9500 MPR Validation for Electric Utilities

Revision 1
1/27/2016

9500 MPR Validation for Electric Utilities

prepared for

Nokia

Project No. 85604

Revision 1
1/27/2016

prepared by

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1.0 EXECUTIVE SUMMARY

Electric utilities commonly use microwave radio networks to transport mission-critical communications for power system operations. Digital microwave radios which only have a time-division multiplexed (TDM) architecture are being discontinued by manufacturers and replaced by a new generation of full-packet-based microwave radios. Since legacy TDM radios are approaching the timeframe when their availability for purchase will end and then eventually support will be discontinued, utilities must begin migrating to packet radios to meet their application needs. Prior to deploying full packet-based microwave radio systems, the strict latency, symmetry, and jitter requirements of utility applications such as teleprotection relaying (TPR) need to be confirmed. Testing the performance of this new generation of packet-based microwave radios for critical electric utility applications is required to manage the risks of this transition and is the purpose of this document.

This report outlines the typical communications parameters of electric utility TPR circuits and documents the performance of Nokia's 9500 MPR Microwave Packet Radio during tests conducted in the Burns & McDonnell laboratory located in Kansas City, Missouri. A simulated utility operations environment consisting of substation relays, network test equipment and the 9500 MPR radios was created to test TPR communications. Critical parameters tested and documented in this report include radio system latency, delay symmetry, network timing, impact of network congestion, and path fading effects. The testing showed that the 9500 MPR delivered a current differential TPR channel through a 3-hop linear radio topology contributing only 3.8 milliseconds (ms) of latency to the 5.3 ms of total latency measured by the relay. This is less than the most stringent latency of 8.0 ms required for differential relaying. The radio system's ability to maintain latency performance in the presence of network congestion was also tested by oversubscribing the radio link by over four times the rated throughput and observing no impact on latency performance of the TPR circuit that was provisioned on the same link. In summary, the performance of the 9500 MPR observed by Burns & McDonnell provided a similar level of performance to a TDM circuit-based system in all test cases.

2.0 BACKGROUND

Communication systems deployed by electric utilities for TPR applications must meet strict requirements for latency, jitter, and delay symmetry. These requirements are necessary to maintain relay and breaker operating times within limits that will prevent equipment damage, and to maintain the security, and dependability of the protection scheme. Security is a measure of the prevention of unwanted operations. Dependability is a measure of the assurance that desired operations will occur. Table 1 below contains typical performance requirements for communication channels supporting three TPR protection schemes. The max channel delays provided in Table 1 are upper thresholds defined by the International Electrotechnical Commission (IEC) in standard IEC-60834 as a limit for protection scheme operation. The recommended channel delay values in the table below are a more representative set of requirements for high voltage transmission lines and will be used to determine pass or fail status for the testing performed on the 9500 MPR. These requirements must be met in order to maintain operating time, dependability, and security within acceptable limits.

Protection Scheme	Channel Types	Protocols	Interfaces	Jitter Sensitivity	Max Channel Delay (IEC)	Recommended Channel Delay	Other Notes
Permissive Overreach Transfer Trip	Direct fiber, SONET, PLC, 4WVF	Mirrored Bits C37.94	RS-232 G.702 4WVF RS-422 G.703	Not sensitive	20 ms	8 ms	
Current Differential	Direct Fiber, SONET, Leased T1	Mirrored Bits C37.94	RS-422 or G.703	Very Jitter Sensitive, 100 µs max	25 ms	8 ms	Channel delay symmetry (1-1.5 ms max)
Direct Transfer Trip	Direct fiber, SONET, T1 Network PLC 4WVF	Serial C37.94	RS232 G.702 4WVF	Not sensitive	40 ms	8 ms	

Table 1 - Protection Scheme Network Parameters

Traditionally, utilities have provided communications service with TDM networks or direct fiber channels. TDM technologies like Synchronous Optical Networking (SONET) and Synchronous Digital Hierarchy (SDH) provide predictable and deterministic latency and bandwidth performance that is crucial to TPR applications.

With the introduction of packet-based communications, companies have experienced reduced cost, increased capacity and increased reliability. Packet-based networks allow for the convergence of multiple application-specific networks into a single common network infrastructure for all voice data and video needs. As demand for the TDM architecture falls, communication equipment manufacturers are focusing on packet-based network technology. As a result, the ability to purchase and support TDM equipment such as SONET multiplexers and TDM radios will diminish with time. For utilities, the challenge that comes with a packet-based network is to attain deterministic network performance. Due to the potential tradeoffs, utilities are approaching the use of packet technology for TPR applications with due caution.

Nokia's TDM-based MDR 8000 microwave radio has a long track record of deployment by electric utilities. The MDR 8000's successor, the 9500 MPR, is an all-packet IP microwave transport platform that supports both Ethernet and TDM (DS1, DS3, and OC3) applications and was introduced in 2009. The 9500 MPR includes provisions for packet prioritization while minimizing packet delay variation (PDV). The 9500 MPR employs quality of service (QoS) features that allow ingress traffic to be classified and assigned to different queues, with each queue providing a set level of service. TDM traffic is packetized by the 9500 MPR using circuit emulated service over Ethernet technology (CESoETH) and is automatically assigned to the highest priority queue. In this way, the TDM packets are always serviced first even during heavy network congestion. On a typical packet-based system, there is a probability that higher priority TDM service packets arrive in the egress queue while the radio is in the middle of transmitting a large, lower priority frame. This phenomenon is known as head-of-line (HOL) blocking. Depending on the size of the lower priority frame, the higher priority frame would typically be required to wait a varying amount of time before being serviced, resulting in a higher PDV. The 9500 MPR mitigates this effect by fragmenting lower priority frames and interleaving the higher priority frames. Since these fragments are uniform in size, the maximum queuing delay is static and PDV is minimized.

Delay symmetry is addressed by the 9500 MPR by ensuring that all traffic flows bi-directionally using the same congruent path. In the case where radios are to be connected using a ring topology, the MPR uses Ethernet Ring Protection Switching (ERPS) that complies with the ITU-T G.8032 recommendation. ERPS is a high-speed ring blocking protocol with improved performance over traditional loop blocking protocols like Rapid Spanning Tree. With ERPS, a link on the ring is chosen as a ring protection link that blocks traffic. As a result, all traffic in the G.8032 ring uses a single bidirectional path on the ring meaning that traffic in either direction has symmetrical latency.

Path failure detection and switch over in G.8032 rings can be configured to occur within 10 ms, exceeding the 50 ms SONET specification. This is accomplished by continuity check messages (CCM) that are sent every 3.3 ms. A counter at the receiver records lost CCM packets, and "fails" the link if three messages are lost, resulting in 10 ms failure detection and path switchover. ERPS also allows protected rings to be configured on a per-service basis. This allows the user to designate the path on the ring that optimally suits the particular application. For example, TPR channels can use the shortest and lowest latency path, while other services can use another topology.

3.0 TESTING OBJECTIVES

The objective was to test the 9500 MPR against the acceptable packet loss, latency, jitter, and delay symmetry requirements for electric utility TPR channels outlined in Table 1. Burns & McDonnell conducted the following tests:

- Radio system latency: Measure end-to-end latency with the Sunrise Telecom test set equipped with C37.94 modules. Measure latency with and without the 9500 MPR to determine the amount of latency introduced by the radio network. Measure latency using the SEL-411 relay's built-in COM 87L report tool to provide one way delay, delay symmetry, error count, maximum delay and maximum delay symmetry measured by the relay. Investigate the effect of adaptive modulation and modem delay, process and buffer delay, and the effects of various 9500 MPR settings.
- Delay symmetry: Measure channel delay symmetry using an IXIA test set and by the SEL 411L.
- Network timing: Verify that channel banks can loop time across the radio network using the 9500 MPR T1 interface. Verify that the 9500 MPR radios will pass Sync-E timing between two routers including timing quality level information.
- Network congestion: Use an Ethernet traffic generator to create congestion on the 9500 MPR and verify that the priority of the CESoETH channels is maintained and measure the resulting packet delay variation.
- Path fading effects: Test the effects of adaptive modulation on the latency and jitter of a TDM channel.

4.0 TEST ENVIRONMENT

4.1 Radio Equipment

A rack of Nokia 9500 MPR radios was staged in Burns & McDonnell's Grid Modernization Lab to perform the tests. The rack consisted of eight 9500MPT-HLC transceivers, four MSS shelves, required interface cards and cables for radio, T1, SONET, copper and fiber Ethernet connections, and path simulation boxes and attenuators. Figure 1 shows equipment staged in the lab.

Figure 1 - Staged 9500 MPR Rack in Test Lab

The testing rack was arranged for two testing configurations: an all-indoor three-hop linear unprotected network using the Nokia 9500 MPR MSS shelf to build TDM and Ethernet circuits, and a one-hop linear network of Nokia 7705 SAR-8 routers equipped with Packet Microwave Cards (PMC) connected to 9500 MPT-HLC indoor modules. Each of these configurations is illustrated in the following figures:

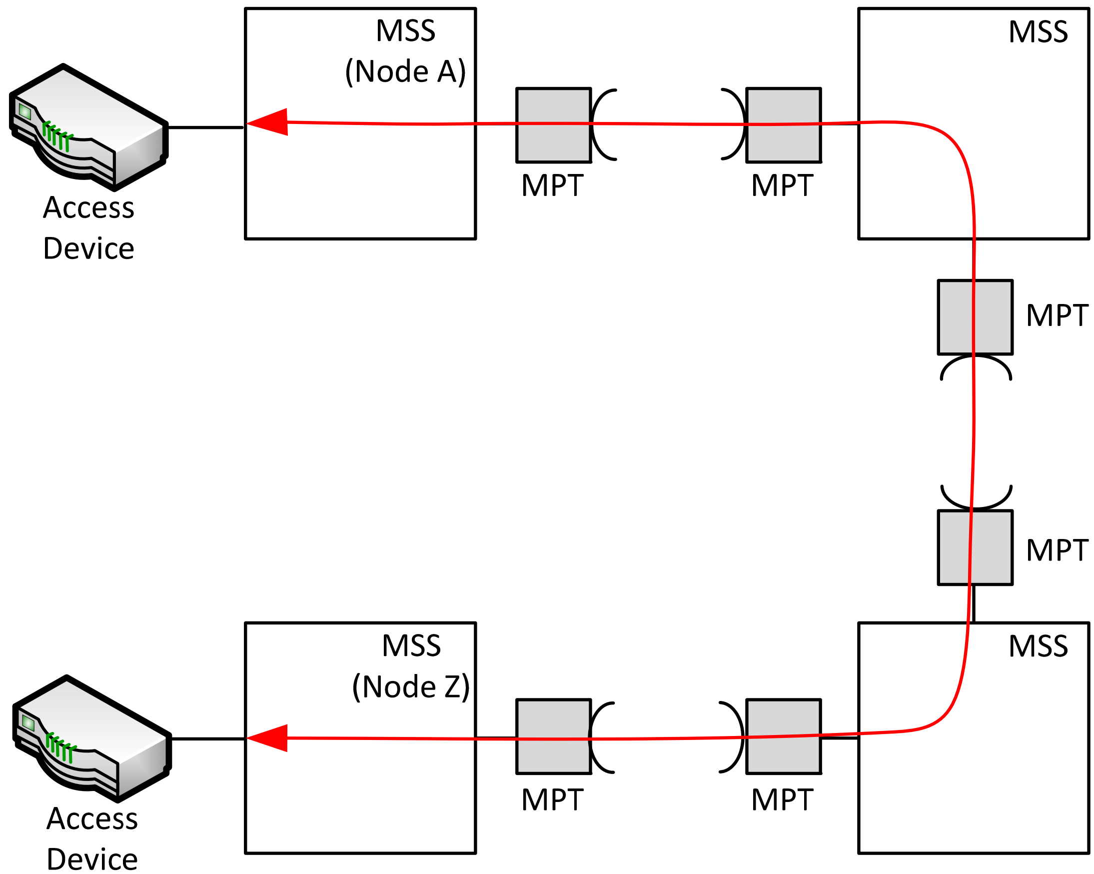

Figure 2 - Three-hop Unprotected Network with MSS

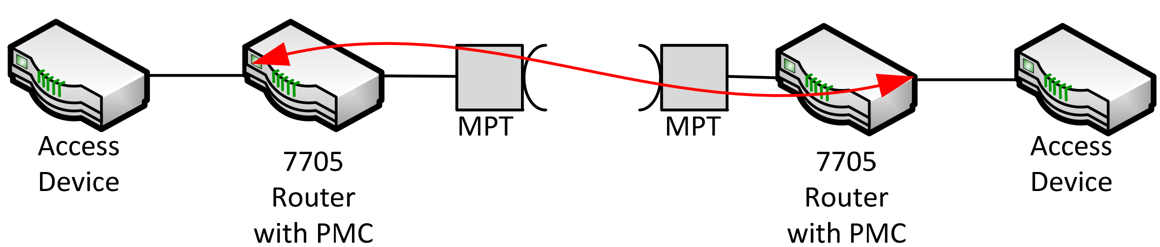

Figure 3 - One-hop with 7705 SAR-8 Packet Microwave Cards

Both Ethernet and TDM flows were provisioned across the radio system in each configuration. The first TDM T1 flow was provisioned to transport a TPR circuit using a channel bank. A second TDM T1 flow was provisioned to connect a T1 test set. In addition, several Ethernet flows were provisioned to transport traffic from an Ethernet traffic generator.

Figure 4 illustrates these connections and circuits.

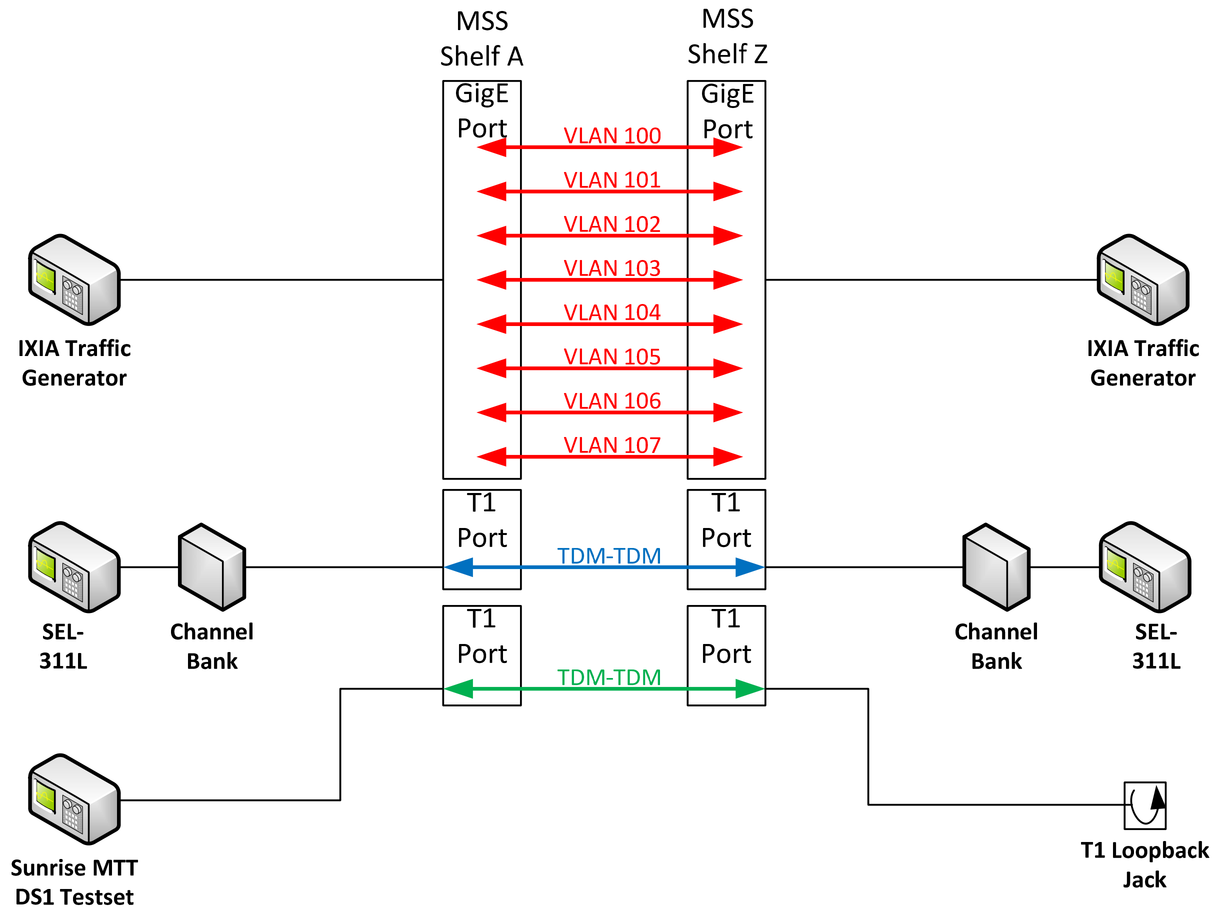

Figure 4 - Overview of Test Setup

The QoS settings on the 9500 MPR MSS reserve the three highest priority queues for TDM circuit emulation and network management, leaving the remaining five lower queues for Ethernet traffic. A T1 that enters the MSS shelf is packetized and automatically assigned to the highest QoS queue. This highest priority level exceeds the level of service provided for network control and management of the radios. Figure 5 shows the queues available.

Service type	Scheduler type	MPT QoS Priority	Weight	
CESoETH TDM-to-TDM	HPQ	#8 Highest	Strict Priority	
CESoETH TDM-to-ETH		#7	Strict Priority	
TMN		#6	Strict Priority	
Ethernet	DWRR or Strict Priority	#5	16	DWRR with adjustable weights
Ethernet		#4	8	
Ethernet		#3	4	
Ethernet		#2	2	
Ethernet		#1 Lowest	1	

Figure 5 - 9500 MPR QoS Queues

Eight different Ethernet flows were provisioned on a per VLAN basis between gigabit Ethernet ports on the radios on the each side of the system. The 9500 MPR MSS shelves were configured to map the Ethernet traffic based on the 802.1p bit classification and assign traffic to the following forwarding classes shown on Table 2.

802.1p Priority Bit Setting	QoS Priority Forwarding Class	Weight
7	5 (Highest Available)	16
6	4	8
5	3	4
4	3	4
3	2	2
2	2	2
1	1 (Lowest)	1
0	1 (Lowest)	1

Table 2 – QoS Forwarding Class Mapping on the 9500 MPR MSS

In the second radio configuration, Nokia's 7705 SAR-8 MPLS routers were equipped with packet microwave cards (PMC) that allow the routers to connect directly to the radios without the use of the MSS shelves. TDM and Ethernet circuits were provisioned on the MPLS routers using C-pipes and E-pipes, respectively. E-pipes and C-pipes were provisioned to provide circuit configuration shown in Figure 4. QoS policies were configured on the routers as follows:

```
sap-ingress 1900 create
            description "TDM cpipe Service SAP"
            queue 1 create
            exit
            fc "h1" create
                queue 1
            exit
            default-fc "h1"
            default-priority high
        exit
 sap-ingress 1901 create
            description "Ixia QoS Policy Mapping"
            queue 1 create
            exit
            queue 2 create
            exit
            queue 3 create
            exit
            queue 4 create
            exit
            queue 5 create
            exit
            fc "af" create
                queue 3
            exit
            fc "be" create
                queue 1
            exit
            fc "h2" create
                queue 5
            exit
            fc "l1" create
                queue 4
            exit
            fc "l2" create
                queue 2
            exit
            dot1p 0 fc "be" priority low
            dot1p 1 fc "l2" priority low
            dot1p 2 fc "af" priority low
            dot1p 3 fc "l1" priority low
            dot1p 4 fc "h2" priority low
            dot1p 5 fc "h2" priority high
            dot1p 6 fc "ef" priority low
            dot1p 7 fc "ef" priority high
        exit
```

Note that in the above QoS settings, “sap-ingress 1900” is the port-based ingress policy that is applied to all TDM ports and “sap-ingress 1901” is the port based ingress policy applied to the Ethernet ports.

Although 8 data streams were set up as was the case with the MSS testing, here the 7705 allows access to the top three queues that are fixed as strict priority in the MSS. Instead of having 8 flows mapped into 5 queues of Ethernet and the T1 traffic mapped into the highest strict priority, the test with the 7705 allowed some of the Ethernet traffic to access queue 6 of 8. Queue 6 in the MSS test would not pass anything but T1 traffic. In the case of the 7705 test, some Ethernet traffic would share one of the T1 queues.

4.2 Network Test Equipment

The IXIA network traffic generator pictured Figure 6 was used to inject Ethernet traffic streams into the radio system.

Figure 6 - IXIA Network Traffic Generator

The IXIA was configured to send 8 traffic streams using a VLAN-tagged gigabit Ethernet interface as shown in Table 3.

Stream ID	VLAN ID	802.1p Priority Bit Setting
1	100	0
2	101	1
3	102	2
4	103	3
5	104	4
6	105	5
7	106	6
8	107	7

Table 3 - IXIA Traffic Streams

The IXIA is capable of over-subscribing the maximum throughput available on the 9500 MPR by transmitting up to 1 Gbps of data. Based on the QoS policies configured, it was expected that the MPR would drop traffic starting with the lowest 802.1p bit-marked frames during network congestion. As the level of over subscription on the radio system increased, it was expected that the radio system would continue to drop frames in the higher priority queues. The packet size was varied for different tests. Each stream was configured to send a constant data rate using 64-byte frames, 1500-byte frames, and random frame sizes according to the Internet Mix (MIX) traffic profile. The IXIA was used to perform the following measurements for each data stream:

- System data throughput (bits/sec)
- Cut through latency (µsec)
- Sequence gaps (dropped packets)
- Packet inter-arrival time (µsec)

The Sunset MTT DS1 test set pictured in Figure 7 was used to closely monitor the performance of T1 circuits. Bipolar violation (BPV) and loss of frame (LOF) counters were monitored. On a T1 with B8ZS line coding as used in the lab setup, the test set expects to receive pulses of alternative polarity. A BPV error is recorded when a pulse is lost during transmission causing two pulses to arrive consecutively with the same polarity. LOF errors are recorded when the test set detects errors in the framing bits of the T1. If the TDM traffic experiences excessive latency or jitter as it is emulated over the packet network, then the test set will record LOF and BPV counts from lost bits and buffer slips on the T1.

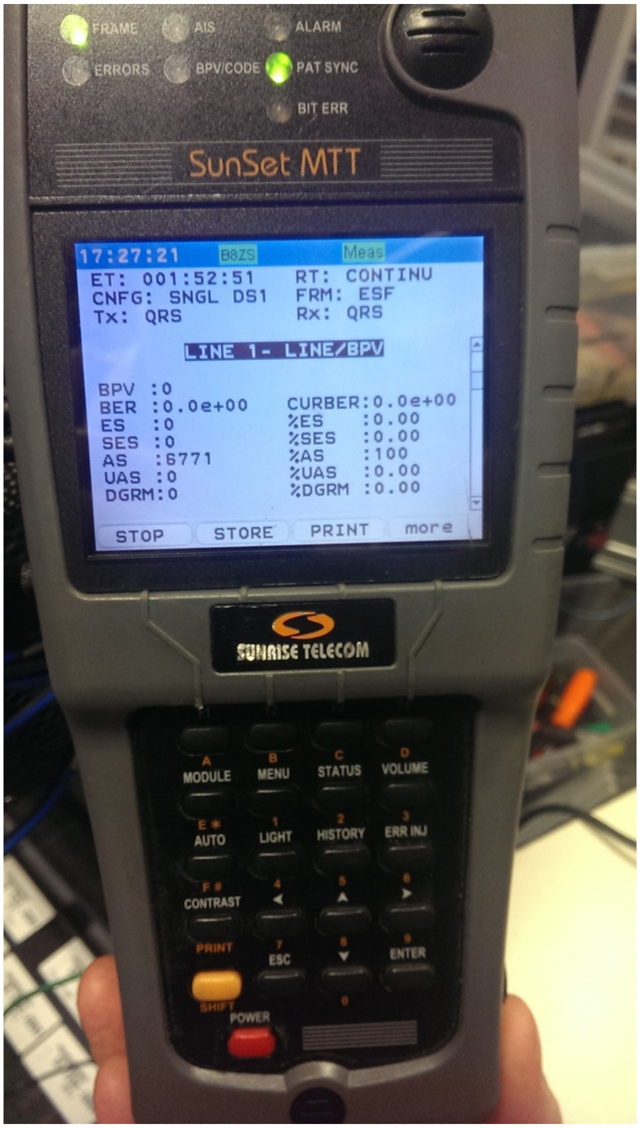

Figure 7 – Sunset DS1 Test Set

4.3 Piloted Relaying Equipment

Differential relays were chosen for this compliance testing because they have the strictest PDV and delay symmetry requirements. When differential relays were first developed, a copper pilot wire was connected between the relays and so the scheme expected zero latency between the relays. Modern differential relays eliminate the pilot wire and pass a digitized measured current value back and forth using a communications channel. If a single packet is lost due to a degraded communications channel, the relay will disable its 87L element for a minimum of 2 electrical cycles, or about 33 ms. This has a negative impact on the protection system's dependability, because the relays would not operate should a fault occur during the 33 ms.

Latency introduced in the communication channel reduces the relays' ability to accurately reconstruct the current vector received from the far end. To compensate, the relays must measure the channel latency and correct the incoming current vector accordingly. This latency is assumed to remain constant, and significant latency deviation is interpreted as a potential electrical fault. The maximum allowable latency deviation for current differential relay is 100 µs.

To model a piloted TPR channel, two separate pairs of relays were tested: a pair of SEL-411L differential relays and a pair of SEL-311L differential relays. A current differential relaying scheme was modeled in the lab using a 3-phase AC source, shorting test switches and relays as illustrated in Figure 8.

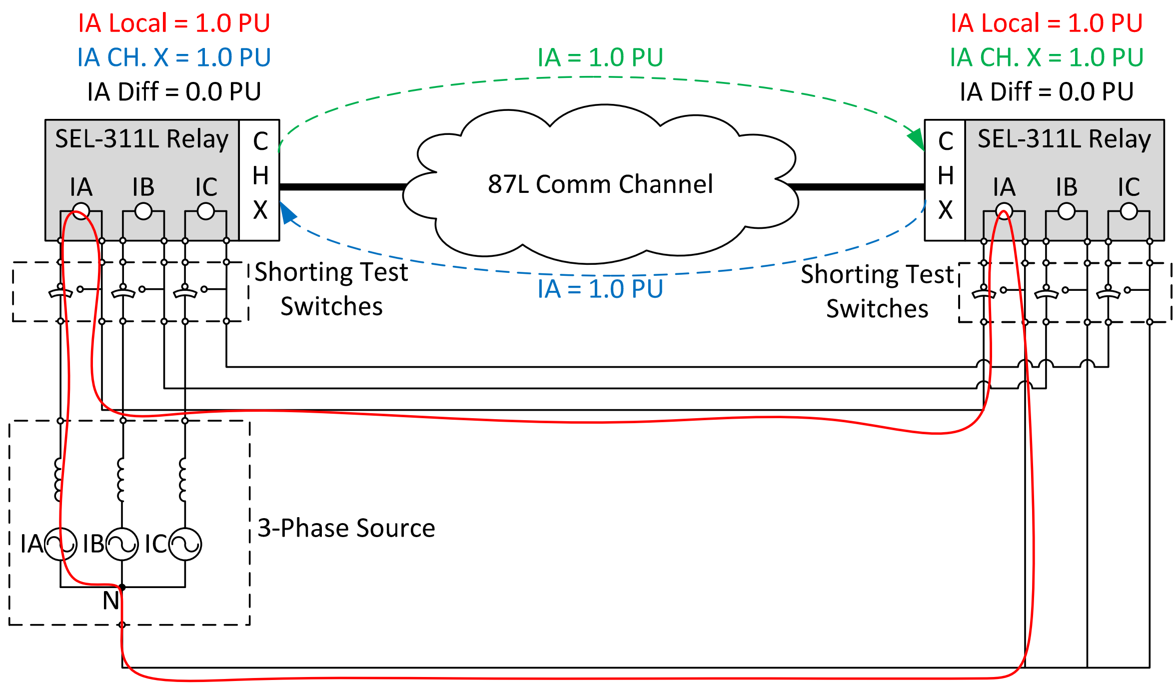

Figure 8 - Current Differential Lab Schematic

Both relays are wired in series with the 3-phase source in the lab. The red line in the schematic represents the path of the instrumentation current loop in the lab. During normal operation, both relays read a phase current of 1.0 per unit (PU) Amps on their IA input hard-wired to the current source and 1.0 PU Amps from the 87L communications channel, computing a difference of 0 PU Amps. A differential current is simulated by opening one of the shorting test switches. Figure 9 illustrates a simulated differential current.

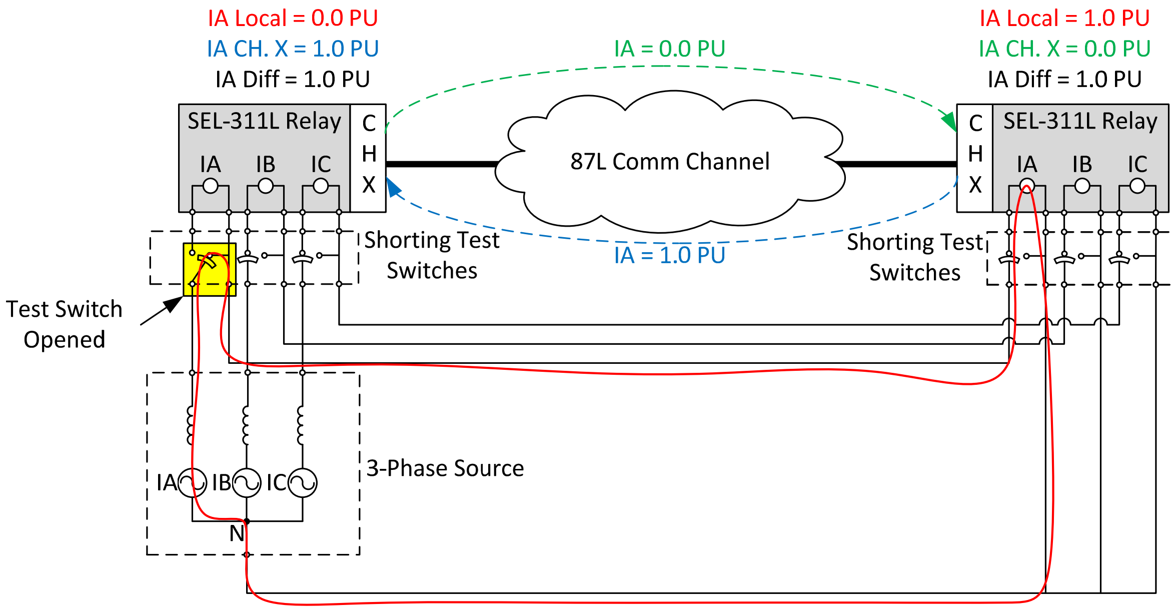

Figure 9 - Differential Current Simulation

When the test switch is opened, the current loop bypasses the relay creating an unbalanced differential current that causes the relay to operate.

Figure 10 shows the SEL-311L relay and test switches used to simulate the differential relaying scheme.

Figure 10 - Current Differential Relay

The time data used for latency compensation in the 87L communications channel can be viewed on the SEL-311 using the “COM X” command on the relay’s command line interface. This data was used frequently during testing to record the latency measured by the relay. Figure 11 shows a sample of this report.

```
COMMUNICATION LOG SUMMARY         COMMUNICATION STATISTICS
# of Error records    0           Last error
Data Error            0           Longest failure           0.000 sec.
Dropout               0           Lost Packets, prev. 24 hours         0
Test Mode Entered     0           One Way Delay (Ping-Pong)     4.8 msec.
```

Figure 11 - COM X Report on a SEL-311L Relay

If a GPS clock is connected to each relay, the SEL-411L relays can measure and compensate for channel delay symmetry. Similar to the COM X report, the SEL-411L has a "COM 87L" report that provides latency measurements as well as delay symmetry. A screenshot of the COM 87L report is shown below.

```
87L APPLICATION STATUS
                       2SD - Two terminals with dual serial channels
                       MASTER

MEDIUM/PROTOCOL        Configuration                   Status
Serial Channel 1       850nm C37.94 Fiber, 2SD Primary  OK
Serial Channel 2       850nm C37.94 Fiber, 2SD Standby  OK
Synchronization        Channel-based                   High precision

CHANNEL ADDRESSING
Local Address          1
Remote Address 1       2
Remote Address 2       2

STATISTICS             Channel 1          Channel 2
Channel Status         OK                 OK
Channel Role           In use             Available
2SD Role / 24hr Usage  Primary (100.0%)   Standby (0.0%)
Receive Status         OK                 OK
Synch Config           Channel-based      Channel-based
Synch Status           Channel-based      Channel-based
Synch Accuracy         High precision     High precision
Time Status            --                 --
High Lost Packet Count --                 --
High Latency           --                 --
High Asymmetry         --                 --
Round-Trip Delay (ms)    0.8                0.0
Transmit Delay (ms)      0.4                0.0
Receive Delay (ms)       0.4                0.0
Asymmetry (ms)           0.04               0.01
Lost Packet Count 40s  0                  0
Lost Packet Count 24hr 0                  0
```

.

Figure 12- COM 87L Report on a SEL-411L Relay

5.0 TEST RESULTS

5.1 Baseline Measurements

The 87L communications channel used by the SEL was initially connected using direct fiber to create the following baseline measurements for testing:

Latency (one way) = 0.6 ms

Delay Symmetry (measured as Asymmetry) = 0.0 ms

Next, the 87L channel was connected through a channel bank with a directly connect T1 cable to measure the following latency and asymmetry introduced by the channel bank.

Latency (one way) = 1.5 ms

Delay Symmetry (measured as Asymmetry) = 0.11 ms

*Delay Symmetry (measured as Asymmetry) = 0.13 ms through 3 hops of MSS and MPT-HLC*The latency values will be subtracted from any values measured during testing to determine the latency contribution solely attributed to the 9500 MPR. For example, by subtracting the direct fiber latency measurement reported by the relays from the latency measured when the circuit was connected through the channel bank, the resulting value was 0.9 ms. It is concluded that the minimum latency for the 87L communications channel is 0.6 ms and that the channel bank adds 0.9 ms of latency.

5.2 Network Congestion Testing

5.2.1 3-Hop Linear Radio Configuration with 9500 MPR MSS Units

The IXIA traffic generator was used to oversubscribe the 9500 MPR with eight traffic streams. Each stream had a unique 802.1p bit setting to allow the 9500 MPR to classify and prioritize the traffic flows. The radio path attenuation was minimized to allow the radio to operate at its peak modulation rate of 1024 QAM. Traffic generation on the IXIA was increased from 0 Mbps to the maximum aggregate rate of 950 Mbps distributed evenly as eight 118 Mbps streams. Table 4 shows the received data statistics recorded while the IXIA was transmitting 950 Mbps into the MSS shelf.

Stream ID/ 802.1p Priority	QoS Forwarding Class Assigned	Latency (ms)	Forwarding Class Throughput (Mbps)	Forwarding Class Throughput % of Total	Total # Frames Received	Sequence Gaps (Lost Frames)	Frame Loss Rate
0 (lowest)							
1	fc1	3139	7.319	3.2%	6,481,697	6,199,010	95.64%
2							
3	fc2	1519	14.641	6.5%	12,724,469	12,356,526	97.11%
4							
5	fc3	807.9	29.298	12.9%	25,113,394	12,700,220	50.57%
6	fc4	54.4	58.57	25.8%	33,264,360	1,223,738	3.68%
7 (highest)	fc5	2.48	117.1	51.6%	34,537,991	3,010	0.01%
Total			226.928		112,121,911	32,482,504	28.97%

Table 4 - Network Congestion Test Traffic Stream Measurements

Since 950 Mbps of traffic is being transmitted into a 227 Mbps communications link, the MSS shelf is required to prioritize and drop traffic at a rate of 723 Mbps. The “Forwarding Class Throughput % of Total” column data demonstrates that the radio is servicing each forwarding class as expected according to the weighting detailed in Table 2 because each queue is being provided half of the throughput of the next highest queue. Due to the non-strict fair weighting on QoS forwarding classes fc1 through fc5, packet losses were observed on forwarding class fc5, the highest available for Ethernet traffic. Since the MSS reserves the highest priority queues (HPQ) fc6, fc7 and fc8 for TDM traffic, the IXIA Ethernet test set data could not be sent over these queues and so the IXIA was not capable of monitoring these queues. It was expected that, due to the low frame loss rate of forwarding class fc5 and the strict servicing of the HPQ, no frame losses occurred on the TDM circuits. To confirm this hypothesis, the performance of these HPQ was measured using the T1 test set and through the SEL relay’s COM X report. Figure 13 shows the data output from the T1 test set for a congestion testing duration of 2.4 hours.

```
LINE 1- SUMMARY

NO ERROR
Lpp : 0.1 dB          FREQ : 1544039

LINE 1- LINE/BPV

BPV :0
BER :0.0e+00           CURBER:0.0e+00
ES  :0                 %ES   :0.00
SES :0                 %SES  :0.00
AS  :8633              %AS   :100
UAS :0                 %UAS  :0.00
DGRM:0                 %DGRM :0.00

LINE 1- ALARM

AISS:0                 LOSS:0
YELS:0                 LOFS:0
EXZS:0                 LDNS:0
AS  :8633              %AS :100
UAS :0                 %UAS:0.00

LINE 1- FRAME

FE  :0                 FER   :0.0e+00
OOFS:0                 CUFBER:0.0e+00
LOFS:0                 FSLIP :NOREF
ES  :0                 %ES   :0.00
SES :0                 %SES  :0.00
AS  :8633              %AS   :100
UAS :0                 %UAS  :0.00
```

Figure 13 - Sunset MTT T1 Test Set Congestion Testing Measurements

The 87L COM X channel measurement report on the SEL-311L taken during the same test is shown in Figure 14 below.

COMMUNICATION LOG SUMMARY		COMMUNICATION STATISTICS	
# of Error records	0	Last error	
Data Error	0	Longest failure	0.000 sec.
Dropout	0	Lost Packets, prev. 24 hours	0
Test Mode Entered	0	One Way Delay (Ping-Pong)	5.3 msec.

Figure 14 - Network Congestion Testing SEL-311L 87L Channel Report

No data integrity issues were observed on either the T1 test set or the SEL-311L during full network congestion while the 9500 MPR was actively dropping traffic from the highest priority IXIA Ethernet streams. The T1 test set showed zero loss of signal seconds (LOSS), zero loss of frame seconds (LOFS), and zero bipolar violations (BPV). The T1 test set showed available seconds (AS) of 8633 confirming that the test set was run for the entire 2.4 hour testing time with zero errors.

The SEL-311L recorded a one-way latency of 5.3 milliseconds. This latency remained constant as the traffic generation rate was increased on the IXIA. The SEL-311L reported zero lost packets, zero dropout errors, and zero data errors during the test period. In this testing scenario, the teleprotection traffic was sent over a T1 whose QoS was set for strict priority scheduling. Packets with strict priority scheduling are sent preferentially to all other queues, and this is why there were no packet losses, no dropout errors and no data errors. The Ethernet traffic was sent over DWRR (Deficit-Weighted Round Robin) queuing in which case packets in each queue have a weighting level (some queues have higher priority than others, but all queues are serviced). If the teleprotection traffic was to be sent over Ethernet, the queue carrying the teleprotection traffic would be configured for strict priority scheduling, in which case the teleprotection traffic would have priority always, despite whatever traffic was on any of the DWRR queues.

5.2.2 One-hop Radio Configuration with 7705 SAR-8 and PMC Cards

The same 8 IXIA traffic streams were transmitted over the radio setup that used the 7705 SAR-8 routers and PMC cards to replace the MSS shelves. In this case, the 7705 router and 9500 MPR were configured with QoS policies to place packetized T1 frames at the highest available priority queue. This queue was configured with strict priority scheduling, so that the T1 frames were excluded from participating in the fair weighted round-robin scheduling and servicing of non CESoPSN Ethernet frames. In addition, to mitigate the effect of head of line blocking, the strict scheduling of packetized TDM frames on the 9500 MPR makes use of High Queue Preempt (HQP) to keep PDV to a minimum. The IXIA recorded received data statistics for each priority level queue. As with the MSS shelf test setup, the 7705 SAR-8/PMC correctly prioritized traffic, by delaying and dropping frames starting with the lowest priority forwarding classes. Table 5 shows the latency and lost packet count reported by the SEL-311L as the IXIA traffic generation rate was increased. Delay Symmetry (measured as Delay Asymmetry) was 0.07 ms over the two 7705s using a8 vt cards to replace the channel banks.

IXIA Tx Rate (Range in Mbps)	SEL-311L Latency (ms)	SEL-311L Lost Packets	Note
0-210.6	3.6	0	All Ethernet Traffic Delivered
210.6-283	3.6	0	Queue 1 and 2 Frame Losses Start
283-460	3.6	0	Queue 3 Frame Losses Start
460-473	3.6	0	Queue 4 and 5 Frame Losses Start
473-950	3.6	0	Additional Ethernet Frame Loss in all Ethernet Queues, No Impact on 87L Channel or T1 Circuit

Table 5 – SEL-311L Relay Performance during Network Congestion with 7705 SAR-8 PMC

The SEL-311L relay channel performed flawlessly up to the maximum tested level of traffic oversubscription of 950 Mbps. At this maximum rate of Ethernet traffic running simultaneously over the microwave path with the TDM circuits being tested, the MPR was oversubscribed in excess of 4 times the maximum channel capacity. While this level of congestion should not occur on a properly engineered network, the event of such congestion has zero impact on the latency and reliability of TDM circuits provisioned on the 9500 MPR.

Comparing the performance of the 7705 SAR-8 with PMC cards to the MSS shelf configuration, the SEL-311L's 87L channel withstood the same level of congestion in both test cases. With either the MSS shelf or a 7705 SAR-8 router equipped with PMC cards, TDM traffic can be transported reliably under extraordinary levels of traffic congestion as long as the QoS capabilities of systems are engineered and implemented appropriately. In the test cases studied in this report, both the MSS test and the PMC card test implemented QoS policies that primarily performed two functions to maintain the dedicated level of service for TDM data:

1. The QoS policy assigned packetized TDM frames to use the highest available traffic queue by placing all Ethernet traffic in lower priority queues.
2. The traffic scheduler was set to strictly service the TDM queue. The requirement for the traffic scheduler to inspect and service Ethernet frames in lower queues using a weighted round robin discipline was removed.

Regardless of how much Ethernet traffic was sent or the priority marking that was placed on the Ethernet traffic, T1 traffic throughput remained constant.

5.3 Network Timing Testing

5.3.1 T1 Loop Timing

The test verifies that a channel bank can loop time using the T1 that traverses the 9500 MPR MSS shelf. A common concern is that excessive PDV can impair the recovered T1 clock rate required for synchronization. To mitigate the effect of PDV, the 9500 MPR uses differential clock recovery, a common reference clock frequency, and time stamps. At location A of the test setup, the channel bank was configured to use its internal oscillator to time its T1. At location Z the channel bank was configured to time the T1 using the incoming T1 provided across the 9500 MPR radio. During all tests that required use of the channel bank, this timing method was robust, and zero frame errors were observed on the T1.

5.3.2 Sync-Ethernet Timing and Timing Quality SSM Messaging

The 9500 MPR was tested to determine if two 7705 SAR-8 routers can synchronize over the radio link using synchronous Ethernet. A Symmetricom SecureSync Clock was connected to a router on one side of the radio link. The clock provided sync status messaging (SSM) to tell the router that it is a stratum 1 primary reference source (PRS). The second router was connected at the other end of the radio connection and configured to synchronize using its Ethernet connection to the radio. The second router was able to lock onto the reference source and collect SSM timing quality level information. Figure 15 illustrates the arrangement used to synchronize the routers across the radio system.

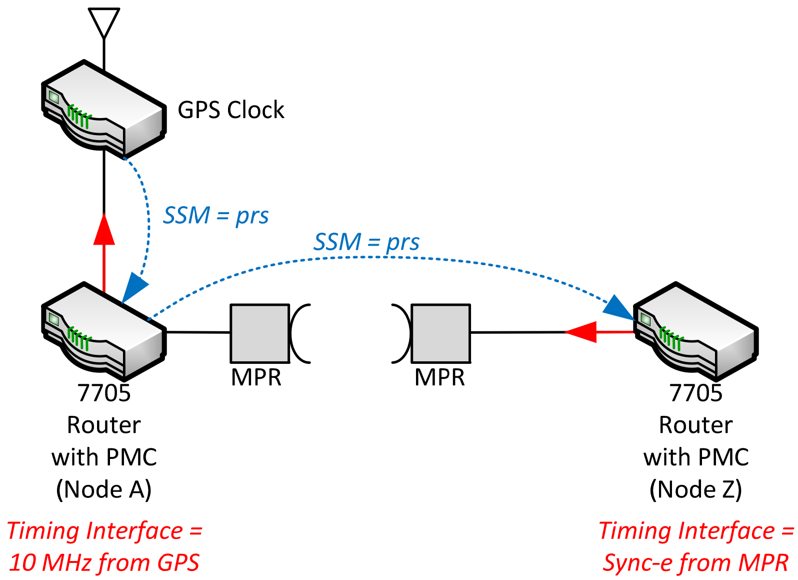

Figure 15 - Sync-E Timing over 9500 MPR

During testing of pseudowire services between the 7705 SAR-8 routers and the MPR, buffer underrun counters and overrun counters were monitored. At no time were any buffer slips observed during testing. It is concluded that synchronization can be successfully recovered across the MPR using synchronous Ethernet.

5.4 Radio System Latency Testing

Table 6 outlines the latency that was recorded in each of the test scenarios.

Line	Test Setup	Latency (ms)	Latency Contributed by 9500 MPR (ms)	Notes
1	SEL Relay → Direct Fiber → SEL Relay	0.6	N/A	Baseline Measurement
2	SEL Relay → Channel Bank → SEL Relay	1.5	N/A	Baseline Measurement to Subtract from Line 3, 4 and 5 Latency
3	SEL Relay → Channel Bank → MSS TDM-TDM Flow → Channel Bank → SEL Relay	5.3	3.8	
4	MTT C37.94 Set → Channel Bank → MSS TDM-TDM Flow → Channel Bank → Fiber Loopback	5	3.5	1 ms measurement resolution
5	SEL Relay → Channel Bank → SAR-8 Router → PMC Card/ MPR → SAR-8 Router → Channel Bank → SEL Relay	3.6	2.1	
6	SEL Relay → a8-VT SAR-8 Card → SAR-8 Router → Fiber → SAR-8 Router → a8-VT SAR-8 Card → SEL Relay	3.5	N/A	Baseline Measurement To Subtract from Line 7 Latency
7	SEL Relay → a8-VT SAR-8 Card → SAR-8 Router → PMC Card/ MPR → SAR-8 Router → a8-VT SAR-8 Card → SEL Relay	3.9	0.4	The a8-vt card provides a C37.94 interface directly on the 7705 SAR-8 Router

Table 6 - Summary of Latency Measurements for All Test Configurations

The latency contribution from the 9500 MPR is caused by packetization of the TDM channel at the ingress of the network, modem latency across each link, air delay as the signal propagates between each radio, and process and buffer delay when the data is converted back into a TDM signal at the network egress. In each of the cases, the end to end latency measured by the SEL relays was below the maximum recommended channel latency for TPR circuits.

5.5 Path Fading Testing

A variable path attenuator connected across one of the radio hops was used to fade the radio path. By fading the path, the radio is forced to jump to lower modulation levels to accommodate lower received signal strength while maintaining adequate bit error rate. This test verifies that the radio can switch modulation levels with no effect on the TDM traffic flows and that the SEL-311L reports a consistent latency and zero dropped 87L packets. Note that this test was performed while congesting the radio network by injecting 900 Mbps of data using the traffic generator. This level of traffic over subscription is much greater than would be expected on a properly engineered communication network, however it can occur due to user error like connecting a loop in a Layer 2 broadcast network. Table 7 shows the measurements recorded as attenuation was slowly added to the radio system during a single test:

Additional Path Loss Set on Path Box (dB)	Radio Modulation Level	IXIA Traffic Output (Mbps)	Throughput Observed (Mbps)	Over-subscription Multiplier	SEL-311L Latency (ms)	SEL-311L #Lost Packets	T1 Test Set Loss of Frames (LOF)	T1 Test Set Bipolar Violations (BPV)
0	1024 QAM	900	227	3.96	5.3	0	0	0
22	512 QAM	900	206	4.37	5.3	0	0	0
25	256 QAM	900	182.5	4.93	5.3	0	0	0
29	128 QAM	900	160	5.63	5.3	0	0	0
32	64 QAM	900	135	6.67	5.3	0	0	0
35	32 QAM	900	112	8.04	5.3	0	0	0

Table 7 - Path Fading and Adaptive Modulation Test Results

The modulation level of the radio dropped as attenuation was increased resulting in a lower throughput as expected. During all modulation level transitions, there were zero loss of frame errors and zero BPVs observed on the DS1 test set. This was also expected since the DS1 traffic had a strict priority and would be passed before any Ethernet traffic. The measured channel latency on the SEL-311L was a constant 5.3 ms. Subtracting the channel bank latency of 1.5 ms, the latency impact of the radio system was recorded as a stable 3.8 ms. Packet losses on the 87L channel were zero throughout the entire test.

5.6 Packet Delay Variation Measurement

On the MSS, the top three queues are reserved for TDM traffic (in this case T1 traffic). They are assigned as strict priority, meaning that any TDM packet will be transmitted as soon as it comes in, to the exclusion of any other packet. There is no Ethernet traffic on the strict priority queues. Packet Delay Variation is not a measurement available on the TDM T1 test set, so when T1 traffic is packetized, PDV cannot be directly measured. Instead, the effect of PDV can be observed. According the manufacturer's data, a PDV in excess of 100 μs would trip the SEL-411L and 311L relays and a PDV in excess of 130 μs would trip the GE L90 differential relay. The PDV experienced during testing was not sufficient to trip any relays and zero 87L packet losses occurred.

For Ethernet streams on the MSS, PDV could be calculated from direct measurements. The PDV (also referred to as Jitter) was measured on the IXIA by recording the inter-arrival time of frames transmitted at a precise frame rate. The IXIA records the minimum and maximum frame inter-arrival time. The difference between the maximum and minimum inter-arrival time is then calculated to determine the peak-to-peak packet inter-arrival jitter. To maintain jitter measurement accuracy in the event that a frame is dropped, the IXIA performs sequence number checking on incoming frames so that measurements are only taken on sequential packets. The traffic streams and 9500 MPR were set up in a number of configurations during this test to measure the effect of varying packet sizes and amount of traffic.

Table 8 shows the Jitter (PDV) measurements using circuits provisioned on the MSS shelf with three radio hops:

IXIA Tx Rate (Mbps)	230	230	1000	1000
Steam Packet Size (bytes)	1514	IMIX	1514	IMIX
Stream ID/Priority Queue Level	**Inter-Arrival Max-Min (ms)**	**Inter-Arrival Max-Min (ms)**	**Inter-Arrival Max-Min (ms)**	**Inter-Arrival Max-Min (ms)**
1	0.11124	2.04368	Not Recorded	1.93244
2	0.29021	1.79268	Not Recorded	1.50247
3	0.13392	1.30668	Not Recorded	1.17276
4	0.44497	1.27362	Not Recorded	0.82865
5	0.3699	0.8874	Not Recorded	0.5175
6	0.22448	1.11272	Not Recorded	0.88824
7	0.13826	0.59982	Not Recorded	0.46156
8	0.1123	0.37884	Not Recorded	0.26654

Table 8 - Max Jitter under Various Conditions Using 9500 MPR MSS Shelf

The data in Table 8 shows that Jitter (PDV) is minimal when all traffic has an identical frame size. When network traffic consists of a blend of frame sizes, jitter increases significantly. The amount of PDV also decreases as the priority queue increases. This is illustrated below in Figure 16.

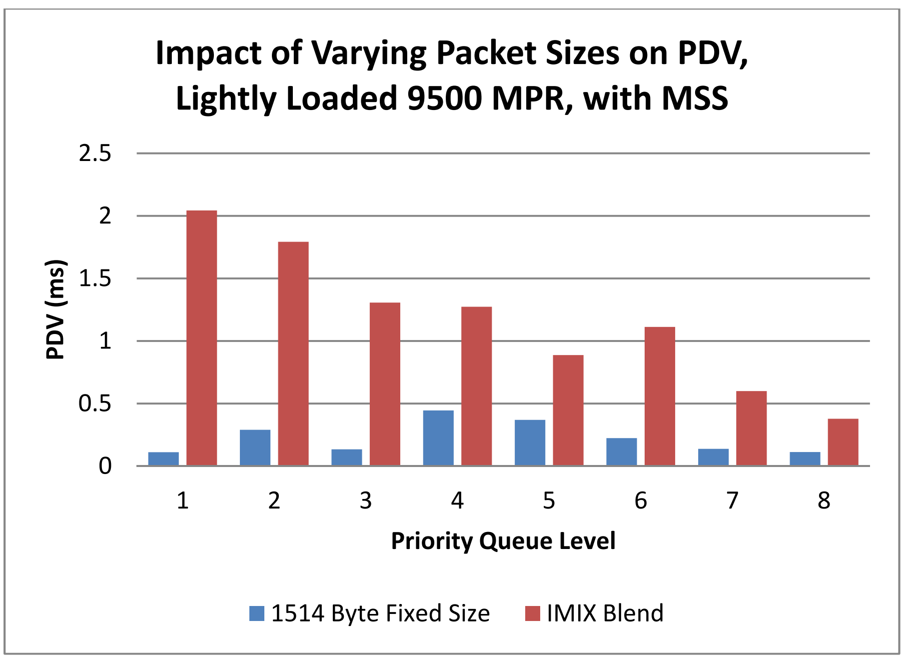

Figure 16 – Impact of Varying Packet Sizes on PDV

Table 9 shows the PDV measurements using circuits provisioned on the 7705 SAR-8 equipped with PMC cards over a single radio hop.

IXIA Tx Rate (Mbps)	50	50	230	230	1000	1000
Steam Packet Size (bytes)	1514	IMIX	1514	IMIX	1514	IMIX
Stream ID/Priority Queue Level	**Inter-Arrival Max-Min (ms)**	**Inter-Arrival Max-Min (ms)**	**Inter-Arrival Max-Min (ms)**	**Inter-Arrival Max-Min (ms)**	**Inter-Arrival Max-Min (ms)**	**Inter-Arrival Max-Min (ms)**
1	0.14742	0.82418	0.07182	0.82694	Not Recorded	4.0577
2	0.07404	0.9074	0.54448	1.63924	Not Recorded	4.47012
3	0.06948	0.92888	0.58036	2.07656	Not Recorded	5.90268
4	0.07344	0.8818	0.1676	0.80566	Not Recorded	2.54778
5	0.13834	0.68852	0.08016	0.45062	Not Recorded	1.2296
6	0.09332	0.76876	0.07822	0.53854	Not Recorded	2.71634
7	0.09282	0.54864	0.08158	0.29726	Not Recorded	0.99116
8	0.11234	0.66068	0.08216	0.38454	Not Recorded	0.78956

Table 9 - Max Packet Delay Variation under Various Conditions Using 7705 SAR-8 PMC Cards

Again, PDV is minimized when the traffic stream was held at a constant frame size. PDV increased when the traffic stream included a blend of frame sizes. This is shown in Figure 17.

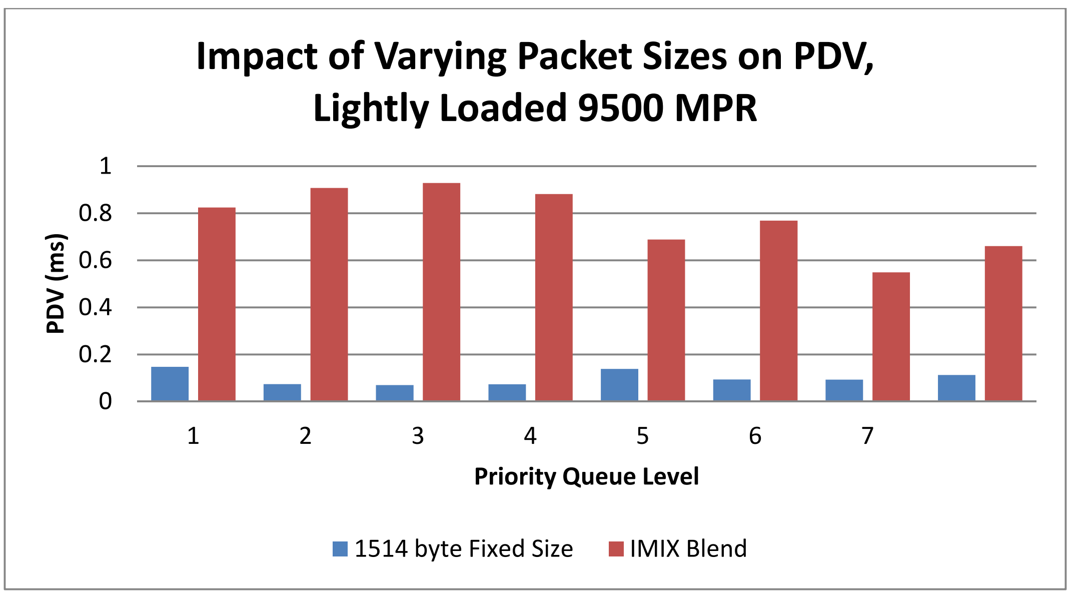

Figure 17 – Impact of Traffic Frame Sizes on PDV

As the traffic sent over the 9500 MPR increases from 20% to 100% utilization, PDV increases in the lower priority queues, but remains approximately constant for higher priority queues as shown in Figure 18.

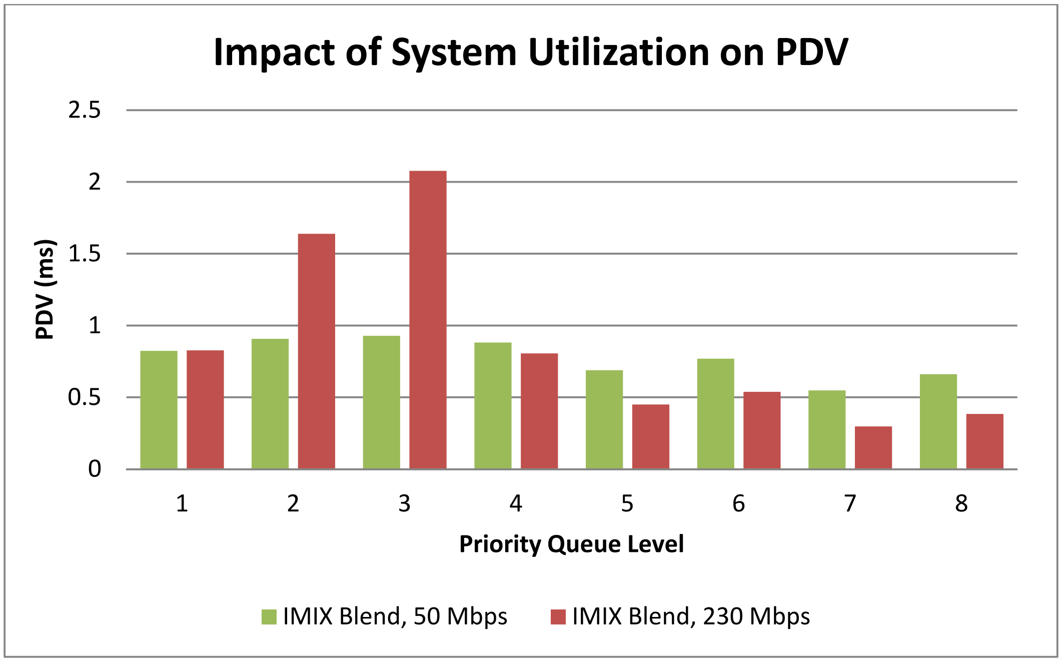

Figure 18 – Impact of System Utilization on PDV

TDM circuits are not affected since PDV observed across the 9500 MPR is significantly less than its 1.1 ms TDM buffer. PDV is maintained at a constant level for high priority traffic during network congestion with a wide variety of packet frame sizes.

6.0 CONCLUSION

Tests performed to simulate a utility operations environment and measure the performance of the 9500 MPR radio for radio system latency, delay symmetry, network timing, network congestion and path fading effects were all completed successfully. Using the 9500 MPT-HLC with the MSS shelf, a traffic oversubscription of more than 4 times the nominal carrying capacity of the link, had no effect on the T1 traffic or the Transfer Trip. When the 9500 MPT-HLC was coupled with the 7705 SAR-8, the configuration allowed Ethernet traffic and T1 traffic to be mixed, and at an oversubscription rate of more than 4 times the nominal carrying capacity of the link, the 311L differential relay performed without interruption. It is recommended that the T1 traffic must remain as a strict priority and not be mixed with Ethernet traffic to ensure that Transfer Trip traffic not be interrupted under any possible condition. Both the 7705 SAR-8 and the 9500 MPR MSS shelf can be configured to provide the necessary strict priority scheduling on the packetized T1 circuits. The 9500 MPR provided circuit-level QoS for its TDM flows, and in all test cases demonstrated performance that exceeded the operating requirements of TPR circuits. The following table summarizes the testing results and compares the results to the recommended communications parameters for TPR circuits.

Testing Parameter	Passing Requirement	Testing Observation	Result
Radio System Latency	< 8 ms system latency	9500 MPR contributed 2.1-3.8 ms	PASS
Delay Symmetry	< 1.5 ms for current differential	the channel bank reports asymmetry ranges and displayed 100% of the readings in the 0-0.25 ms range	PASS
Network Timing	T1 loop timing and sync-Eth functionality over 9500 MPR	T1 loop timing and Sync-E successfully passed across 9500 MPR	PASS
Network Congestion	Congestion to have no impact on TDM traffic	TDM traffic not impacted by severe network oversubscription as long as Ethernet traffic is not allowed to share the dedicated T1 Queues.	PASS
Path Fading	Path fading and adaptive modulation to have no impact on TDM traffic	TDM traffic not impacted by severe path fading	PASS
Packet Delay Variation	< 100 µs for current differential 87L measurement packets	Although PDV on T1 circuits could not be directly measured, transfer Trip operated normally, indicating PDV remained below the 100 µs limit.	PASS

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