SPaRC

Secure Pathways for Resilient Communications

Direct Underreaching Transfer Trip Testing – Technical Summary

This document provides a technical summary of the Direct Underreaching Transfer Trip (DUTT) Testing completed through the Secure Pathways for Resilient Communications (SPaRC[1]) program under the Office of Electricity.

[1] https://securecomms.ornl.gov/

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ACRONYMS

CAST	Center for Alternative Synchronization and Timing
CRC	Cyclic Redundancy Check
CT	Current transformer
CTRW	Current-transformer ratio
DCB	Directional Comparison Blocking
DCE	Data Communication Equipment
DTE	Data Terminal Equipment
DTT	Direct-transfer trip
DUTT	Direct Underreaching Transfer Trip
GOOSE	Generic object-oriented substation event
Ibase	Base current
Iphase	phase current of conductor
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
K0	Zero-sequence compensation factor
LL	Line Length
LLG	Line-to-Line-to-Ground
MPLS	Multiprotocol Label Switching
MTA	Maximum Torque Angle
NTP	Network Time Protocol
OT	Operational Technology
POTT	Permissive Overreaching Transfer Trip
PUTT	Permissive Underreaching Transfer Trip
PT	Potential Transformer
PTRY	Potential-Transformer Ratio
QoS	Quality of Service
RBADx	Receive Bits and Data (x is channel)
RMBx	Received Mirrored Bit (x is channel)
RTDS	Real Time Digital System
RX	Receive
Sbase	Base apparent power
SEL	Schweitzer Engineering Laboratories
SER	Sequence of Event Report
SLG	Single Line-to-Ground
SPaRC	Secure Pathways for Resilient Communications
TCP	Transmission Control Protocol
TDM	Time-division multiplexing
TMBx	Transmit mirrored bit (x is channel)
TX	Transmit
UART	Universal Asynchronous Receiver-Transmitter
UDP	User Data Protocol
USB	Universal Serial Base
Vbase	Base voltage
VLN	Voltage Line to Neutral

VLL	Voltage Line-to-Line
VNOMY	Nominal voltage for the secondary line-to-line voltage
WITT	Weak Infeed Transfer Trip
Z0ANG	Zero-sequence line-impedance angle
Z0MAG	Zero-sequence line-impedance magnitude
Z1ANG	Positive-sequence line-impedance angle
Z1MAG	Positive-sequence line-impedance magnitude
Z1G	Zone 1 ground pickup
Z1P	Zone 1 phase pickup
Z2G	Zone 2 ground pickup
Z2P	Zone 2 phase pickup
Z2T	Zone 2 timer
Zbase	Base impedance

1. Overview

This document provides technical summary of the overall **D**irect **U**nderreaching **T**ransfer **T**rip (DUTT) Test Methodology and Results document. This document summarizes the work from each of the national labs involved in the DUTT testing through the SPaRC (**S**ecure **Pa**thways for **R**esilient **C**ommunications) program under the Office of Electricity (OE).

2. Testing Methodology

The SPaRC project has four contributing National Labs, Idaho National Laboratory (INL), Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL), and Sandia National Laboratories (SNL). To ensure coordination in testing and pertinent results, the methodology for the project has the following components:

1) **POWER SYSTEM**: Establishing a common baseline power system at each lab to enable similar protection scheme implementation under similar faulted conditions.
2) **PROTECTION SCHEME**: Implementation of a protection scheme over communications for Direct Underreaching Transfer Trip to ensure common results.
3) **COMMS TESTING:** Implementation of different comms methods and the testing to failure via multiple methods of impairing the communication protocol.
4) **RESULTS**: Evaluating the relay performance with DUTT under fault conditions and constrained communication pathways.

This coordination allowed each laboratory to investigate and test the performance of the protection scheme under impaired/constrained communications under many different scenarios ensuring a known power system and expected results from faulted conditions. Hence the results from each lab present their findings based upon the communications and protection protocol implemented. As an example, INL implemented SEL Mirrored Bits protocol as the direct transfer trip communication mechanism over both serial cable and with serial over impaired internet protocol (IP) communications, PNNL validated the baseline with alternate simulation software and a substation controller, ORNL examined serial interference on wireless and serial links, and SNL examined GOOSE as the direct transfer trip communication mechanism over impaired networks.

3. Baseline Power System

The first component of the testing was to establish a consistent power system model for the distance relaying configuration.

This was important to leverage different modeling and hardware in the loop resources (Power World, RTDS, and Opal-RT). The Baseline model ensured each lab was examining similar conditions while impairing communications.

3.1 Transmission Base Line Parameters.

Transmission line parameters were selected from the IEEE 39 Bus model, specifically line T2 which is the transmission line between bus 1 and bus 39 in the IEEE 39 Bus model. This provides an open-source model that is readily accessible with known parameters. Following are the parameters used in the IEEE 39 Bus model:

The system we will simulate is a 345kV transmission line from the IEEE 39 Bus model, specifically Bus 1 and Bus 39 from the model.

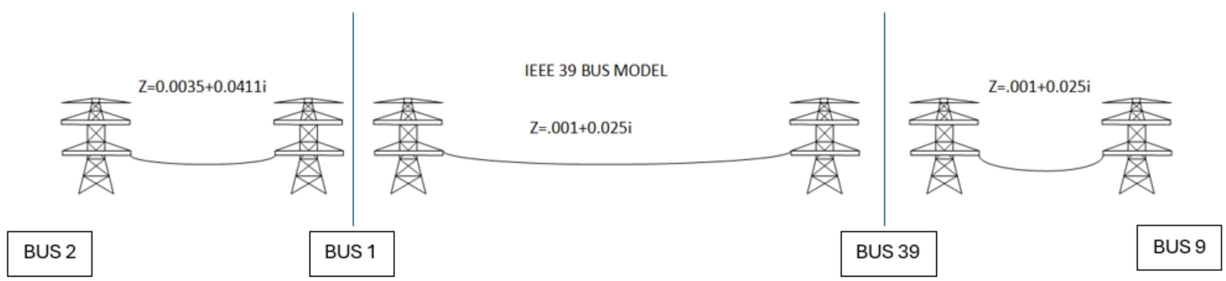

Figure 1: Line T2 from IEEE 39 Bus Model

Additional Base units include: Sbase = 100 MVA, Vbase = 345kV.

Where: $Z_{base} = \frac{V_{baseLL}^2}{S_{base3\emptyset}}$ $I_{base} = \frac{S_{base3\emptyset}}{\sqrt{3}V_{baseLL}}$ $Y_{base} = \frac{1}{Z_{base}}$

Resulting in the following base values:

Table 1: Base Values for IEEE 39 Bus Model

Base Parameter	Magnitude	Units
Sbase	100	MVA
Vbase (LL)	345	kV
Zbase	1190.25	Ohms
Ybase	0.00084016	Siemens
Ibase	167.35	Amps

The resulting line impedance for T2 is $Z_{Actual} = 1.19025 + 29.75625i = 29.780\angle 87.709$ with $Y_{shunt} = 0.75i$. The line impedance is a core parameter for configuration of the relays as well as determining relay test set settings and the zones in a Distance Protection scheme.

3.2 Baseline Relay Parameters

The Distance Protection scheme was common to all laboratories and provided a basis for the test plan in generating faults at different locations to ensure the same expected behavior of the protection scheme.

The Distance Protection scheme was established based upon each relay having two zones of protection, Zone1 and Zone 2. Zone 1 was established at 80% of the line facing the opposing relay, and Zone 2 was established at 120% of the line facing the opposing relay.

Zonal protection was established with both phase and ground pickups in the relay based upon the percentages of each zone. Fig. 2 is a representation of the zone for the relays.

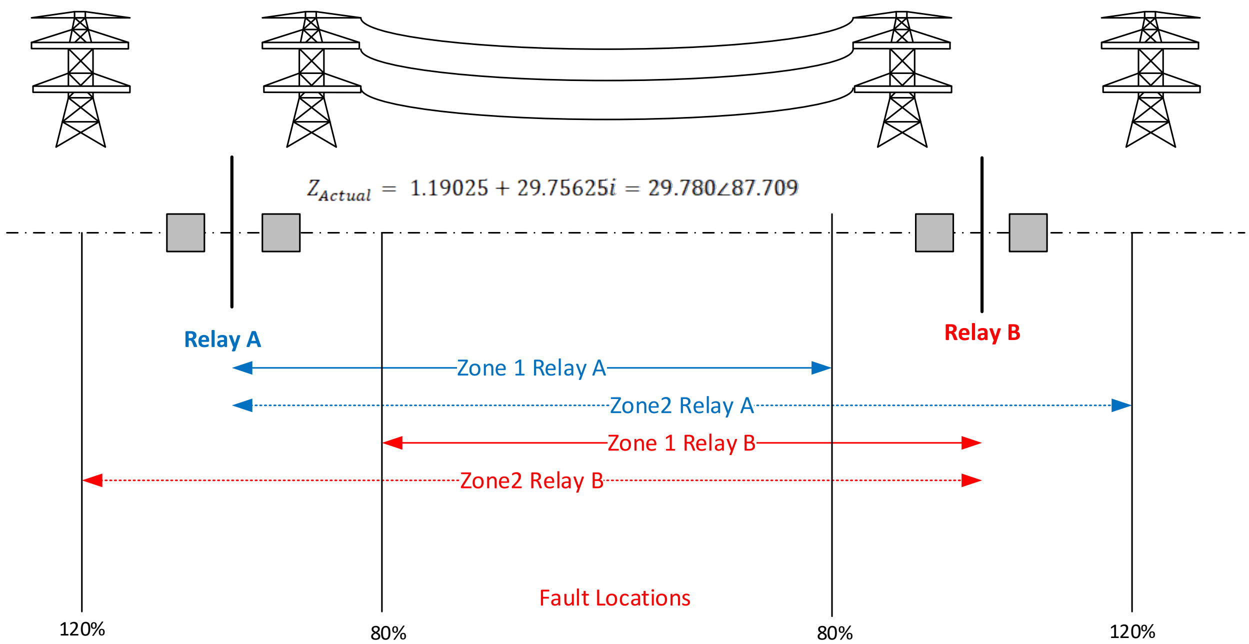

Figure 2: Relay Location with Zones

3.2.1 Zonal Protection

The function of each relay in Distance Protection is to measure the impedance of a fault to determine if the fault is within either of the zones of protection. From a graphical perspective, zones can be represented relative to the transmission line impedance in an impedance diagram (real impedance is x-axis and imaginary impedance is y-axis). Fig. 5 represents a Mho diagram of the transmission line (green vector from origin) and the zones of protection, Zone 1 and Zone 2 for the line.

Note that Zone 1 and Zone 2 are circles or vectors representing 80% and 120% of the magnitude of line T2 over 360 degrees centered at 50% of the original impedance.

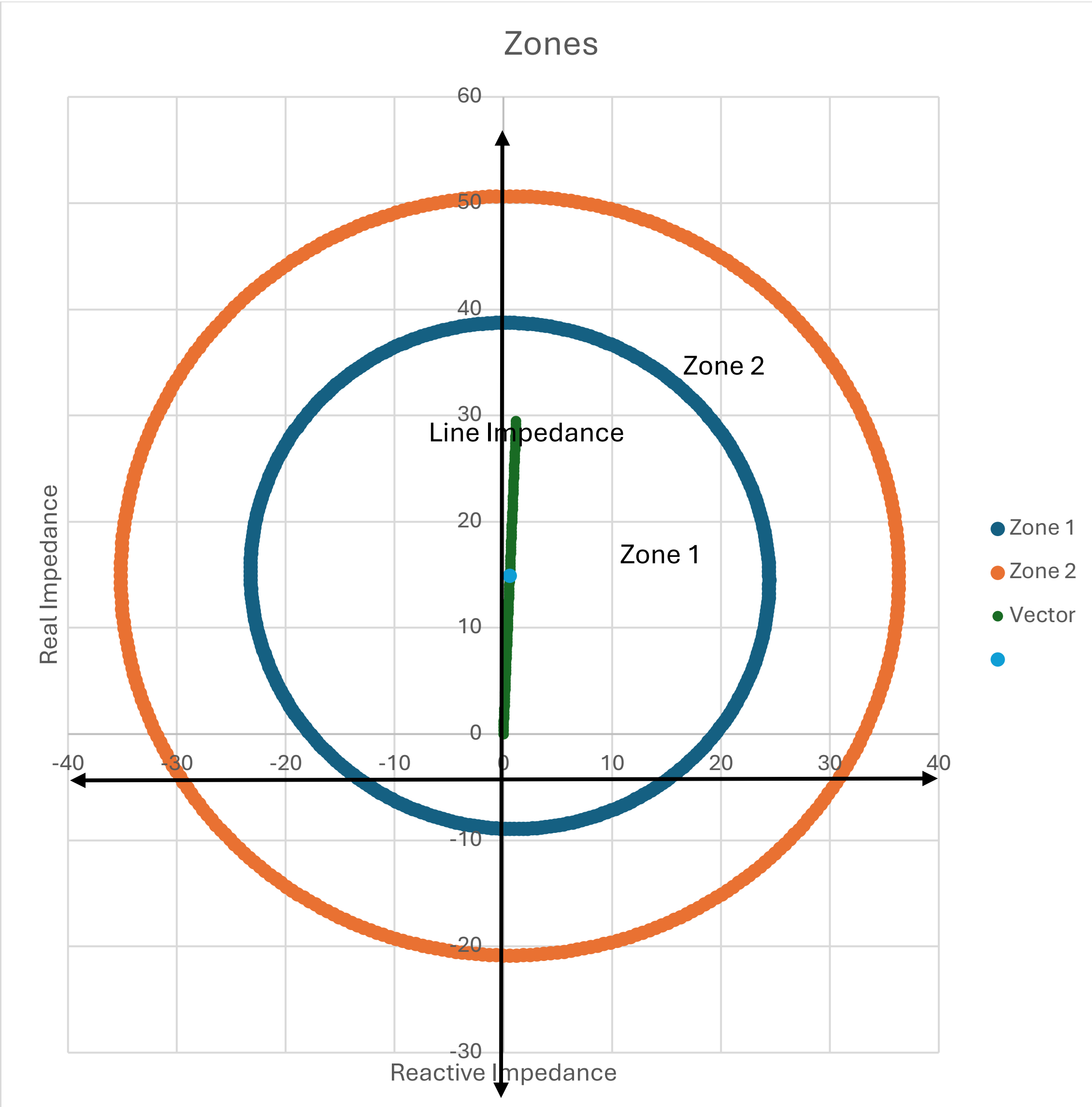

Figure 3: Mho Graph of Line Impedance and Zones

Green Line – Impedance of T2 centered at Origin – 29.79 at 87.71 degrees.
Center of Zone 1 and Zone 2 -50% of T2 or (14.88 at 87.71 degrees (Z=0.59517 + 14.8831i)
Zone 1 – circle with Radius of the Zone1 Magnitude (23.832)
Zone 2 – circle with Radius of the Zone 2 Magnitude (35.748)

The relay is continuously measuring current and voltage on the CT and PT secondary circuits and computing impedance where $Z = \frac{V}{I}$. When a computed values falls on or within the zones the relay asserts the corresponding bit (often referred to as "picks up") (ZxP or ZxG). For example, a fault outside Zone 1 (blue) and inside Zone 2 (orange) will set the Z2P or Z2G pickup depending on the fault type. An impedance that falls within Zone 1 automatically falls within Z2, hence Z1P and/or Z1G pickup along with Z2P and/or Z2G. In the configuration a fault detected in Zone 1 will trip the relay immediately, while a fault detected in Zone 2, the relay will wait for a pre-defined time before tripping. In the configuration this value is set to 20 cycles under Distance Element Common Time Delay (Z2D) while Zone 1 was 80% of the line and Zone 2 is 120% of the line.

4. Protection Scheme – Direct Underreaching Transfer Trip

The primary goal in relay protection communications schemes is to communicate status or relay states from one relay to another to advance trip decision making based upon improved situational awareness. DUTT uses a one-way communication channel to send a signal that a fault has been identified with a specific distance (underreaching zone) by the local relay. In Fig. 4 a fault is detected near relay A, which results in a Zone 1 detection versus relay B which detects the fault in its Zone 2. In DUTT relay A will immediately communicate to relay B to trip and isolate the transmission section between relays. Without communications relay B will generally wait a pre-configured amount of time before tripping and clearing the line to ensure proper coordination.

DUTT allows for faster clearing of the fault and isolation of the line mitigating transients in the larger power system and protecting life and equipment.

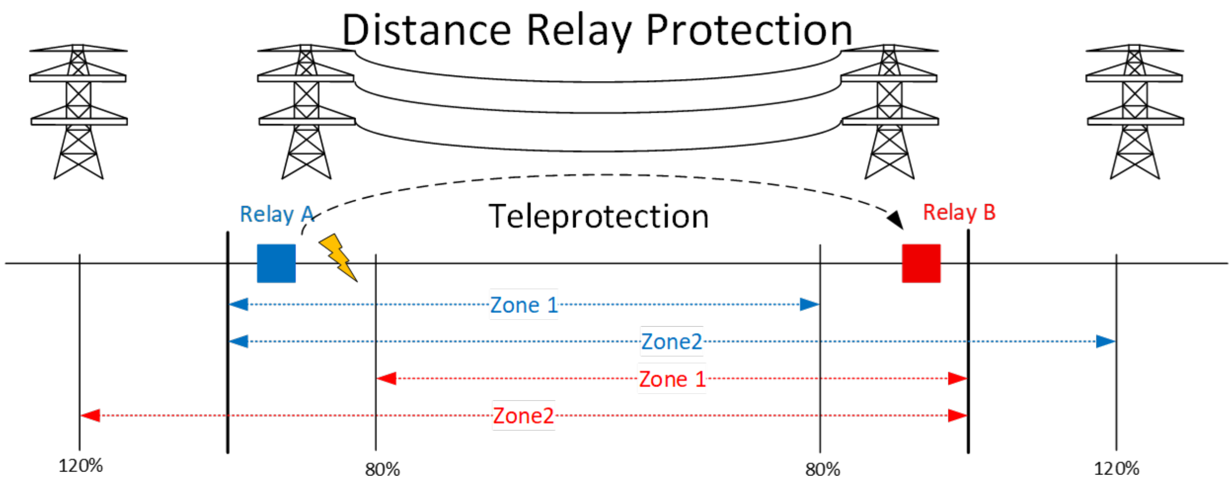

Figure 4: DUTT: Example Fault in Zone 1 for Relay A

In the Distance Protection scheme, we utilize implementation of Direct Transfer Trip (DTT) with various protocols. DTT uses data communications to send relay state status from one relay to the other, specifically in a Zone1 / Zone 2 pickup for relays at the end of a line. Several proprietary and open standards exist to implement this communication scheme. The most deployed schemes in the U.S. grid include "mirrored bits", the SEL MIRRORED BITS® protocol, and IEC 61850 - Generic Object-Oriented Substation Event (GOOSE) messaging. Implementation of the underlying communications to support the protection protocol can vary widely. The SPaRC program is designed to address these types of challenges by bringing to bear the capability of four national labs to examine different communication implementations and the effects on the relay protection scheme.

SEL Mirrored Bits is a proprietary protocol from Schweitzer Engineering laboratories (SEL) used in relay-to-relay communications introduced in the 1990s. Mirrored Bits is implemented on an asynchronous serial communication link and implements traditional serial error (sync, framing, overrun, parity) and security checks (identification error, CRC error, no message received in the time three messages have been sent). Mirrored Bits technology supports numerous protection, control, and monitoring applications. Mirrored Bits communications effectively sends bit status from one relay to another. Mirrored Bits can send 64 bits or eight 8-bit words between devices. Fig. 5 represents the transfer of relay bit states.

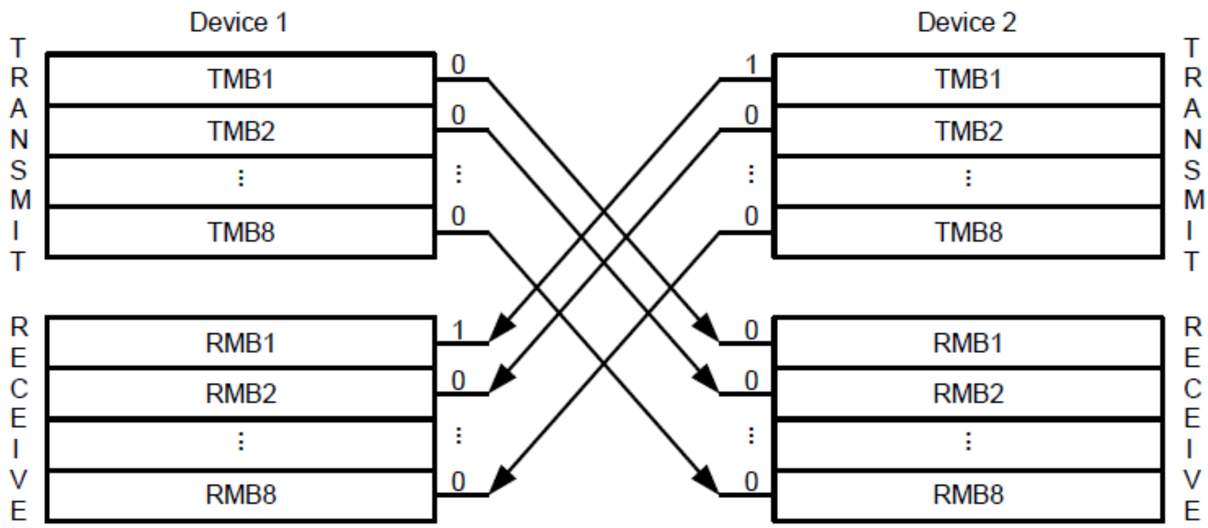

Figure 5: SEL Mirrored Bits Communications Bit Relationship

For DUTT in distance relaying, when a relay has a Zone 2 pickup it waits a specific amount of time to determine if it should trip, this is called the Zone 2 timer (ZT2) and in this configuration is set to 20 cycles or 0.33333 seconds. Under DUTT for distance relaying a relay that picks up a Zone 1 fault will transmit this state to the far end expediting the tripping of the entire line and isolating the fault from the system (see Fig. 4). Note that the Z2T is always present whether or not a remote signal from the other relay is received. In this configuration, this translates to each relay being identified as A or B and transmitting a bit (TMBx) to the far end relay where that far end relay would utilize that bit to trip. As an example, if relay A detects a fault in Z1 (0-80% of the line), that relay will trip instantaneously as well as transmit that status (TMBx) to the far relay which is monitoring constantly. Upon receipt of that bit at relay B, now called (RMBx), the relay will trip.

IEC 61850 GOOSE is an open standard messaging protocol based upon Layer 2 Ethernet (peer-to-peer) communications used in power substations and can be configured between relays to support DUTT. GOOSE provides a similar function of communicating state from one relay to another as Mirrored Bits, and in the DTT case Protection State Variables (PSV) was utilized between relays versus the TMBx and RMBx bits in the similar pickup conditions for Zone 1 and Zone 2.

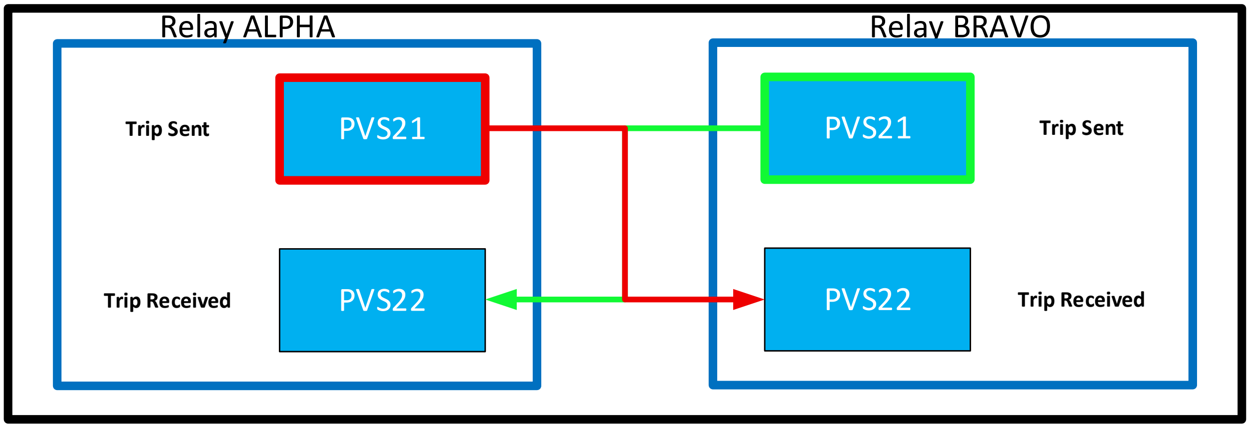

Figure 6: Simplified Diagram of Protection State Variables over GOOSE between relays

4.1.1 Synchronization and Timing

Timing synchronization is critical to understand the behavior of relays during faults, and with the additional impairment of communications, it is even more critical to understand impacts and validate either expected or non-expected behavior of the relay. Timing was provided to the SPaRC network via CAST and or traditional GNSS timing to ensure common reference synchronization between relays and test equipment. A detailed description for each setup can be found in the full test report.

4.1.2 Trip Configuration

The protective relay measures voltage and current on the CT and PT secondary inputs to the relay. These analog measurements are compared against configuration of parameters call pickup parameters. In this configuration several pickup parameters have been configured and include:

1) Zone 1 Phase (Z1P)
2) Zone 1 Ground (Z1G)
3) Zone 2 Phase (Z2P)
4) Zone 2 Ground (Z2G)

The Trip Equation used by the relay compares specific parameters to call for tripping. In this configuration the activation of the trip equation causes the normally open (N/O) contact (output 101) of the relay to close briefly.

TRIP EQUATION: Z1P OR Z1G OR Z2T AND RMB1A OR RMB2A. *(MIRRORED BITS)*

TRIP EQUATION: Z1P OR Z1G OR Z2T AND PSV22 *(GOOSE)*

This equation is enabled under any of the 5 conditions identified in the "OR" statement.

<u>Condition 1</u>: Zone 1 Phase pickup is high
<u>Condition 2</u>: Zone 1 Ground pickup is high
<u>Condition 3</u>: Zone 2 Timer has expired – Zone 2 time is 20 Cycles after Z2P or Z2G is picked up.
<u>Condition 4</u>: Receipt of RMB1A/RMB2A OR PSV22 depending on implementation

For testing purposes while using the relay test set, the Output port (101) was assigned for the Trip to evaluate the speed of the relays with the relay test set. Connection of the output contact to the relay test set provided a common reference to when the fault was initiated by the test set and when the relay closed the output port.

5. Communication Implementation

Each of the protection schemes identified can be supported via many different type of communication implementations. Most relay protection schemes involve relay to relay communication supported along the transmission system and can include multiple physical layer types that can support serial and Ethernet such as fiber, microwave, or transmission line conductors which may support Time Division Multiplexing, Power Line Carrier, and packet-based networks. Multiple communication implementations were examined for support of the protection schemes including:

- Serial over direct cable
- Serial over 900 MHz radio
- Ethernet
- Conversion of serial to IP over switched, routed, and microwave

5.1.1 Impairment of Communication Channel

The approach to impairment of the channel was dictated by each lab in their testing based upon availability of test equipment and include network emulators and wireless interference for wireless links.

Impairment via network emulator (Dropped, Altered, Delayed, Duplicated packets uni/bi directionally) was the primary tool for impacting any packet-based communications. For the microwave link, interference at different spectrum and power levels were implemented that translated to dropped packets on the microwave link, ultimately resulting in a similar test as dropped packets with the network emulator.

Impairment of the communication network directly relates to the QoS of the communication path. The diagram below represents how we implemented impairing communications.

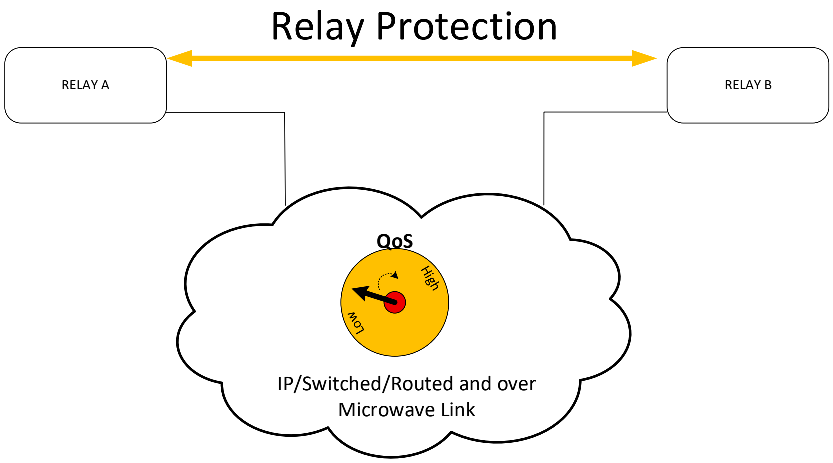

Figure 7: Path QoS impairment

A challenge in this testing was translation of an impaired packet-switched network carrying serial/IP traffic and the effects of the Mirrored Bits protocol from a serial perspective. Serial errors can be classified as parity, framing, or overrun errors that may come from an impaired channel. Translating this into delayed, dropped, altered, or duplicated packets of the converted serial/IP to UDP packets does not have a direct correlation. Outcomes via the relay statistics and states can provide insight but cannot translate directly how an impairment via a network emulator affects how the relay understands the serial connection to be functioning.

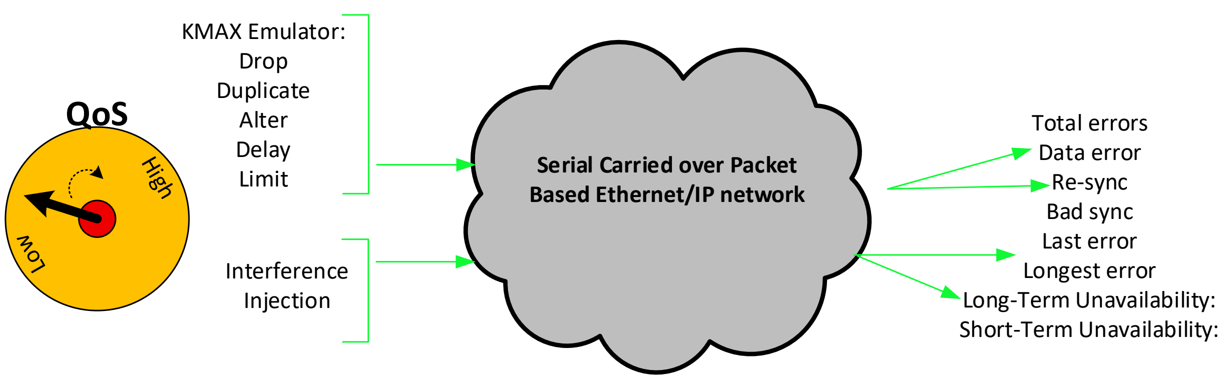

Figure 8: Packet Based Impairment to Serial in Mirrored Bits

5.2 Mirrored Bits protocol supporting DUTT

Mirrored Bits in a serial/IP configuration (TCC TC-3847-3) was robust and reliable for high-speed relay protection. The native serial protocol "guardrails" and SEL implemented security protocols provided secure and repeatable boundaries for performance of the Mirrored Bits protocol in several different impaired communication conditions. The primary indicator by the SEL relay was the ROKx bit which represented the condition of staying within the serial guardrails and security protocols.

We found that altering of the packet as well as dropping of the signal had the largest impact and translated directly to violation of the serial guardrails and/or security protocols, thus resulting in the relay indicating via the ROKx bit that the channel was not active. Under all tested impairments the Mirrored Bits protocol performed in a binary fashion, the communication channel was either good or bad, and the relay acted accordingly. Even in conditions when the delay of the path was extended past the Zone 2 timer (Z2T), the relay would trip on the timer and still received the RMBx bit afterwards. Below are some of the findings. For the full set, see the Test Methodology and Results document.

DELAY: In general, the delay of packets (under 100 msec) provided no unexpected behavior with the relay's performance and provided no errors on the Mirrored Bit channel. If delay was uniform in both directions the Mirrored Bit channel functioned well through all testing to 400msec of delay. In some extreme cases of large delta between direction delay (260 msec (A-B) vs 60 msec(B-A) data errors could be generated, however the Mirrored Bit channel recovers. In this case it is assumed that the relay is seeing a frequency check failing, but this is not available to be verified by statistics on the relay. In all cases the relays performed accordingly based upon the time of the received remote bit (RMB2A) relative to the Zone 2 timer (Z2GT, Z2PT). If the remote bit was received before the Zone 2 timer, the relay tripped as designed. If the remote bit was received on or after the time expiration, the relay tripped on the Zone 2 timer expiration and not the remote bit.

DUPLICATE: This impairment did not affect the Mirrored Bit Protocol and was assumed to be compensated 100% by the TCC Serial/IP unit dealing with duplicate packet arrival. At no level of percent duplicate (0 to100%) did the relay fail a check or produce an error.

DROP and ALTER: Both impairments affected the checks or guardrails of the Mirrored Bits protocol. Both impairments easily created a down state for the communication channel (ROKA de-asserted) with errors accumulating as either data errors, re-sync, and some cases bad sync. Unidirectional impaired traffic affected the receiving relay as expected and bidirectional impaired traffic affected both. During the testing for this setup, drop and alter setting were identified to be able to cause check failures frequently enough to cause the receiving relay comms path to bounce up and down consistently. As an example, at 0.75% of dropped packets the ROKA bit is de-asserted every few seconds providing an ON-OFF-ON-OFF pattern for the communication channel. When faults are injected to the relay, the relay consistently either received the remote bit (ROKA Asserted) or relied on the Zone 2 timer (ROKA de-asserted). This impairment was utilized in the field test below.

5.2.1 No Communications

The following table (table 2) presents the amount of time for the relay to detect and send the open command to the breaker without communications involved.

In this case a Zone 2 pickup by the relay will wait for the prescribed timer (Z2T) before tripping. Note that a breaker on a 345kV transmission line can add 30 to 80 milliseconds to clear the line electrically.

Table 2: Average Trip Times from Relay Test Set and Relays (NO COMMS)

NO COMMS	**All Fault Types**	
Average Trip Time from Relay Test Set	**Seconds to Clear**	**Cycles to Clear**
10%	0.3633	21.8
50%	0.0231	1.4
90%	0.3644	21.9
Average Maximum Trip Time of Relay A and Relay B		
10%	0.36351	21.8
50%	0.02307	1.4
90%	0.36428	21.9

5.2.2 Results WITH Communications NOT impaired

Table 3 differs from Table 2 in the fact that the relays are communicating in Zone 2 pickups allowing a faster trip and clearing of the line.

Table 3: Average Trip Times from Relay Test Set and Relays (COMMS)

COMMS	**All Fault Types**	
Average Trip Time from Relay Test Set	**Seconds to Clear**	**Cycles to Clear**
10%	0.0226	1.4
50%	0.02338	1.4
90%	0.02432	1.5
Average Maximum Trip Time of Relay A and Relay B		
10%	0.0223	1.3
50%	0.0232	1.4
90%	0.0237	1.4

5.2.3 Comparison of the clearing time averages

This comparison of the clearing times between different scenarios with and without communication demonstrates that DTT when used in distance relaying protection can improve clearing times in near-end and far-end faults when one of the relay's pickup is Z2.

Average improved clearing time is slightly greater than 20 cycles or 0.33333 seconds. 20cycles is approximately the Zone 2 Timer configured in this testing.

The results show on average 20.4 and 20.5 cycles which relates to the fact that faults near the relay are picked up sooner, instantaneously tripping and sending the TMRB1A to the other relay, often tripping that relay prior to the relay pickup of Z1 or Z2 resulting in faster than 20cycle savings in clearing time.

Table 4: Average Trip Times from Relay Test Set and Relay

	All Fault Types - NO COMMS		*All Fault Types - COMMS*	
Average Trip Time from Relay Test Set	**Seconds to Clear**	**Cycles to Clear**	**Seconds to Clear**	**Cycles to Clear**
10%	0.3633	21.8	0.0226	1.4
50%	0.0231	1.4	0.02338	1.4
90%	0.3644	21.9	0.02432	1.5
Average Maximum Trip Time of Relay A and Relay B				
10%	0.36351	21.8	0.0223	1.3
50%	0.02307	1.4	0.0232	1.4
90%	0.36428	21.9	0.0237	1.4

Table 5 represents date from the longer communication path between relays (80-miles with 2.4-mile microwave link). In this case degradation of the communication path QoS was able to be provided by both network emulators and interference injection on the wireless link.

Table 5: Short vs Long Data Path

% Line	**Average Trip (sec)**	**Relay A to Relay B TMBXA - RMBXA (Transmission Latency + Processing Latency)**	**Relay B to Relay A TMBXA - RMBXA (Transmission Latency + Processing Latency)**	**From To**
Network Emulator in BYPASS				
10%	0.0224	0.0090		A to B
50%	0.0234		0.0101	B to A
90%	0.0243	0.0096		Total
Long Distance Path with Interference				
10%	0.1123	0.0840		A to B
50%	0.0012		0.1045	B to A
90%	0.0815	0.0942		Total

5.3 Mirrored Bit Testing Summary

Through many conditions of Drop, Alter, Duplicate, and Delay, we could cause the Mirrored Bits protocol to de-assert the ROK bit and essentially take the Mirrored Bits protocol to a down state.

We found that the Serial/IP TC3847-3 was robust in its ability to handle the serial communications of UDP, even being able to maintain a connection with 100% duplication of packets in both directions and even maintaining delay in the circuit that was longer than the Zone 2 timer. (In this case we could show the protocol up and running, just with the RMBx bit arriving after the Z2T expired). The cases of alter and drop packets both had low thresholds (>1.0%) that would violate the SEL Mirrored Bits protocol guardrails and security measures ultimately de-asserting the ROK bit. It should be noted at the time of testing SEL did not recommend a configuration for serial over IP. Testing with the SEL 2890 ethernet transceiver would not synchronize the protocol, and Mirrored Bits could not come up.

Note: Synchronized trip timing with the start of the fault was not implemented in the longer distance communication with microwave, hence the first relay bit to pickup was used as reference.

Table 6: Total Latency Bi-Directionally

% Line	Average Trip (sec)			
10%	0.0176 s	0.0173 s		A to B (sec)
50%	0.0023 s		0.0172 s	B to A (sec)
90%	0.0171 s	0.0173 s		Total (sec)

Final testing included a longer communication circuit (80 miles) with a short microwave link (2.4 miles) with injection of interference into the wireless link reproducing dropped packets. Additionally, we tested the entire line with the same impairments of Drop, Duplication, Alter, and Delay without any unexpected results.

5.4 Mirrored Bits with 900 MHz radio

Additional testing was completed by ORNL on a SEL-3031 900MHz radio that supported Mirrored Bits between relays in an alternative protection scheme. In this setup Mirrored Bits was used as Direct Transfer Trip for sending a 51S1 bit (representing measured current exceeding the 51S1 pickup setting for a duration of the time dial and current magnitude of time-over-current curve) and TRIP bit. ORNL was able to demonstrate interference to the 900MHz channel with LoRa and Z-Wave devices which transmit in the 900MHz range. These two IoT protocols are frequently used in the low powered radio application space.

This means they are not intended to be constantly streaming data and are meant to send information sporadically.

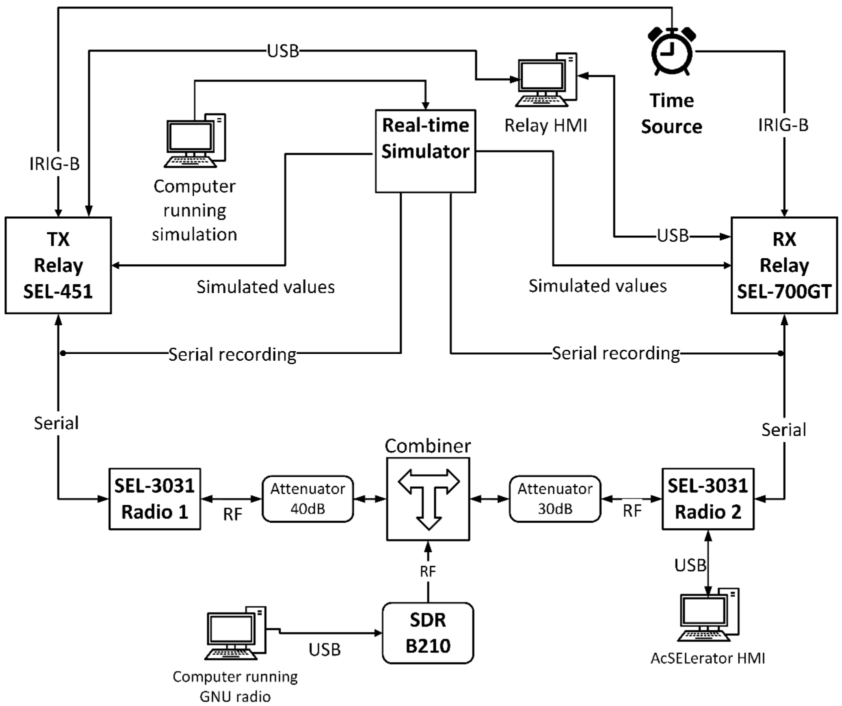

Figure 9: ORNL 900 MHz setup

In a real-world situation, the likelihood of an SEL-3031 transmitting at the same time as LoRa or Z-Wave receiver is sporadic at best. Additionally, the SEL-3031 hops around the spectrum, so any IoT radios transmitting in a single channel will only affect the SEL-3031 for a single frequency transmission.

If these radios are configured to utilize the Mirrored Bits serial protocol the resiliency of this communications link is increased. One reason for this is that the Mirrored Bits messages are very short which leads to a high update rate from one relay to another. Not only is the update rate very high for each message, but there are built in communication checks in the Mirrored Bits® protocol.

5.5 GOOSE Protocol Results and Findings

GOOSE protocol testing saw similar results to the Mirrored Bits test and was robust to delays, jitter, and packet duplication. **Error! Reference source not found.** present the results for the tests comparing no communication and varying delay lengths on the GOOSE messages. The difference in clearing times between the scenario with no communication and the scenario with no delay is ~200 ms. The clearing time with no delay up through the clearing time that matches the Zone 2 detection are the fastest possible clearing times, since Bravo waits for the detection of the Zone 2 fault before tripping even if a communications signal is received. The 400 ms network delay is effectively operating without communication to clear the fault.

Table 7: Comparison of Clearing Times with Network Delays

	Relay ALPHA	Relay BRAVO	Difference
No Comms Average	0.01534 s	0.34784 s	0.3325 s
No Delay Average	0.0154 s	0.1494 s	0.134 s
5 ms Average	0.01563 s	0.14927 s	0.13364 s
50 ms Average	0.01535 s	0.14864 s	0.13329 s
100 ms Average	0.01483 s	0.14877 s	0.13394 s
150 ms Average	0.01539 s	0.1721 s	0.15671 s
200 ms Average	0.01519 s	0.221783 s	0.206593 s
250 ms Average	0.0.1507 s	0.27123 s	0.25616 s
400 ms Average	0.01604 s	0.34709 s	0.33105 s

Figure 10 present the results using the network emulator to delay the communication between the relays. The Bravo Z2 pickup remains constant during the testing which is expected. Network delays between 5ms and 125ms did not affect the time it took to remove the fault. However, after 125ms of network delay is when clearing time for the removal of the fault starts to increase.

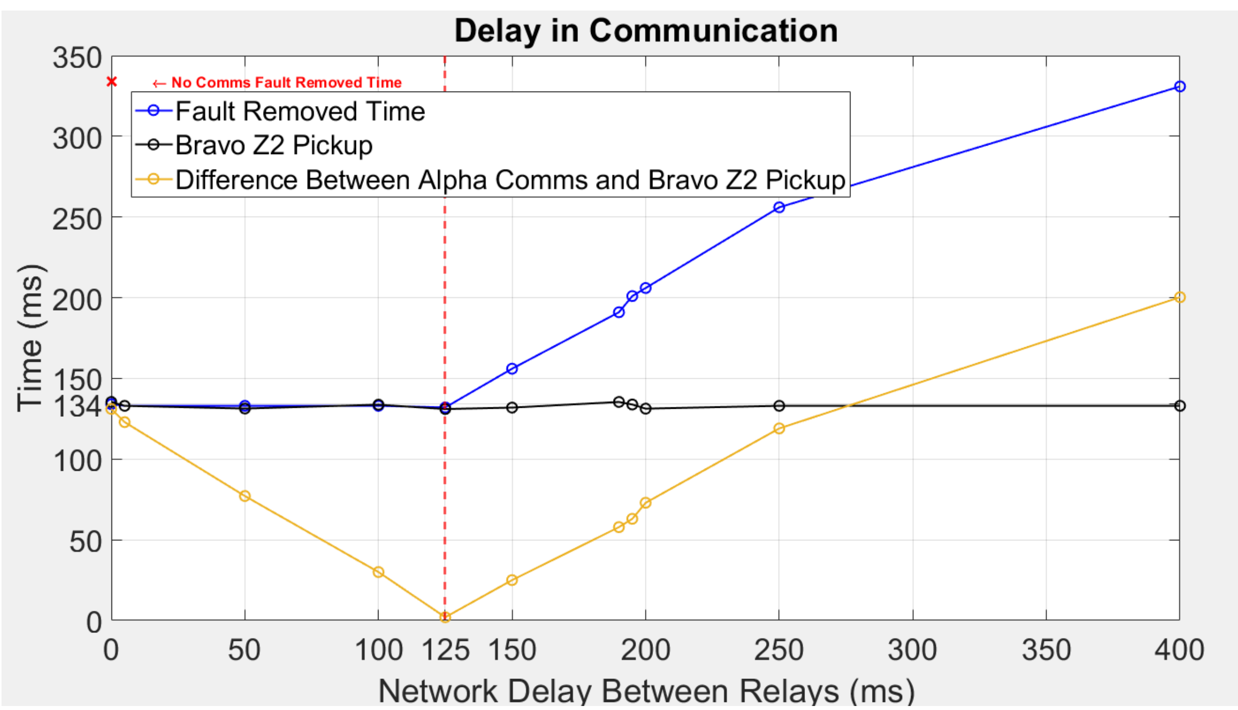

Figure 10: Comparison of Communication Delay and Difference in Tripping Times Between Relays

The GOOSE protocol had less predictable behavior under packet alteration by the network emulator. The network emulator can alter packets in several different ways, including bit or packet corruption or payload corruption only. In bit corruption a probability is applied to every single bit that is part of the packet and various ones are altered based on the results. For packet corruption only a single bit within that packet is altered. If the payload alteration checkbox is selected, the alterations are applied only to elements of the payload and not the packet header.

For example, **Error! Reference source not found.** presents the results of a testing scenario with 100% probability of packet corruption. The timing difference from test 1 and test 6 indicate the trip signal was not received or correctly interpreted by the relay for these tests. This could be caused by an alteration in the header of the packet, preventing the message from reaching its destination or an alteration in the packet payload that does not allow the information to be interpreted correctly.

Table 8: 100% Probability of Packet Alteration SNL Communication Testing

Electrical Trip Diff.	Relay ALPHA	Relay BRAVO	Difference
Test 1	0.01444 s	0.34704 s	0.3326 s
Test 2	0.01439 s	0.14699 s	0.1326 s
Test 3	0.01624 s	0.14684 s	0.1306 s
Test 4	0.01544 s	0.15009 s	0.13465 s
Test 5	0.01474 s	0.14779 s	0.13305 s
Test 6	0.01584 s	0.34789 s	0.33205 s
Test 7	0.01538 s	0.15014 s	0.13475 s
Mean	0.15106667 s	0.181481667 s	0.166375 s

Applying either packet or bit corruption to the GOOSE packets resulted in the Bravo relay losing communication assisted tripping functionality in some of the tests. It was also determined that after applying test scenarios that caused the Bravo relay to lose communication, the only way to gain the communication assisted tripping functionality back was to reset the relays and the software defined network (SDN) switch. A full study to determine the specifics of payload level corruption that caused this failure was not conducted.

6. Summary and Findings

The testing methodology used across the four different laboratories provided a robust testing environment to establish comparable results.

The following are key findings:

- Mirrored Bits protocol is reliable and resilient and can be better understood with knowledge of the potential errors of asynchronous serial protocols, the SEL security checks and the impact to the ROK bit.

- The TCC TC-3847-3 serial to IP converter provided a robust and highly resilient tool to move older traditional serial communications to a packet switched network.

- Impairment of the communication path through dropped and altered packets readily impacted the ROK bit as expected based upon the serial protocol error types and security checks of the Mirrored Bit protocol. Note this condition would exist in a serial application or the serial-over-IP simulated at INL.

- Similar to Mirrored Bits, under a variety of delay conditions to the GOOSE protocol, the relay behaved as expected. Receipt of the communications trip signal prior to detection of a Zone 2 fault resulted in the relay waiting for the fault to be detected and tripping. receipt after detection of the Zone 2 fault and the starting of the Zone 2 timer resulted in immediate tripping; and receipt of the communications trip signal after the Zone 2 timer expired and the relay tripped resulted in no change.

- Under some packet corruption scenarios with the GOOSE protocol, the bravo relay would fail to respond to communications until both the SDN switch providing the connection, and the relay were rebooted. Observation of network traffic suggests that this was not an issue with the switch, traffic was still being passed, however the relay simply stopped responding. If this condition was triggered by the corruption, it persisted until rebooted even if unaltered packets were sent.

- Protection schemes are a critical and important configuration of protective relays in the electric grid today, and more attention needs to be brought to the fusion of communications and power systems. It is important to develop integration steps for utilities to migrate to more modern communication systems that have performance parameters needed to support high-speed protective relaying.

Critical gaps in simulation capabilities were identified. Specifically, several software candidates fail to model all 10 classic fault types, restricting the ability to validate protection schemes against every required fault scenario.

The US Department of Energy's SPaRC (Secure Pathways for Resilient Communications) program is leading grid communications research and development through a multi-National Lab testbed, established to design, test, evaluate, and benchmark next-generation secure communications architectures and technologies. A secure communications system protects the end-to-end physical pathway that transports data from origin to destination. Key SPaRC activities include the Grid Communications Test Bed, Next-Generation Communication Experiments, and Education & Technical assistance. For more information see: https://securecomms.ornl.gov/