

MPLS NETWORKS FOR INTER SUBSTATION COMMUNICATION FOR CURRENT DIFFERENTIAL PROTECTION APPLICATIONS IN DIGITAL SUBSTATIONS

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Abstract

Surveillance video, data security, access controls, data exchange and communications are just a few examples of the networked services that are part of modern digital substations. The need to provide services with different requirements and constraints has pushed for the development of new transport networks. Multiprotocol Label Switching (MPLS)-based Packet Switched Networks (PSN) are designed specifically to provide a single platform that can adapt to the needs of any kind of service that is required to be provided end to end. MPLS significantly extends the capabilities of native Ethernet transport by providing traffic separation and virtualization for wide-area point-to-point, point-to-multipoint and multipoint-to-multipoint services; traffic engineering, dedicated bandwidth services, a variety of network topologies, including redundancy, and many other benefits - all in a single network.

This paper details the results of testing a line current differential system on a MPLS based Ethernet PSN. This paper demonstrates the use of MPLS to meet the stringent requirements of current differential protection and how an MPLS network can be adapted to reliably support the needs of line current differential protection, with empirical results recorded in a simulation environment, whilst improving the system reliability and efficiency compared with conventional approaches.

1 Line Differential Protection

1.1 Line Differential Operation

Current differential protection is based on Kirchhoff's current law. IEDs in different parts of the network analyse the vector sum of the measured currents and detect faults in the protected area.

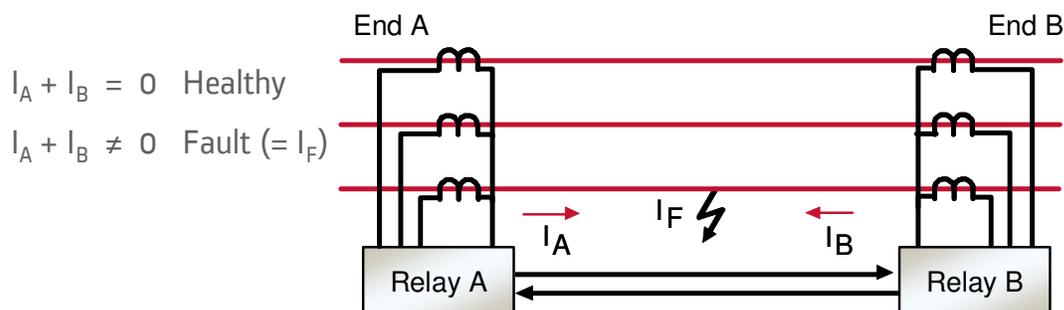


Fig. 1. Line differential protection principal

To perform the differential function, the samples, at different ends, need to be compared at the same instant of time because the propagation delay introduced by the communication media can cause spurious differential trip.

To avoid this problem and compensate the propagation delay, the Alstom relays use one of the following techniques to calculate the differential current. Common time source referenced (e.g., GPS-synchronized) relays with time stamped current vectors, or Asymmetrical sampling with a ping-pong delay measurement technique when GPS reference is unavailable.

For each application, there are certain requirements for the communications network to achieve a reliable vector exchange.

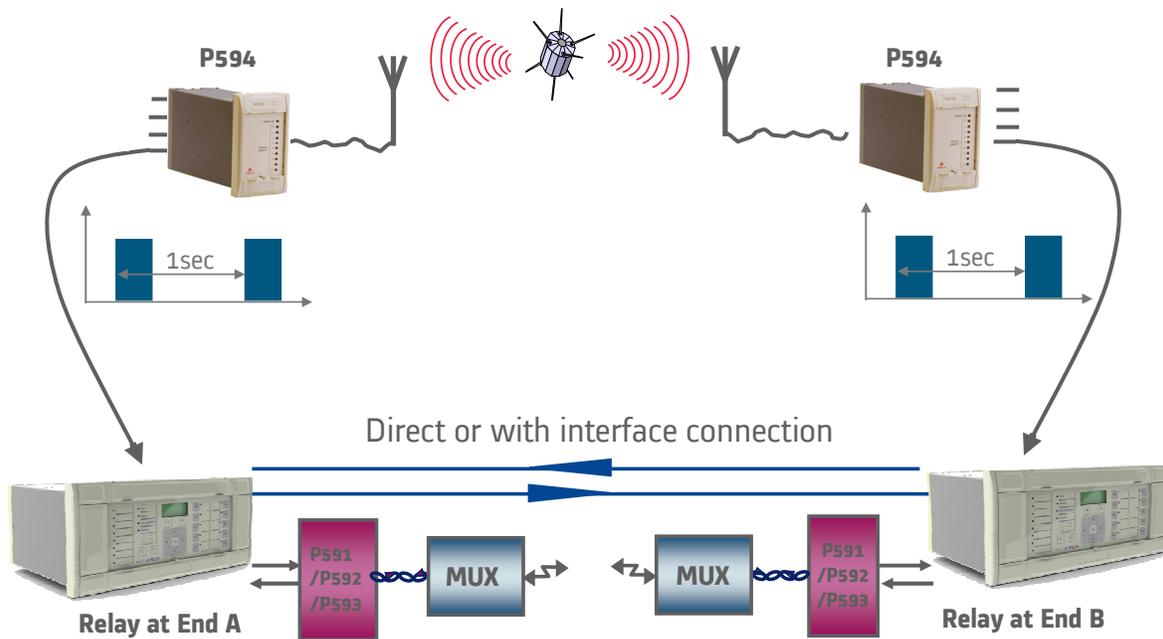


Fig. 2. GPS-synchronised scheme

The paper defines how an MPLS network can be adapted to provide a solution for each requirement, and will show empirical results recorded in a laboratory environment using commercially available hardware.

1.2 Communication Channel Requirements for Line Differential

Line differential protection imposes very strict requirements from communications system for the following parameters: low latency, latency symmetry, and low jitter. Of these three parameters, latency symmetry, and low jitter are only applicable to line differential protection schemes that rely on asynchronous sampling (ping-pong technique). However, most line differential protection schemes deployed using GPS assist are configured to fallback to asynchronous sampling to protect against GPS signal failure. In such situations, the MPLS network must be reliably engineered to minimize latency and jitter, while providing path symmetry.

Communications channel latency impacts the time it takes for the datagram encoding the current samples to make it across to the remote end for comparison, thereby impacting the time it takes the relay to detect the presence of a fault differential.

Latency asymmetry and jitter only impact line differential operation when asynchronous sampling is used.

Asynchronous sampling is based on a continual time difference measurement, and vector transformation performed by the differential function to align current samples. Time difference measurement is performed

based on a technique know as the ping-pong scheme, which averages the delay between send and receive times, assuming symmetrical latency in Tx and Rx directions between the two relays. The presence of asymmetrical delay in the receive and transmit directions result in incorrect vector alignment, which manifests as a false differential current, and may result in a false tripping of the protection.

Similarly, the presence of jitter in the communications channel leads to a constant change in the average delay computation. The time difference between two consecutive telegrams must be the most constant possible to avoid an incorrect vector alignment and hence incorrect differential current.

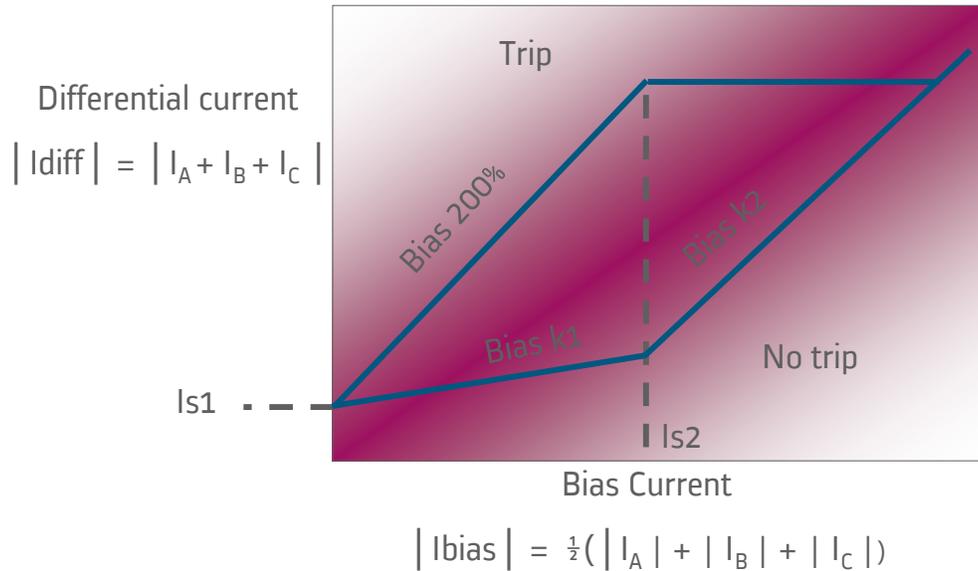


Fig. 3. Line differential restrain algorithm

The relays can be configured to tolerate up to 1msec change in propagation time. When change in propagation time on the communication channel exceeds this value, the relay will change the line differential protection to a self-restrain algorithm as shown in Fig. 3, with reduced sensitivity of the differential function.

Disturbances in data link and data conversion are supervised by the line differential function and typically the function is setup to tolerate a 25% loss of telegrams within a 100msec window size before the differential scheme starts running in a “Degraded Mode” with a consequent delay to the tripping time. The relays will restore the normal operation mode after 300ms if communications is restored.

2 Line Differential Protection over IP/MPLS

The tests were performed using Alstom MiCOM P545 Differential Protection relays with two different types of interfaces between the relays and the MPLS nodes to validate Line Current Differential Protection over MPLS/IP WAN.

2.1 Line Differential Configuration

Figures 4 and 5 show the communication channel and the differential functions setting configured on the Alstom MiCOM P545 Differential Protection relays.

Communication Channel Settings

| | | MiCOM AGILE | S1 |
|------------------|------------------|----------------|-------|
| PROT COMMS/ IM64 | | | |
| ..... | Scheme Setup | Dual Redundant | 20.01 |
| ..... | Address | 1-A | 20.03 |
| ..... | Comms Mode | Standard | 20.10 |
| ..... | Baud Rate Ch1 | 64kbits/s | 20.11 |
| ..... | Baud Rate Ch2 | 64kbits/s | 20.12 |
| ..... | Clock Source Ch1 | External | 20.13 |
| ..... | Clock Source Ch2 | External | 20.14 |
| ..... | Comm Delay Tol | 350.0 us | 20.17 |
| ..... | Comm Fail Timer | 10.00 s | 20.18 |
| ..... | Comm Fail Mode | Ch 1 or 2 Fail | 20.19 |
| ..... | GPS Sync | GPS Disabled | 20.1A |
| ..... | Char Mod Time | 500.0 ms | 20.1B |
| ..... | Alarm Level | 25.00 % | 20.1F |
| ..... | Prop Delay Stats | Enabled | 20.20 |
| ..... | MaxCh1 PropDelay | 15.00 ms | 20.21 |
| ..... | MaxCh2 PropDelay | 15.00 ms | 20.22 |

Fig. 4. Line differential communication configuration

Differential Function Settings

| | | MiCOM AGILE | S1 |
|----------------------|------------------|----------------|-------|
| GROUP 1 CURRENT DIFF | | | |
| ..... | Phase Diff | Enabled | 33.01 |
| ..... | Phase Is1 | 200.0 A | 33.06 |
| ..... | Phase Is2 | 2000 A | 33.07 |
| ..... | Phase k1 | 30.00 % | 33.08 |
| ..... | Phase k2 | 150.0 % | 33.09 |
| ..... | Phase Char | DT | 33.0A |
| ..... | Phase Time Delay | 0 s | 33.0B |
| ..... | PIT Time | 200.0 ms | 33.0E |
| ..... | Ph CT Corr'tion | 1.000 | 33.0F |
| ..... | Compensation | None | 33.10 |
| ..... | PIT I selection | Remote | 33.17 |
| ..... | Transient Bias | Disabled | 33.38 |
| ..... | NEUTRAL DIFF | | 33.3F |
| ..... | In Diff | Disabled | 33.40 |
| ..... | Ph Diff Stub Bus | Disabled | 33.60 |

Fig. 5. Line differential function configuration

During all tests, the test centre (an RTDS or Omicron test equipment) injected three phase currents and voltages into the relays to test the stability of the differential function, under various communications schemes. The hardware in the loop arrangement is illustrated below:

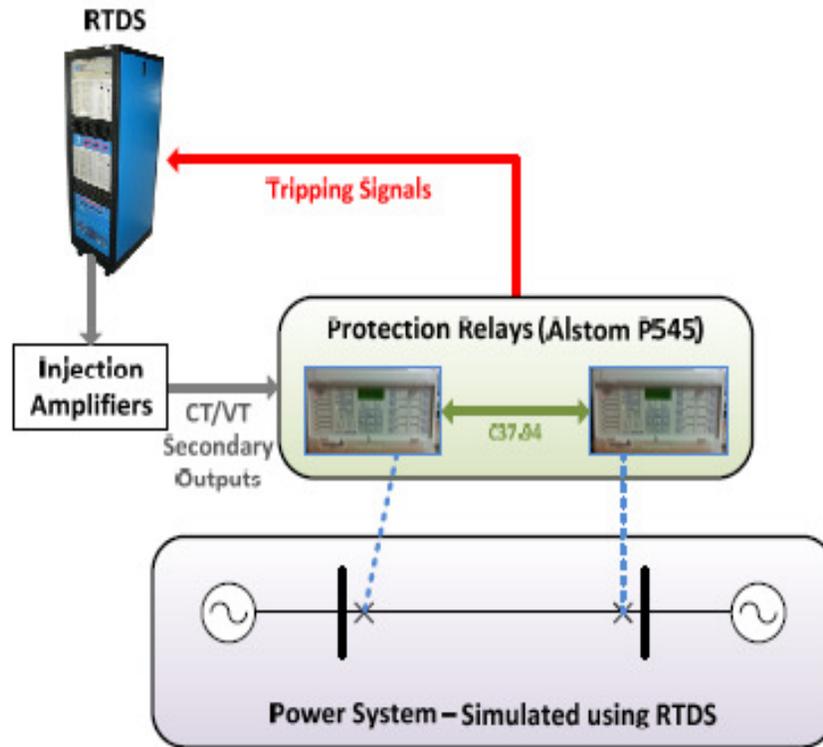


Fig. 6. Secondary injection scheme

2.1.1 Alstom - Cisco Configuration

The first configuration involves using Alstom Serial Converters to convert the 64kbps optical signal (data rate from Alstom relays over the optical interface is 64kbps) into a 2 Mbps E1 clear channel signal and CISCO ASR-903 routers.

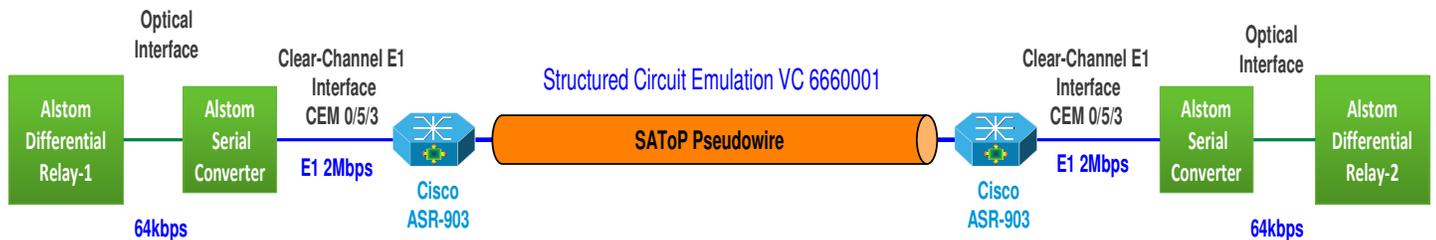


Fig. 7. Alstom-Cisco scheme configuration

The ASR-903 substation routers enable TDM Circuit Emulation for transporting E1 relay telegrams to the remote end using a MPLS based Structure-Agnostic TDM over Packet (SAToP) pseudowire. The SAToP pseudowire de-jitter buffer was configured at 1msec and the pseudowire is carried over RSVP TE tunnels using explicit routing to ensure symmetrical forward and return paths. The substation routers perform hardware based forwarding and Quality of Service (QoS) scheduling. The platform supports two low-latency high-priority QoS queues PQ1 and PQ2. The line differential datagrams on the SAToP pseudowire are always mapped to Priority Queue 1 (PQ1) to guarantee a low-latency, low-jitter, Expedited Forwarding (EF) behavior in the network.

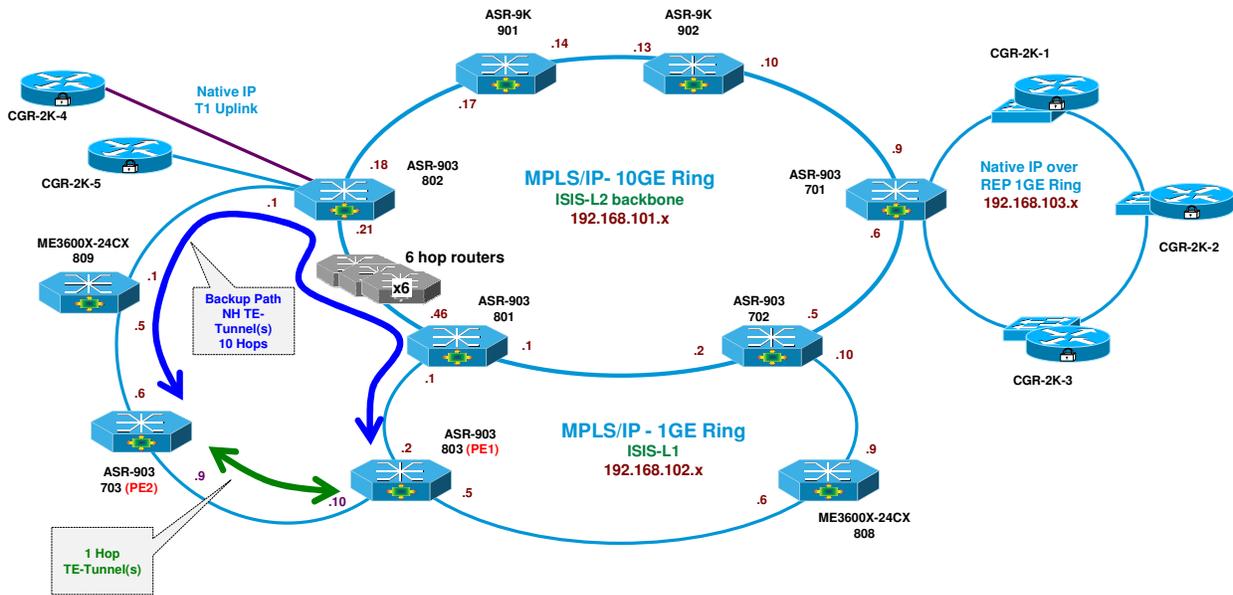


Fig. 8. Fist IP/MPLS scheme configuration

The substation routers are frequency synchronized for TDM circuit emulation using SyncE and TE-FRR protection is used to achieve sub 50msec recovery against failures in the transport network.

2.1.2 Alstom – Alcatel-Lucent Configuration

The second configuration involves using frames in IEEE C37.94 interface format between the line differential relays via the Alcatel-Lucent 7705 SAR routers.

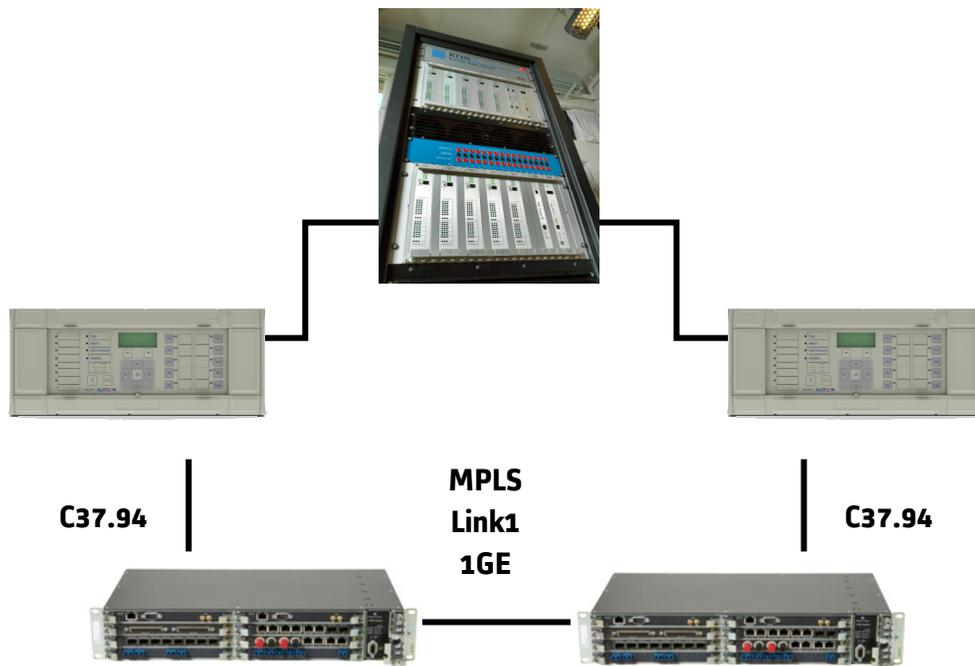


Fig. 9. Second scheme configuration

The Alstom protection relays connect natively to the 7705 SAR substation routers via the optical C37.94 interface. The incoming C37.94 frames are encapsulated in MPLS packets using CESoPSN (Circuit Emulation Service over Packet Switched Networks) where the individual time slots can be selected for transport to the remote end. The RSVP protocol is used to signal the tunnels between the end points, ensuring symmetrical forward and return paths and enabling FRR functionality if required. The service tunnel, named SDP, uses this RSVP signaled MPLS LSP.

On service level, the CESoPSN Pseudo Wire in Alcatel-Lucent terminology named '*cpipe vc-type cesopsn*', two parameters have key impact on the delay in the transport of the protection relay frames:

1. payload-size of the MPLS packet
2. size of the de-jitter buffer

The first parameter controls the size of the MPLS packet in which the C37.94 (or other TDM or serial data) data is stored: the bigger the packet, the more bandwidth efficient but the higher the end-to-end delay as the first data stored in the MPLS packet will have to wait before transmitted to the remote end. On the remote end, a de-jitter buffer is configured storing the incoming MPLS packets until the buffer is half full and then the stored packets are played out. The larger the de-jitter buffer the more jitter (packet delay variation) the PW can handle but also the higher delay.

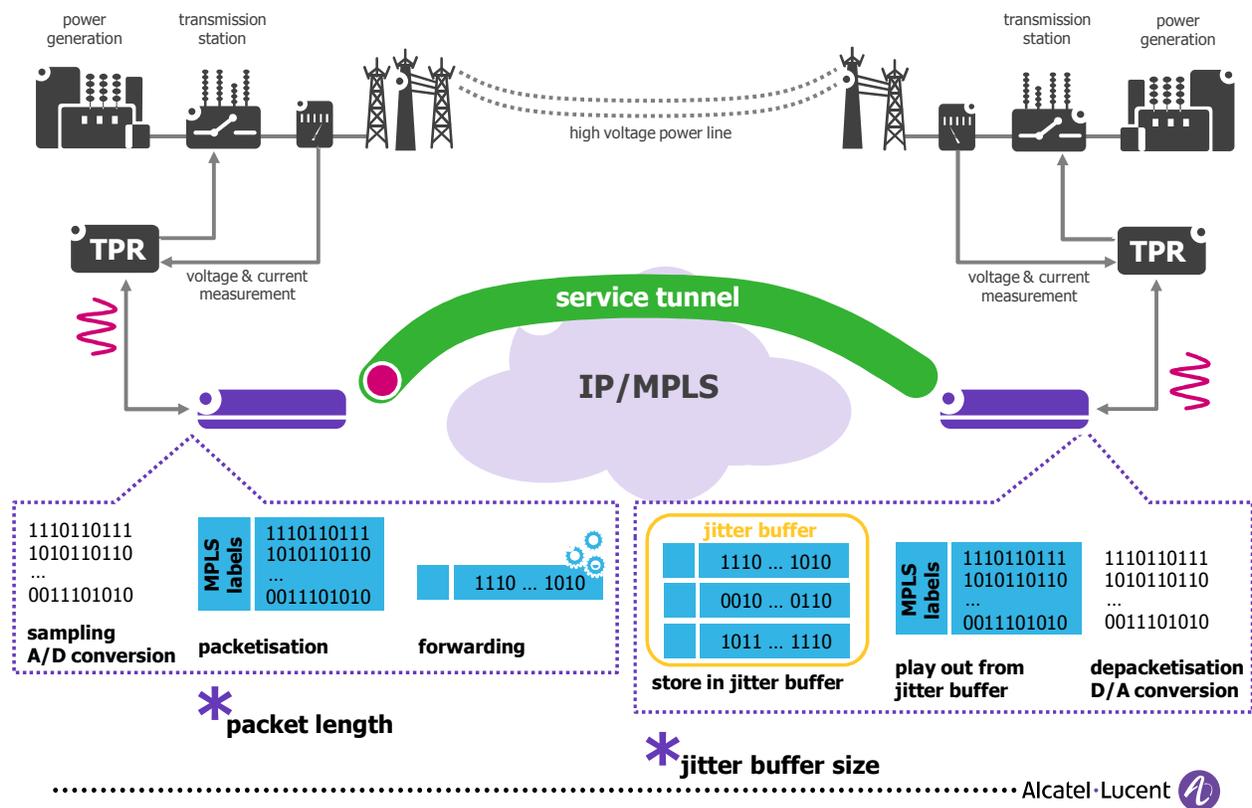


Fig. 10. Functioning of a teleprotection service over an IP/MPLS network (from left to right)

Note: that the de-jitter buffer will start playing out the stored MPLS frames when half full, so a de-jitter buffer with a configured size of 2 microseconds will contribute to 1 microseconds to the overall transport delay.

All involved 7705 SAR substation routers are synchronized using SyncE to ensure an identical clock between the remote ends.

The relevant part of the configuration parameters of the 7705 SAR-8 router used during the line differential testing is as follows:

```
port 1/2/1
  tdm
    tpif
      channel-group 1
        encap-type cem
        timeslots 1-12
        no shutdown
      exit
    no shutdown
  exit
exit
mpls
  path "loose"
    no shutdown
  exit
  lsp "lsp-7705-B"
    to 2.2.2.2
    from 1.1.1.1
    cspf
    fast-reroute facility
  exit
  primary "loose"
  exit
  no shutdown
exit
no shutdown
exit

sdp 12 create
  far-end 2.2.2.2
  lsp "lsp-7705-B"
  keep-alive
  shutdown
  exit
  no shutdown
exit

cpipe 10 customer 1 vc-type cesopsn create
  sap 1/2/1.1 create
    cem
    packet jitter-buffer 2 payload-size 24
  exit
  exit
  spoke-sdp 12:10 create
  exit
  no shutdown
exit
```

Fig. 11. Second IP/MPLS scheme configuration

3 Test Results

3.1 Latency over MPLS Network

The primary MPLS label switched path (LSP) traverses a direct link between the two ASR-903s and the backup MPLS LSP traverses 10 ASR-903 routers.

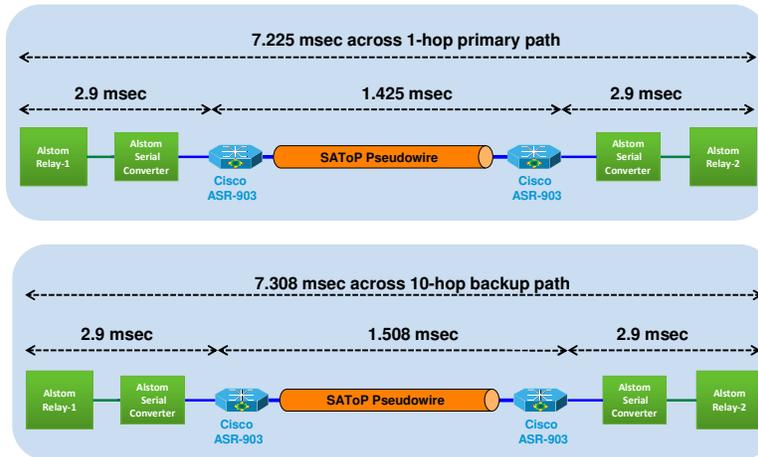


Fig. 12. Latency between 1 Hop and 10 Hop using E1 protocol

The difference in latency between the 1-hop and 10-hops path is only 83 μ s due to the ASR-903 centralized architecture and the Cisco low-latency application specific integrated circuit (ASIC).

The next results shown the latency between relays using dual redundancy channels on MPLS Alcatel-Lucent 7705 SAR routers and IEEE C37.94 protocol is as follows:

| <i>Alcatel-Lucent</i> | | <i>Alstom Grid</i> | | <i>Communication</i> | |
|-----------------------|-----------------|--------------------|---------------|----------------------|-----------------------------|
| MPLS packet size | 24 bytes | Protocol | C37.94 | Status | OK |
| De-jitter buffer | 2 ms | Number Channels | 2 | Prop. Delay CH1 | 2.120 ms |
| Number Slots | 12 | Number slots CH1 | 12 | Prop. Delay CH2 | 2.140 ms |
| Bandwidth | 1 Gbps | Number slots CH2 | 12 | Com. Prop. Delay | 35 μs |

Fig. 13. Latency using IEEE C37.94 protocol

Note: The main reason for the time difference seen between Fig. 12 and Fig. 13 is the relay protection interface speed. In Fig.12 the relay outputs 1 channel at 64kbps, while in Fig. 13 the relay outputs 13 channels at 12x64kbps = 768kbps speed. The net result of the slow speed 64kbps channel in Fig. 12 is that the Alstom Serial converters have to buffer the data the source and destination sides, which adds additional latency.

The latency value reflected here do not account for distances between substations; add 1ms propagation delay (speed of light through fiber optic) for every 200km between substations.

3.2 Operation when Propagation Delay Introduced without GPS

A 2ms delay was introduced using an Anue test impairment tool to simulate 400km of fiber length, resulting in the relays reporting a total latency of 9.112ms.

An Omicron injection test unit was used to energize the line to full load of 1kA, and a 5kA fault was applied on Phase-A.

Alstom S1 Agile Fault Record indicated a duration of 27ms from fault occurrence to trip which includes 8.7ms from pickup to trip. The Omicron test unit reported 32.6ms from fault injection to circuit breaker open signal received from relay.

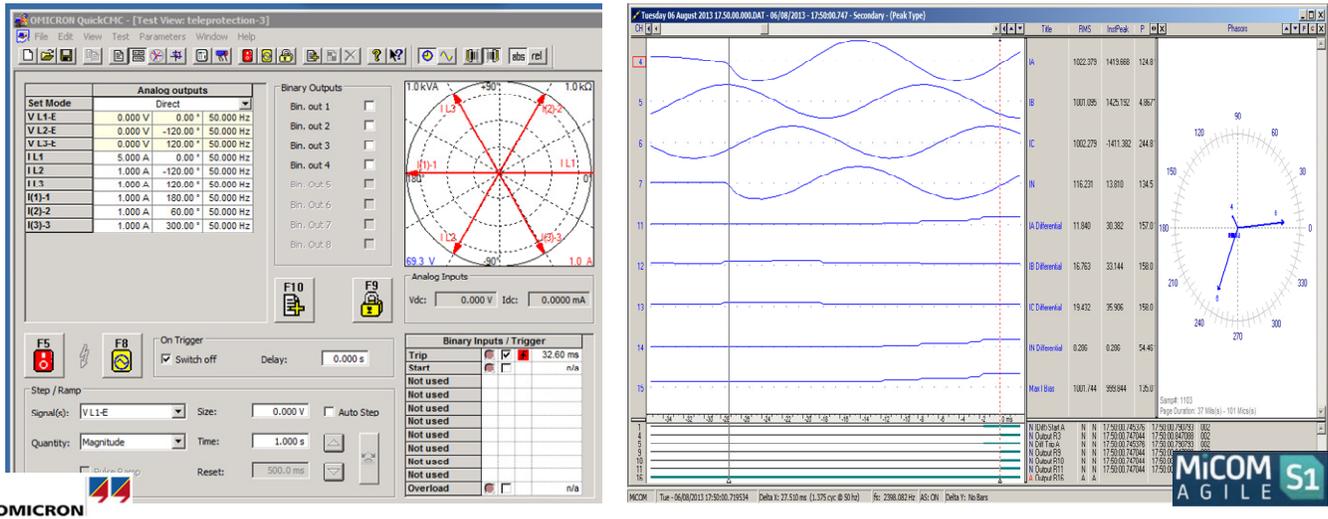


Fig. 14. Omicron and S1 Agile reports

3.3 Operation under External Line Fault without GPS

When a 5kA 3-phase external fault was injected on the line, using the injection test unit, the relay reliability (i.e., security) was maintained, as required, the relay did not trip because the current entering the protected circuit was the same as the one leaving it.

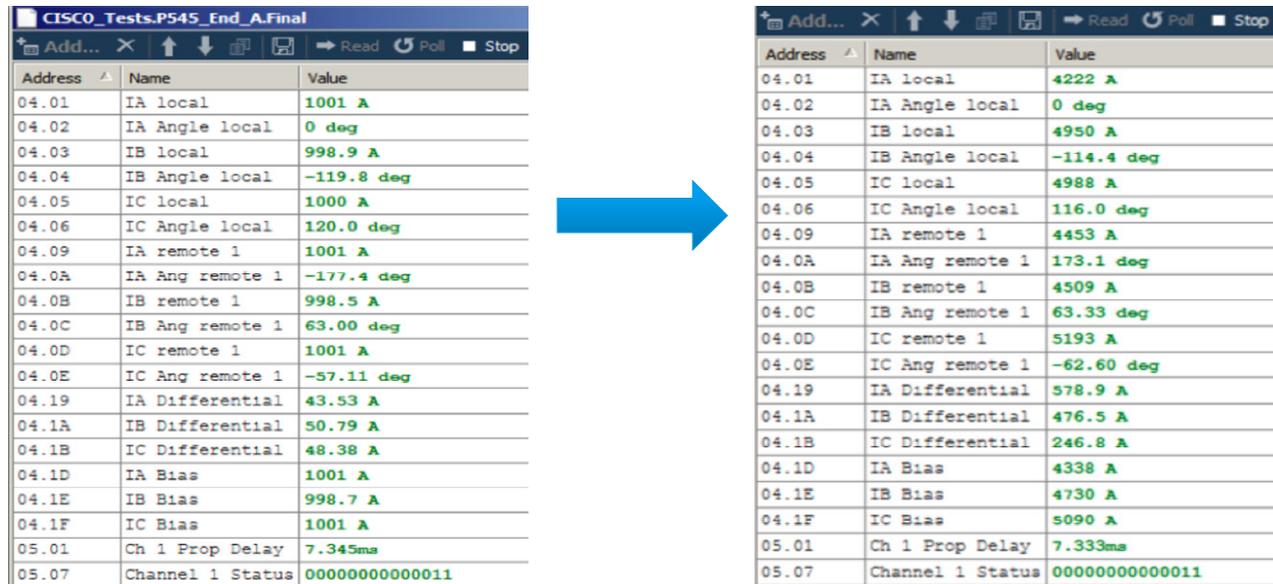


Fig. 15. S1 Agile reports

3.4 Operation under Full Traffic Load without GPS

The network is oversubscribed with a full traffic load profile to cause congestion on the 1GE core MPLS interface of the router as shown in Fig. 16.

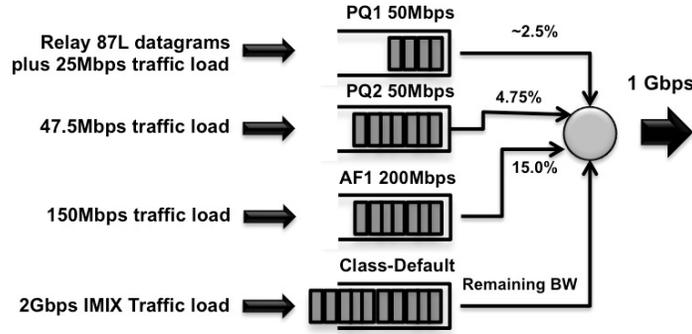


Fig. 16. Traffic Load Profile

The priority queue (PQ1) is policed at 50Mbps. In addition to the line differential datagrams that are mapped to this queue, an additional 25Mbps of traffic with fixed frame size of 1000 bytes is also injected into this queue to load the queue to a little over 50%. Priority queue (PQ2) is policed at 50Mbps and loaded up to 95% capacity with fixed frame size of 1000 bytes. Assured forwarding queue (AF1) has 200Mbps of bandwidth reserved, and loaded up to 75% with fixed frame size of 1000 bytes. The egress interface is congested by injecting 2Gbps of IMIX traffic consisting of varying 70, 594, 1518 byte sized frames with a distribution of 7:4:1 into the Best effort (class-default) queue. The QoS scheduler ensures that the PQ1, PQ2, and AF1 traffic classes are served with the configured service level agreements (SLA) without any packet loss, and only the best effort 2Gbps traffic experiences drops on the congested 1GE core interface.

Under this fully loaded, highly oversubscribed network condition, the relays report 7.229ms latency across the 10-hop network path.

The injection test unit is used to energize the line to full load of 1kA, and a 5kA fault is injected on Phase-A. The Alstom S1 Agile Fault Record indicated 29.6ms from fault occurrence to trip, which includes 13.7ms from pickup to trip. The Omicron test unit reported 34.6ms from fault injection on line to circuit breaker open signal received from relay.

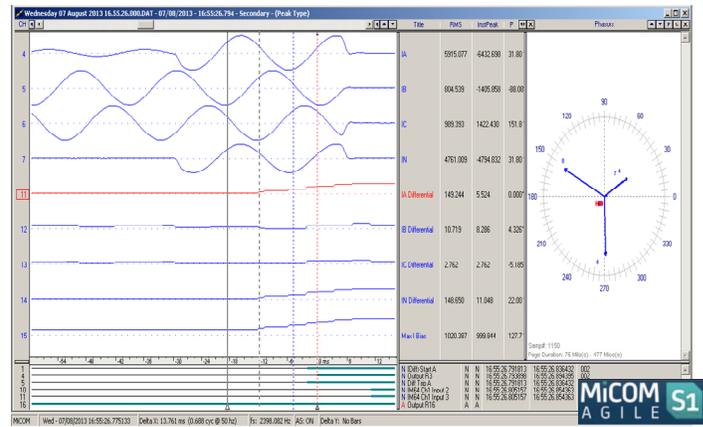
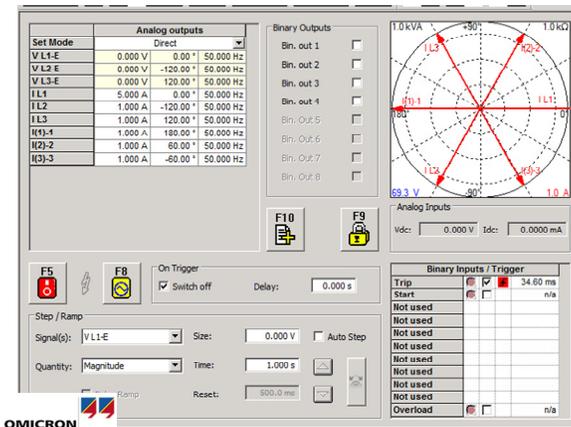


Fig. 17. Omicron and S1 Agile reports

3.5 Operation under Network Link Fail (without GPS)

With only one single protection interface enabled on each relays, S1 Agile reported a latency of 7.212ms across 1-hop in the network with full traffic load as described in Fig. 18 under normal operating conditions.

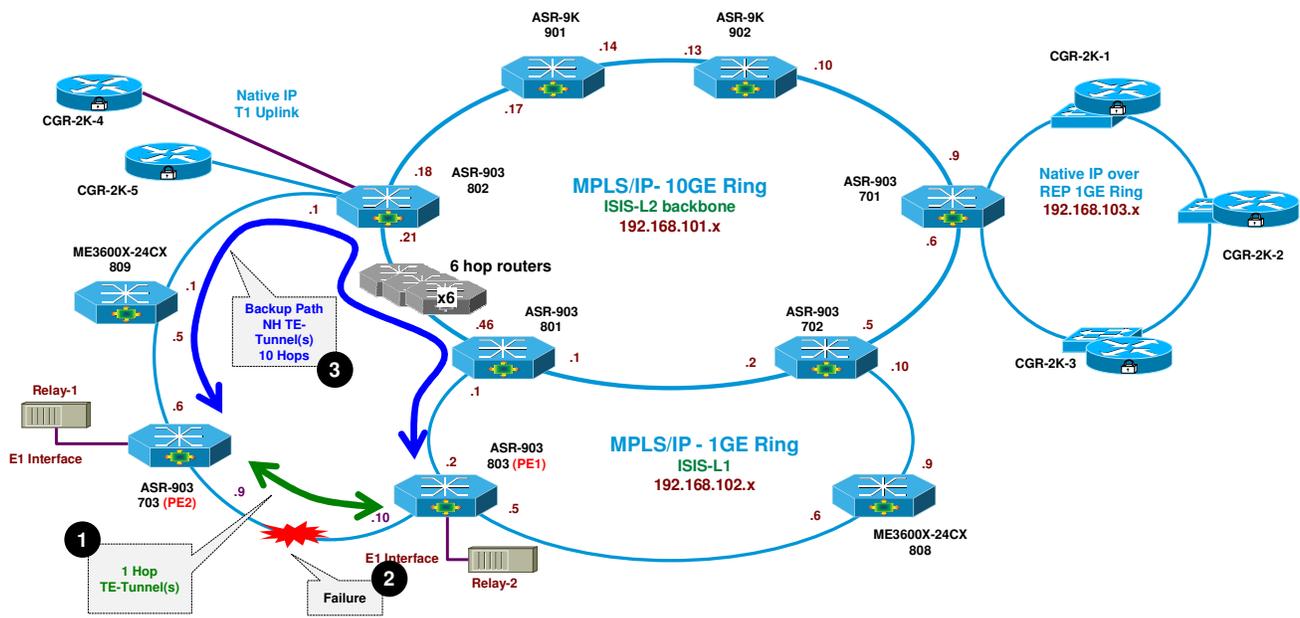


Fig. 18. Network fail link configuration

A bidirectional test traffic stream is injected in the network using an Ixia traffic generator along the same path as the relay communication to measure convergence time during failure conditions. The direct link is failed and TE FRR performs a local-repair to reroute the traffic from the (green) Primary Tunnel to the (blue) Backup Tunnel. The Ixia traffic tool indicates that the test stream incurs delays of 7.3ms and 16.64ms, for re-convergence for each direction of traffic.

Alstom S1 Agile reported that the relay detects the disturbance (*Comm Delay Alarm On*) but does not change to Degraded Mode due to the sub 25ms traffic loss. The 16.64ms delays approximates to less than 3 telegrams lost during re-convergence.

| Parameter | Value |
|---------------------------------------|----------------------|
| Wednesday 07 August 2013 16:39:44.871 | Output Contacts1 |
| Wednesday 07 August 2013 16:39:44.870 | Comm Delay Alarm OFF |
| Wednesday 07 August 2013 16:39:44.345 | Output Contacts1 |
| Wednesday 07 August 2013 16:39:44.344 | Comm Delay Alarm ON |
| Wednesday 07 August 2013 16:39:44.344 | Comm Delay Alarm ON |
| Wednesday 07 August 2013 16:38:03.698 | Output Contacts1 |
| Wednesday 07 August 2013 16:38:03.697 | Comm Delay Alarm OFF |
| Wednesday 07 August 2013 16:38:03.188 | Output Contacts1 |
| Wednesday 07 August 2013 16:38:03.187 | Comm Delay Alarm ON |
| Wednesday 07 August 2013 16:38:03.187 | Comm Delay Alarm ON |
| Wednesday 07 August 2013 16:34:53.063 | Output Contacts1 |
| Wednesday 07 August 2013 16:34:52.878 | C Diff Failure OFF |
| Wednesday 07 August 2013 16:34:52.658 | SignalFail Ch1Tx OFF |
| Wednesday 07 August 2013 16:34:52.563 | Output Contacts1 |
| Wednesday 07 August 2013 16:34:52.562 | C Diff Failure ON |
| Wednesday 07 August 2013 16:34:52.560 | SignalFail Ch1Tx ON |

Fig. 19. S1 Agile reports

3.6 Operation with GPS Synchronization

When the line differential communications was synchronized by GPS, the relays reported a latency of 7.712ms across the 1 hop network and very low values of differential current due to the GPS assisted time synchronization when sampling the current values from the 3-phase line. However the results for a fault operation reported by both systems (with and without GPS) are similar.

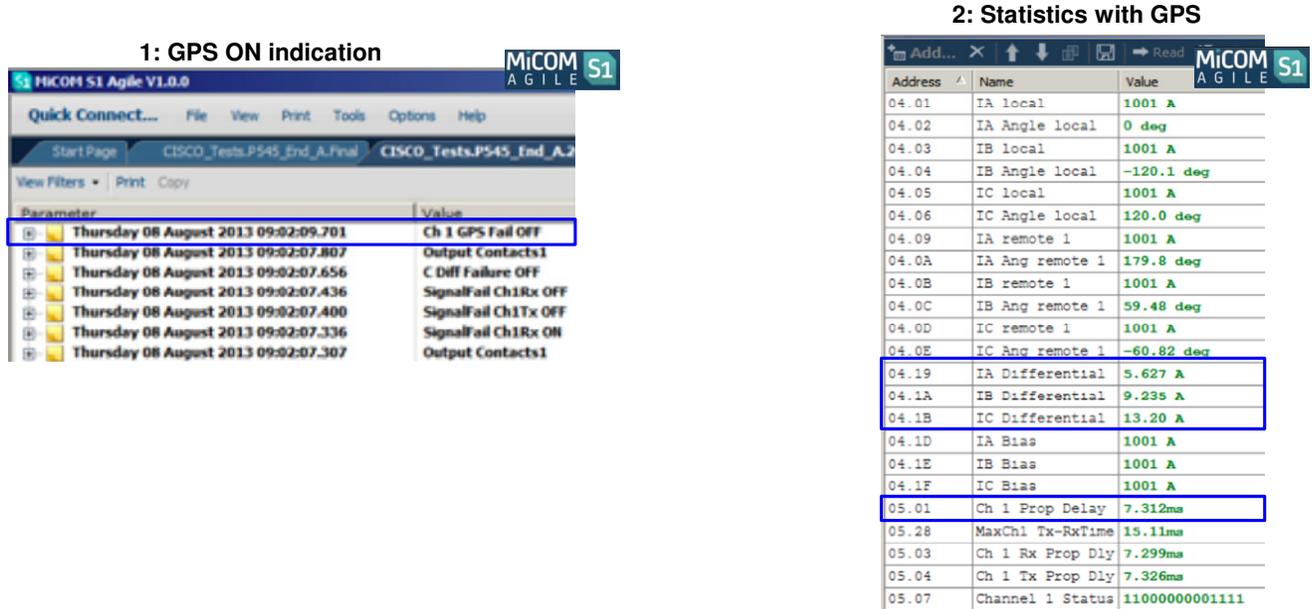


Fig. 20. S1 Agile reports

3.7 Operation under Adverse Jitter Conditions

The following table shows performance of the de-jitter buffer set to 1msec, when artificial jitter is introduced in the network path by using the network impairment test tool.

| PDV Introduced around fixed propagation delay of 3.0 msec | Traffic Flow | Traffic Drop | Measured PDV (usec) | | | Average Two-way Delay Asymmetry (usec) |
|---|--------------|--------------|---------------------|---------|-------|--|
| | | | Min | Max | Avg | |
| 0/0 | PE1-PE2 | No | 0 | 173.160 | 4.392 | 52.332 |
| | PE2-PE1 | No | 0 | 154.920 | 4.667 | |
| -10/+10 usec | PE1-PE2 | No | 0 | 151.580 | 4.205 | 43.489 |
| | PE2-PE1 | No | 0 | 200.600 | 5.136 | |
| -100/+100 usec | PE1-PE2 | No | 0 | 169.560 | 4.949 | 39.373 |
| | PE2-PE1 | No | 0 | 188.280 | 5.862 | |
| -120/+120 usec | PE1-PE2 | No | 0 | 251.080 | 4.667 | 33.636 |
| | PE2-PE1 | No | 0 | 251.340 | 4.940 | |
| -125/+125 usec | PE1-PE2 | No | 0 | 267.880 | 7.294 | 55.248 |
| | PE2-PE1 | No | 0 | 251.580 | 8.128 | |
| -130/+130 usec | PE1-PE2 | Yes | | | | |
| | PE2-PE1 | | | | | |

Fig. 21. Performance of the de-jitter buffer set to 1 ms

As described in Section 1.2, line differential schemes relying on asynchronous sampling using the ping-pong scheme are very sensitive to jitter. This section highlights the impact on the line differential function when artificial jitter is introduced in the network using a network impairment test tool.

The TDM circuit emulation pseudowire operation employs a de-jitter buffer to compensate for the network Packet Delay Variation (PDV). On ASR-903 routers, the de-jitter buffer is configurable between 1-500msec.

The Anue impairment tool is set to introduce jitter by inserting variation of (min, max) delay = (2.0, 4.0) ms around a fixed value of 3.0 ms of propagation delay using a Gaussian distribution. The Ixia traffic generator is used to inject a traffic rate of 500 PPS with 128byte frame size for measurements. As the table shows, the buffer set at 1ms size compensates up to $\pm 125\mu\text{s}$ of variation introduced by the impairment tool.

| Address | Name | Value |
|---------|------------------|----------------|
| 04.01 | IA local | 999.6 A |
| 04.02 | IA Angle local | 0 deg |
| 04.03 | IB local | 999.5 A |
| 04.04 | IB Angle local | -120.1 deg |
| 04.05 | IC local | 999.6 A |
| 04.06 | IC Angle local | 119.7 deg |
| 04.09 | IA remote 1 | 998.5 A |
| 04.0A | IA Ang remote 1 | 178.3 deg |
| 04.0B | IB remote 1 | 998.5 A |
| 04.0C | IB Ang remote 1 | 58.25 deg |
| 04.0D | IC remote 1 | 998.5 A |
| 04.0E | IC Ang remote 1 | -61.35 deg |
| 04.19 | IA Differential | 27.09 A |
| 04.1A | IB Differential | 30.73 A |
| 04.1B | IC Differential | 20.86 A |
| 04.1D | IA Bias | 999.1 A |
| 04.1E | IB Bias | 999.0 A |
| 04.1F | IC Bias | 999.0 A |
| 05.01 | Ch 1 Prop Delay | 9.252ms |
| 05.07 | Channel 1 Status | 00000000000011 |
| 05.13 | Chl No.Vald Mess | 14186359 |
| 05.14 | Chl No.Err Mess | 260 |

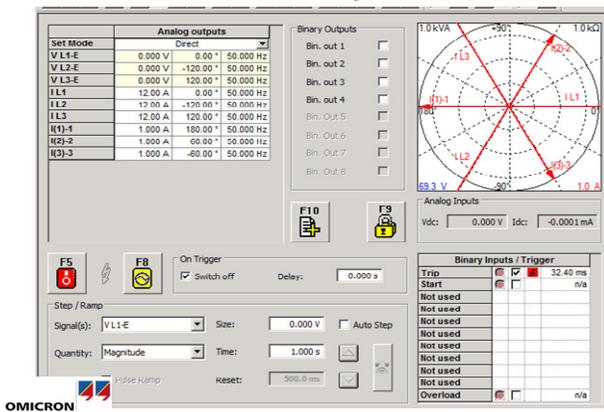
Fig. 22. S1 Agile reports

The relays are set to communicate through the direct link across routers using the SAToP pseudowire that is configured with a 1ms de-jitter buffer size and the test equipment was used to energize the line to full load current of 1kA.

Then Anue impairment tool was setup to introduce jitter to stress the TDM pseudowire 1ms de-jitter buffer compensation limit, by inserting a variation of (min, max) delay = (1.0, 3.0) ms around a fixed value of 2.0 ms propagation delay, with a step size of $\pm 125\mu\text{s}$ using a Gaussian distribution

The relays indicate a 9.252ms latency corresponding to the ~7 ms baseline plus the 2ms introduced propagation delay and we can notice the increase in differential current due to the impact of jitter on the accuracy of the echo (ping-pong) synchronization by the relays.

Omicron 5kA fault inject on Phase-A



Alstom S1 Agile Disturbance Record

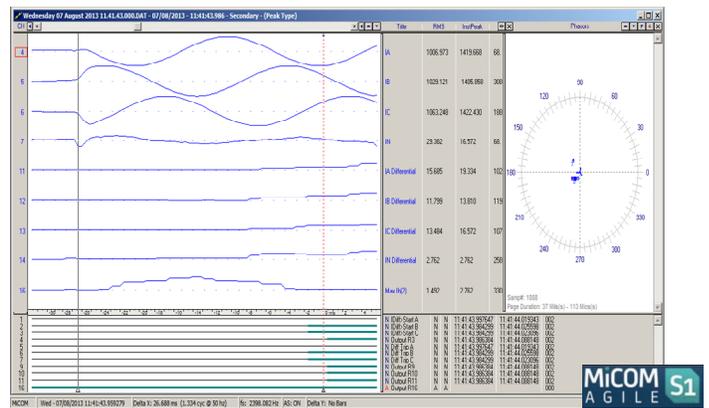


Fig. 23. Omicron and S1 Agile reports

Under the adverse jitter conditions introduced by the Anue test tool, the test equipment was used to inject a 12kA 3-phase fault on the fully loaded 1kA line. Alstom S1 Agile Fault Record indicates 22ms from fault to trip, which includes 8.3ms from pickup to trip, and the test unit reports 32.4ms from fault inject on line to breaker open signal received from the relay.

Note: The high values of artificial jitter introduced in these tests were done to demonstrate the impact on line differential operation in adverse theoretical conditions. In carrier grade MPLS networks, jitter due to queuing delays is very low due to hardware based forwarding and QoS scheduling.

3.7 Operation under Asymmetry Latency without GPS

As described in Section 1.2, line differential schemes relying on asynchronous sampling using the ping-pong scheme are very sensitive to asymmetric latency on the communication channel. This section highlights the impact on the line differential function when artificial latency asymmetry is introduced in the network using the network impairment test tool to simulate asymmetric path conditions.

The MiCOM P545 Relays can be configured to tolerate up to 1msec change in propagation time on the communication channel. If network conditions cause this “Transient Change in Propagation Delay” to be greater than the pre-configured value, the relay will increase the bias from 30% to 200% as described in Fig. 3. If asymmetry condition persists beyond 500msec, the relays can be configured to work in one of the following modes:

- Restraint Mode: Maintain bias at 200% until operator manual reset. The differential function operates with reduced sensitivity under this condition.
- Inhibit Mode: Block Differential function. This option allows the secondary protection scheme to take over.

In theory, latency asymmetry and network path asymmetry are not necessarily coupled parameters. In practice however, asymmetric paths in a packet switched network are very likely to experience different latencies due to the varying traffic load conditions, or the different number of hops involved along the non-congruent paths.

The network impairment test tool is used to inject a one-way delay in the network path between the relays. As shown in Fig. 23 notice the rise in Current Differential between the two scenarios when 1msec and 2msec of latency is introduced along one path of the network to create an artificial path asymmetry condition.

**Relay Latency Statistics
with 1msec Asymmetric Latency**

**MiCOM
AGILE S1**

| Address | Name | Value |
|---------|------------------|----------------|
| 04 01 | IA local | 1000 A |
| 04 02 | IA Angle local | 0 deg |
| 04 03 | IB local | 1000 A |
| 04 04 | IB Angle local | -120.1 deg |
| 04 05 | IC local | 1000 A |
| 04 06 | IC Angle local | 119.9 deg |
| 04 09 | IA remote 1 | 999.5 A |
| 04 0A | IA Ang remote 1 | -173.7 deg |
| 04 0B | IB remote 1 | 999.5 A |
| 04 0C | IB Ang remote 1 | 65.97 deg |
| 04 0D | IC remote 1 | 999.5 A |
| 04 0E | IC Ang remote 1 | -54.33 deg |
| 04 19 | IA Differential | 111.1 A |
| 04 1A | IB Differential | 107.9 A |
| 04 1B | IC Differential | 104.6 A |
| 04 1D | IA Bias | 999.3 A |
| 04 1E | IB Bias | 999.3 A |
| 04 1F | IC Bias | 999.3 A |
| 05 01 | Ch 1 Prop Delay | 7.736usec |
| 05 02 | - | not accessible |
| 05 07 | Channel 1 Status | 00000000000011 |
| 05 08 | Channel 2 Status | 00000000000010 |

**Relay Latency Statistics
with 2msec Asymmetric Latency**

**MiCOM
AGILE S1**

| Address | Name | Value |
|---------|------------------|----------------|
| 04 01 | IA local | 1000 A |
| 04 02 | IA Angle local | 0 deg |
| 04 03 | IB local | 999.9 A |
| 04 04 | IB Angle local | -120.1 deg |
| 04 05 | IC local | 999.9 A |
| 04 06 | IC Angle local | 119.9 deg |
| 04 09 | IA remote 1 | 999.5 A |
| 04 0A | IA Ang remote 1 | -163.2 deg |
| 04 0B | IB remote 1 | 999.5 A |
| 04 0C | IB Ang remote 1 | 76.53 deg |
| 04 0D | IC remote 1 | 999.5 A |
| 04 0E | IC Ang remote 1 | -43.57 deg |
| 04 19 | IA Differential | 294.0 A |
| 04 1A | IB Differential | 290.4 A |
| 04 1B | IC Differential | 285.7 A |
| 04 1D | IA Bias | 999.2 A |
| 04 1E | IB Bias | 999.2 A |
| 04 1F | IC Bias | 999.2 A |
| 05 01 | Ch 1 Prop Delay | 9.260usec |
| 05 02 | - | not accessible |
| 05 07 | Channel 1 Status | 00000000000011 |
| 05 08 | Channel 2 Status | 00000000000010 |

Fig. 24. S1 Agile reports

When a one-way delay of greater than 2msec value is injected into the network, the average of the latencies along the forward and return paths will be perceived as a change in propagation delay greater than the 1msec pre-configured “Transient Change in Propagation Delay” condition. This will cause the differential function to engage the Restraint Mode or Inhibit Mode described above.

Note: The artificial asymmetric latency introduced in these tests was done to demonstrate the impact on line differential operation in adverse theoretical conditions. Such asymmetry will not occur in real operating conditions because RSVP TE is used to ensure that relay communication channels are always co-routed and proper quality of service (QOS) will ensure minimal switching latency. Even under link failure conditions as seen in Section 3.5, since the link failure is repaired in <50msec in both directions, the 500msec relay check limit is never exceeded and the Restraint or Inhibit Modes will not be triggered.

3.8 Operation under Asymmetry Latency with GPS

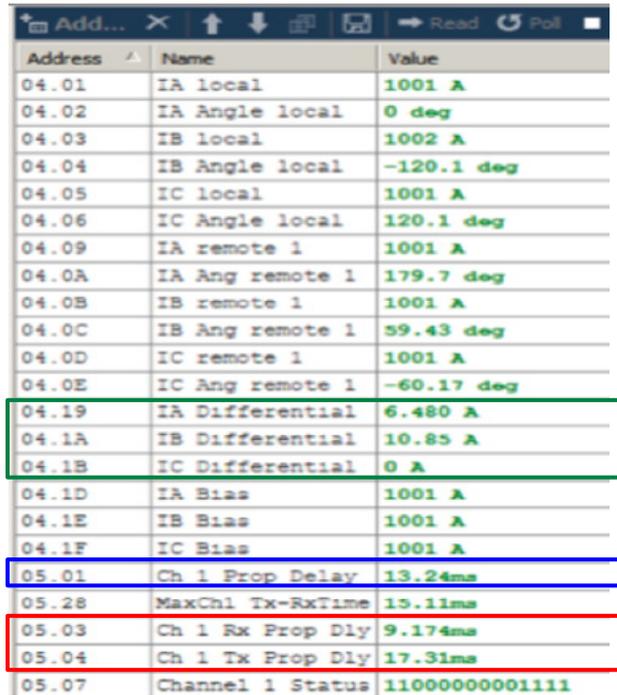
The relays are operated with GPS enabled, with initial conditions involved a fixed 2msec symmetric propagation delay introduced by the Anue network impairment tool. The impairment tool was then modified to inject a 10msec one-way latency in the path.

As shown in the table below, the relay reports an average propagation delay of 13.24 ms, but since the GPS assist is ON, the channel transmit (Tx) and receive (Rx) statistics are now available and the relay detects the change in one way latency as indicated by the Ch1 Rx and Tx Propagation Delays.

Note: The pre-configured *Transient Change in Propagation Delay* setting described in Section 3.7 does not come into play here even though the jump from 2ms to 10ms asymmetric latency exceeds the 1ms value, since GPS is ON.

Also, since GPS time source referenced relay operation is not impacted by channel asymmetry, we notice very low values of differential current values as shown in the table.

**Relay Latency Statistics
With 10msec Asymmetric Latency**



| Address | Name | Value |
|---------|------------------|----------------|
| 04.01 | IA local | 1001 A |
| 04.02 | IA Angle local | 0 deg |
| 04.03 | IB local | 1002 A |
| 04.04 | IB Angle local | -120.1 deg |
| 04.05 | IC local | 1001 A |
| 04.06 | IC Angle local | 120.1 deg |
| 04.09 | IA remote 1 | 1001 A |
| 04.0A | IA Ang remote 1 | 179.7 deg |
| 04.0B | IB remote 1 | 1001 A |
| 04.0C | IB Ang remote 1 | 59.43 deg |
| 04.0D | IC remote 1 | 1001 A |
| 04.0E | IC Ang remote 1 | -60.17 deg |
| 04.19 | IA Differential | 6.480 A |
| 04.1A | IB Differential | 10.85 A |
| 04.1B | IC Differential | 0 A |
| 04.1D | IA Bias | 1001 A |
| 04.1E | IB Bias | 1001 A |
| 04.1F | IC Bias | 1001 A |
| 05.01 | Ch 1 Prop Delay | 13.24ms |
| 05.28 | MaxCh1 Tx-RxTime | 15.11ms |
| 05.03 | Ch 1 Rx Prop Dly | 9.174ms |
| 05.04 | Ch 1 Tx Prop Dly | 17.31ms |
| 05.07 | Channel 1 Status | 11000000001111 |

Fig. 25. S1 Agile reports

4 Conclusions

This paper reported on several configurations according the specification of a line differential protection using an IP/MPLS communications network with the test results for different applications. The salient points to consider are:

- The main factors of the consuming delay budget are the relay protection interface types and speeds and not the packet switched network itself.
- Dynamically signaled MPLS RSVP-TE tunnels or statically provisioned MPLS-TP bidirectional co-routed tunnels can ensure path symmetry when asynchronous sampling with a ping-pong delay measurement technique is by the line differential scheme.
- Synchronous Ethernet (SyncE) or packet transfer based Precision Time Protocol (PTP) IEEE 1588 ensures efficient frequency synchronization distribution to MPLS PEs for circuit emulation.
- MPLS TDM circuit emulation pseudowire de-jitter buffers compensate for network Packed Delay Variation when clocking data on to relay synchronous protection interfaces.
- Efficient QoS mechanisms will ensure Teleprotection traffic is subject to minimum latency (for faster detection) and jitter (for accurate relay synchronization) as it traverses the packet network.

Unlike TDM transport, packet switched technology by its inherent nature of statistical multiplexing is subject to variances in propagation time due to queuing delays. However, modern carrier-class MPLS platforms perform hardware based forwarding and QoS scheduling, to provide deterministic forwarding behaviors. Ultimately, it is important to understand that the level determinism that a packet switched network can provide is dependent on the hardware implementation of the platforms that comprise the network.

As seen from the tests and results presented in the paper, we can conclude that packet switched networks implemented with hardware based data plane forwarding are reliable (dependable & secure) to

support the most stringent Teleprotection schemes with guaranteed service level agreements, well below the required latency budget imposed by line differential protection.

Although demonstrated in a laboratory environment, the study uses real cases and commercially available hardware to determine the best settings in accordance with the various simulations and to show that IP/MPLS can significantly improve the efficiency in a line differential protection communication compared with TDM solutions, whilst improving the reliability on a transport solution for electric grid wide area applications, providing utilities a step forward towards moving to a single, reliable, cost effective and integrated network.

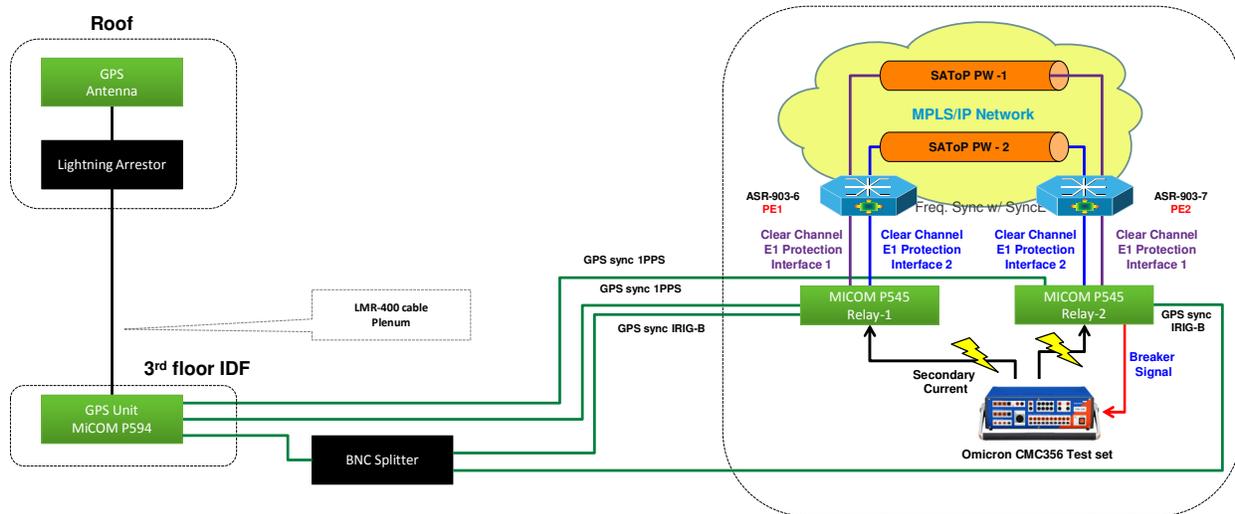


Fig. 26. System Configuration

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