document has specified a binning approach for delay-related measurements. When making measurements of delay variation, normalization is needed.

For the IPDV performance metric, a pair of delay values are normalized by subtracting one from the other and taking the absolute value. Thus, the minimum of any IPDV measurement is 0, and as a consequence bins can be set up without any consideration for the actual magnitude of the delay.

A similar normalization is needed for PDR. PDR is defined as the difference between the Y_{th} percentile of delay and the minimum delay, so each delay observation needs to have the estimated minimum subtracted from it, to get a normalized delay. The PDR performance objective *O* is specified relative to a minimum of zero, as shown below in Figure 35.

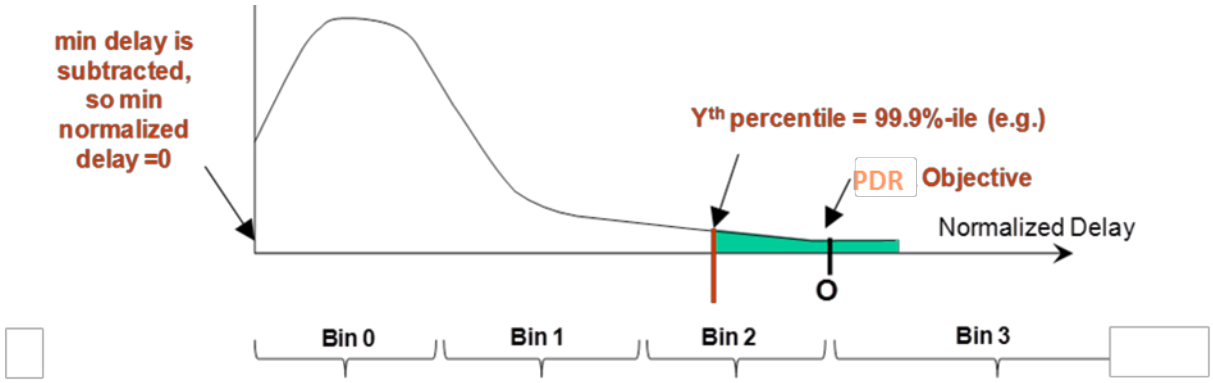

Figure 35 – Example PDR Distribution (normalized), and Bins

The distribution of delay is generally observed to be skewed to the right; i.e., there would be many measurements at or near the minimum delay, and fewer at higher values. Therefore, a good estimate of the minimum can be determined in a time interval much shorter than a Measurement Interval. Once an estimate of the minimum is available, observed delays can be normalized by subtracting the minimum, and then the appropriate bin counters can be incremented as the normalized delay is processed from each received IP SOAM Measurement packet.

One suggested practical approach as shown in Figure 35 is to record the minimum delay of each Measurement Interval, and to use that value as the estimated minimum at the beginning of the following Measurement Interval. As each delay measurement is received, the estimated minimum can be set to the minimum of the current measured delay and the previous estimate. Then each received delay measurement is normalized by subtracting the estimated minimum. With this approach, there would never be a negative value for a normalized PDR measurement.

Very small shifts in the minimum could be observed that would not be significant. Define ε as the threshold below which a shift is not considered significant (e.g., 10% of the objective). Then the SOF/ICM would not take actions if the shift of the minimum was less than ε. If, on the other hand, the minimum at the end of a Measurement Interval has decreased / increased by a value more than ε, the SOF/ICM is expected to consider as invalid the PDR measurements in the associated Measurement Interval(s).

If there are network changes during the Measurement Interval, then PDR measurements during that Measurement Interval may be invalid, and the measurements can be ignored by the SOF/ICM. This is discussed next. However, other MIs would still be valid and contribute to the estimate of PDR during the interval *T*.

Note that this approach is presented as an example, and that alternate implementations may improve on it.

D.1 Topology Shifts

For a fixed topology, the minimum delay is essentially fixed. However, network changes (e.g., in response to a network failure) can result in a shift in the minimum delay that can be significant. The minimum delay can of course shift to a lower or to a higher value.

D.1.1 Minimum Delay Becomes Significantly Smaller

When the delay becomes significantly smaller, as is shown in MI 2 below in Figure 36, it will be obvious at the end of MI 2 that the minimum delay is significantly lower than the minimum delay at the end of MI 1. It would be straightforward for an SOF/ICM to simply consider the PDR measurements of that interval as being invalid, and to ignore them.

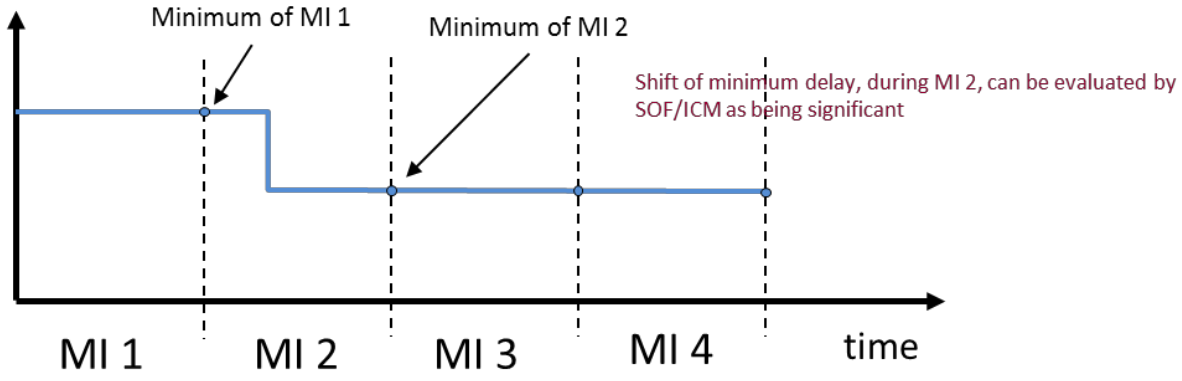

Figure 36 – Reduction in Minimum Delay, due to Network Topology Change

D.1.2 Minimum Delay Becomes Significantly Larger

When the delay becomes significantly larger, as is shown in MI 6 below in Figure 37, it will not be obvious until the end of MI 7 that the minimum delay is significantly higher than the minimum delay observed at the end of MI 5. It would be straightforward for the SOF/ICM to detect that and mark the measurements of MI 6 and MI 7 as being invalid.

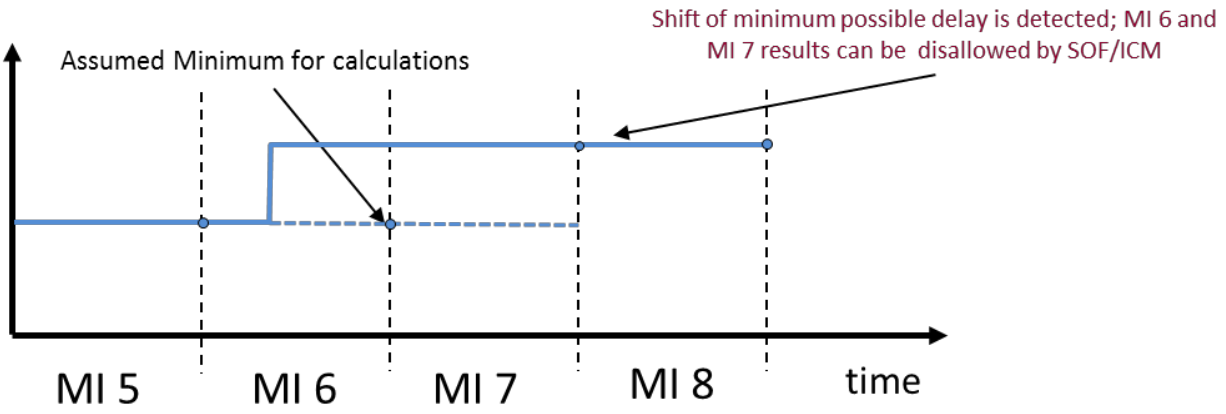

Figure 37 – Increase in Minimum Delay, due to Network Topology Change

D.2 Impact of Lack of ToD Synchronization

When performing One-way measurements using Single-Ended Delay Measurement without ToD synchronization between the MPs, negative packet delay measurements can be seen due to differences in the ToD for each MP. An example of this is shown in Figure 38.

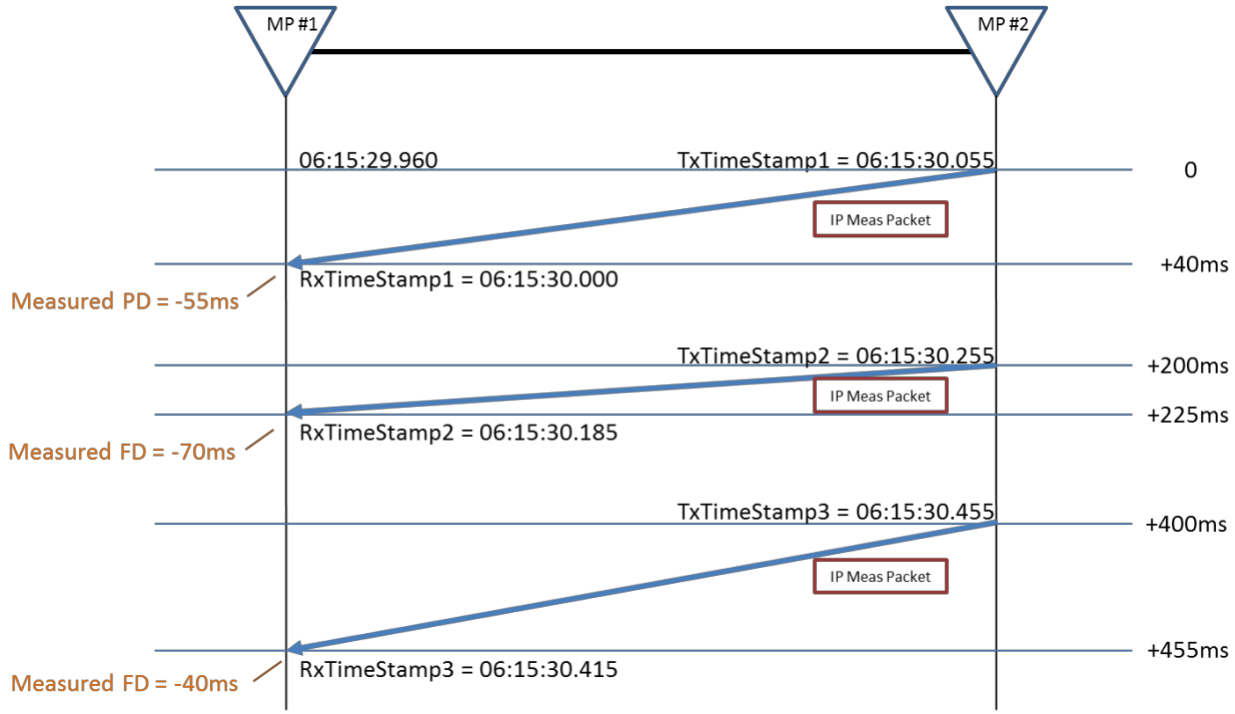

Figure 38 – Lack of ToD Synchronization

In Figure 38, three IP SOAM Measurement Packets are shown. At the time when the first measurement packet is transmitted, the ToD clock at MP #1 reads 06:15:30.055 and the ToD clock at MP #2 reads 06:15:29.960. The PD measured for the first packet, using RxTimeStamp1 – TxtimeStamp1, is -55ms since TxTimeStamp1 > RxTimeStamp1. When determining the minimum PD for PDR in this situation, a “less negative” PD is considered an increase in delay

and a “more negative” PD is considered a decrease in delay. Using the example in Figure, the PD measured for the second packet, RxTimeStamp2 – TxTimeStamp2, is -70ms which indicates that the packet arrived 15ms faster than the first packet. The PD measured for the third packet, RxTimeStamp3 – TxTimeStamp3, is -40ms which indicates that the packet arrive 15ms slower than the first packet.

Implementations that are measuring PDR without ToD synchronization are expected to take this into account and react accordingly to negative PD measurements.

Appendix E Calculation of SLS Performance Metrics (Informative)

This document defines the data sets that devices or virtual applications provide to SOF/ICM, while other MEF specifications and applications need to obtain the performance metrics for SLS. This appendix provides some guidelines for how to calculate SLS performance metrics, using data sets as inputs.

The SLS performance metrics are defined in terms of the performance of every Qualified Service Packet; however, the data sets are primarily based on time-based samples. In the remainder of this appendix we assume that time-based sampling is used and analyze how the data sets can be used to calculate the SLS metrics on that basis.

The data sets are Measurement Interval based. Traditionally, the duration of a Measurement Interval is 15 minutes or 24 hours. This document requires at least that 15-minute Measurement Intervals are supported. When reaching the end of a Measurement Interval, the data set for the current measurement interval is moved to the list of historic Measurement Intervals. The SOF/ICM can retrieve a block of historic data sets from the devices or virtual applications or they are transmitted to the SOF/ICM. Usually the performance metrics are measured against the SLS over a much longer time period T, typically one month or so. The processing of performance metrics for an SLS can be done by ICM, SOF or even the Business Systems. Therefore, the data sets from multiple Measurement Intervals are used for calculating the performance metrics over period T. In the following, we discuss how to obtain the following performance metrics for SLS, using IP SOAM PM defined data sets:

- One-way PD
- One-way MPD
- One-way PL

E.1 One-way Packet Delay

The One-way packet delay for an IP Data Packet that flows between SLS-RP *i* and SLS-RP *j* is defined as the time elapsed from the reception of the first bit of the packet at SLS-RP *i* until the transmission of the last bit of the first corresponding egress packet at SLS-RP *j*. If the packet is erroneously duplicated as it traverses the network, the delay is based on the first copy that is delivered.

The One-way Packet Delay Percentile Performance Metric, $d(T_k, C, S, p)$, is defined in MEF 61.1 [25] for a given time period T_k, CoS Name *C*, set or ordered pairs of SLS-RPs *S*, and percentile *p*. Although it is not possible to calculate this directly, it is possible to determine whether the value meets the objective, using the principle described in Appendix B. If there are *n* Measurement Intervals in time period T_k, then for a given ordered pair of SLS-RPs <*i*, *j*>, the percentile that meets the SLS objective over T_k, $PD(T_k)$, is given by the following equation:

$$PD(T_k) = \frac{\sum^n (Total\ counts\ of\ Meas.Bins\ in\ the\ MI\ that\ meet\ the\ objective)}{\sum^n (Total\ counts\ of\ all\ Meas.Bins\ in\ the\ MI)}$$

Applying the conclusions from Appendix B, it can be seen the objective is met for a given SLS-RP pair if and only if $PD(T_k) \leq 1 - p$. The One-way Packet Delay Percentile Performance Metric,

d(Tk, C, S, p) is defined in MEF 61.1 [25] to be the maximum of the One-way packet delay percentile over all the SLS-RP pairs in set *S*. Therefore, the SLS objective is met if and only if $PD(T_k) \leq 1 - p$ for every ordered SLS-RP pair in *S*.

Note that the Measurement Bin thresholds must be chosen such that the PD objective $\hat{d}$ is aligned with the boundary between two bins, as described in Appendix B.

The same calculation applies to all other SLS performance metrics for which Measurement Bins are used, including One-way PDR and One-way IPDV.

E.2 One-way Mean Packet Delay

One-way Mean Packet Delay is defined in MEF 61.1 [25] as:

- Let *μ(Tk, C, <i, j>)* represent the arithmetic mean of One-way packet delay for all Qualified Packets for time period *Tk*, CoS Name *C* and pair of SLS-RPs *<i, j>* in *S* that are delivered to SLS-RP *j*. If there are no such packets, let *μ(Tk, C, <i, j>)* equal 0.
- Then the One-way Mean Packet Delay Performance Metric *u(Tk, C, S)* is the maximum of the values *μ(Tk, C, <i, j>)* for all *<i, j>* in *S*.

This cannot be calculated directly based on the Measurement Interval Data Sets. However, if there are *n* Measurement Intervals in time period *Tk*, then an approximation for *μ(Tk, C, <i, j>)*, *MPD(Tk)*, is given by:

$$MPD(T_k) = \frac{\sum^n (MPD\ of\ MI)}{n}$$

As *u(Tk, C, S)* is defined to be the maximum of *μ(Tk, C, <i, j>)* over all the ordered pairs *<i, j>* in *S*, an approximation for *u(Tk, C, S)* can be found by taking the maximum of *MPD(Tk)* over all the ordered pairs *<i, j>* in *S*. MEF 35.1 [23] Appendix I discusses other possible methods but concludes that this is the preferred method. See MEF 35.1 [23] for information on the other methods.

E.3 One-way Packet Loss

MEF 61.1 [25] defines One-way Packet Loss Ratio as:

- Let *I(Tk, C, <i, j>)* be the number of Qualified Packets for time period *Tk*, CoS Name *C* and ordered pair of SLS-RPs *<i, j>* in *S* that are received at SLS-RP *i*.
- Let *J(Tk, C, <i, j>)* be the number of unique (not duplicate) Qualified Packets for time period *Tk*, CoS Name *C* and ordered pair of SLS-RPs *<i, j>* in *S* that are transmitted at SLS-RP *j*.
- Let *f(Tk, C, <i, j>)* be defined as:

$$f(T_k, C, <i,j>) = \frac{I(T_k,C,<i,j>) - J(T_k,C,<i,j>)}{I(T_k,C,<i,j>)} \text{ if } I(T_k, C, <i, j>) > 0$$

- Then the One-way Packet Loss Ratio Performance Metric *F(Tk, C, S)* is the maximum of all the values *f(Tk, C, <i, j>)* for all *<i, j>* in *S*.

Based on the Tx and Rx packet counts of the data sets for n MIs during T, the One-way Packet Loss Ratio over T for a given ordered MP Pair can be obtained by:

$$PLR(T_k) = \frac{\sum^n ((Tx\ packet\ counts\ for\ the\ MI) - (Rx\ packet\ counts\ for\ the\ MI))}{\sum^n (Tx\ packet\ counts\ for\ the\ MI)}$$

To calculate the One-way Packet Loss Ratio over T for set S, the maximum of these values over all the ordered pairs in S must be taken.