

WILDFIRE MITIGATION

# Detecting and Isolating Falling Conductors in Midair Using 900 MHz Private LTE at Protection Speeds

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## **Abstract**

The falling conductor protection (FCP) application developed by Schweitzer Engineering Laboratories, Inc. (SEL) depends upon reliable, low-latency broadband communications to de-energize broken distribution power lines as they fall, eliminating the risk of wildfire caused by arcing of live wires on the ground [1] [2] [3]. This paper describes the test bed operation of the FCP application enabled by a private Long-Term Evolution (LTE) network using Anterix's 900 MHz band spectrum. It reports that, in a range of network congestion and signal strength scenarios, the 900 MHz private LTE network successfully supports the FCP application to de-energize the affected circuit section within one second. This is less than the time it takes for a broken conductor to fall to the ground, typically a distance of 25 feet.

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## Introduction

As the need for active protection continues to increase, proper networking and communications systems are becoming important to support the electric grid. As outlined by the California Public Utilities Commission, a modern grid should have increased resilience to wildfire hazards [4]. Further, as outlined in the U. S. Department of Energy's "Grid Modernization Multi-Year Program Plan," increased reliability, enhanced security, and superior flexibility are necessary to respond to variability [5] [6]. Specifically, for active protection systems, falling conductor protection (FCP) technology [7] can be deployed and evaluated in both centralized and decentralized architectures. In both architectures, private networks utilizing LTE (PLTE) are integrated as the broadband wireless technology. Some utilities will collaborate on accelerating the pace of technological development by focusing on grid modernization innovation and wildfire mitigation.

The use of communications networks enables a variety of grid modernization applications, such as protection, fault location, isolation, and service restoration (FLISR), Volt-VAR Optimization (VVO), Advanced Metering Infrastructure (AMI), and SCADA. Power system utilities use diverse communications interfaces, such as fiber, Ethernet, telephone, cellular, and other proprietary mesh or wireless technologies, to exchange information between assets, such as intelligent electronic devices (IEDs) and substations. Typical communications transports for critical infrastructure applications are comprised of multiple standards and protocols, such as Modbus, DNP3, IEC 61850, and others. A robust, secure, and reliable infrastructure to enable efficient communication is required.

Among the grid operation challenges that can benefit from communications, this paper considers reliable protection that focuses on active detection for hazard mitigation. The work presented here particularly focuses on the PLTE infrastructure that is applied in an FCP relaying application in an advanced SCADA topology [8].

In this paper, PLTE is evaluated to implement the communications among active protection equipment in the field via 900 MHz LTE-connected IEDs, or simply LTE IEDs. The objectives are to show proper functionality and to characterize performance over various deployment scenarios. This work will also serve as a source of data for future analysis to fine-tune operational parameters for implementing FCP over PLTE.

### **Overview of the SEL/Anterix 900 MHz Private LTE (PLTE) Experiment**

Standardized and proprietary wired and wireless technologies can be used to facilitate information signaling for this application. This paper focuses on the use of wireless communications within a privately owned network. LTE, in general, provides highly robust wireless communications characterized by broadband bandwidths with low latency. It utilizes advanced physical layer techniques, such as multiple-input, multiple-output (MIMO), adaptive modulation, and space-time resource scheduling. It is a standardized technology that originated from 3GPP since Release 8. Inherently, it is IP-based and can be used for various data planes and voice in both commercial and enterprise end-user applications. It has progressed from data pipeline technology to service tier technology that now encompasses communications not only for voice and mobile phone applications but also for critical infrastructure, such as Internet of Things (IoT), push-to-talk (PTT), video, and others. Since 3GPP Release 13, LTE encompasses enhanced technologies for NB-IoT, Cat-M, and LTE-Advanced-Pro compatibility.

LTE for consumer and commercial use is typically provided to end users via service arrangements on their own mobiles or other LTE user equipment.

Implementing LTE within a privately owned network broadens the scope for the end user to own the entire infrastructure of the LTE network, including the evolved packet core (EPC), radio access network (RAN), and user equipment. In this arrangement, the end users, who are typically enterprise customers, are supplied the entire wireless infrastructure to integrate within their own IT and operational technology (OT) private enterprise.

Benefits include:

- Full end-to-end network control and optimization plus traffic prioritization that seamlessly integrates with IT networks and OT applications.
- End-to-end wireless design and life-cycle management converged with IT networks.
- Robust security and full visibility of the wireless network elements within the enterprise Security Operations Center (SOC)/IT/OT requirements.
- A 900 MHz LTE ecosystem based on 3GPP standards that scales across multiple infrastructure and LTE device vendors.

## **OVERVIEW OF FALLING CONDUCTOR DETECTION SYSTEM**

Application—Detect broken conductors to minimize the risk of wildfire and danger to the public. Broken overhead electrical conductors that reach the ground present a wildfire and public safety risk. The faster the broken conductor can be detected and de-energized, the lower the risk of fire or danger to people.

## **PRIOR DETECTION METHODS**

Historically, detecting downed conductors on high-impedance ground surfaces has been difficult because they do not typically generate high fault currents that can be detected by overcurrent protective relays. An energized conductor in contact with the ground provides a high-impedance path to ground, typically resulting in fault currents that are too low to trip overcurrent protective relays. In some cases of falling conductors, an initial high fault current is seen from a tree falling on the line, or the line contacting another conductor or ground wire, causing the overcurrent relay to open to protect the line. However, the relay will typically not sense a high fault current upon reclosing after the line has contacted a high-impedance ground surface, and the line will remain energized. Various methods have been used to detect downed conductors, including detection of signatures from harmonic and interharmonic energy caused by arcing that is associated with a downed conductor. The one thing these methods have in common is that they do not begin their detection process until the conductor is already on the ground and arcing. It can take several minutes for these detection methods to identify a downed conductor once it has made contact with the ground.

## **NEW FALLING CONDUCTOR DETECTION METHOD**

A new method for broken conductor detection is described in the paper “Catching Falling Conductors in Midair – Detecting and Tripping Broken Distribution Circuit Conductors at Protection Speeds” [7].

This method uses synchrophasor data streamed from both ends of a protected line segment to calculate the rate-of-change of conductor voltage ( $dV/dt$ ) and changes to sequence voltage magnitude and angles to evaluate if a conductor has broken. Using this method, it is possible to detect the presence of a broken conductor and signal protective relays to de-energize the affected line segment in less than 500 milliseconds (which is considerably less than the time it takes for a broken conductor to hit the ground), thereby mitigating the fire and public safety hazards associated with an energized conductor arcing on the ground.

## FALLING CONDUCTOR DETECTION SYSTEM COMPONENTS

The main elements of the falling conductor detection system are the following:

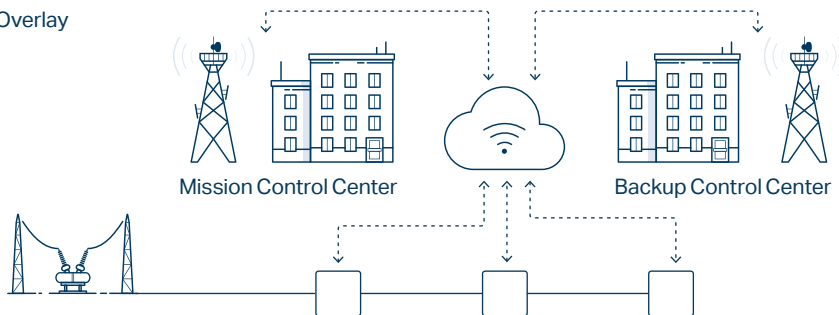
- Protective relays (or recloser controls) and associated switchgear at each end of every line segment covered by the falling conductor detection system. The protective relays act as phasor measurement units (PMUs), to collect phasor data for the line segment and signal the associated switchgear to open and de-energize the affected line segment when a falling conductor is detected.
- High-bandwidth, low-latency communications to transmit phasor data between all PMUs and the phasor data concentrator (PDC)/real-time automation controller (RTAC) running the falling conductor detection algorithm. Each PMU synchronously samples the conductor phasor measurements 30 times per second. Data from all PMUs need to arrive at the PDC within 200 ms of being sampled to be included in the PDC data packet that is passed along to the controller running the falling conductor detection algorithm.
- The RTAC controller that runs the falling conductor detection algorithm, which uses multiple calculations to evaluate the incoming phasor data and detect a falling conductor. The measured values being evaluated by the algorithm do not change instantaneously, requiring some time for the algorithm to decide as to whether a falling conductor event has occurred and signal the protective relays to issue the trip command and de-energize the affected zone. In a typical application, the controller running the falling conductor detection algorithm will simultaneously evaluate each phase of different line segments and will detect the broken conductor and signal only those protective relays on each end of that line segment to open and de-energize the affected circuit.
- High-bandwidth, low-latency communications to transmit IEC 61850 GOOSE trip messages from the RTAC to the protective relays in the event a broken conductor is detected.

## CRITICAL SYSTEM REQUIREMENTS

The key performance requirement of the system is response time. Assuming a typical distribution system conductor is 25 feet above the ground, Newton's Law tells us that a broken conductor will hit the ground about 1.25 seconds after a break occurs. Taking into account the time it takes for switchgear on the line to operate, the system has approximately one second to make a decision and signal the relays to open the breakers and isolate the faulted section. The detection algorithm relies on the quality of the phasor measurement data to make a quick decision as to whether a broken conductor event has occurred. If data from some PMUs is unavailable or if its reception is delayed, the algorithm will take more time to detect a broken conductor. Ensuring reliable and timely reception of the phasor measurement data by the RTAC requires a communications method with adequate bandwidth and low, deterministic latency to transmit the data from the PMUs to the RTAC. These same system characteristics will ensure that the GOOSE trip messages are also received with minimal delay by the protective relays in the event a falling conductor is detected.

## SCADA SYSTEM ARCHITECTURE

### Traditional Overlay



### Advanced Overlay

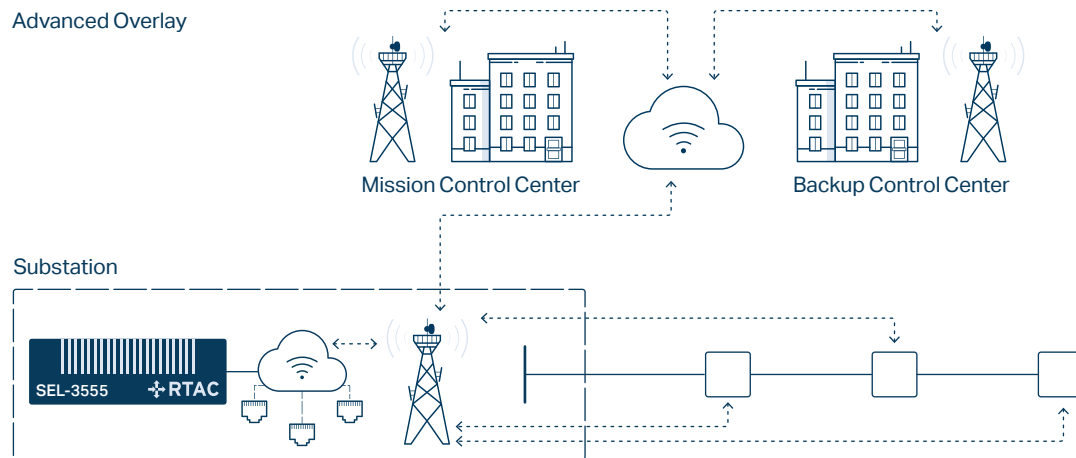


Figure 1—Advanced SCADA architecture versus traditional [8]. Copyright SEL, SDGE, and Quanta Technology, 2016.

For the advanced SCADA architecture demonstrated in this experiment, PLTE is employed as the communications interface. This choice enables flexible control and optimization of advanced SCADA device signaling and provides a resilient and secured wireless communications topology that has broadband performance in both latency and capacity.

## Typical PLTE Metrics and Deployment Scenarios

### APPLICATIONS

To evaluate application performance and latency end to end with PLTE under various network signal and traffic utilization conditions, FCP-triggered events are performed. FCP, as described in the previous section, is a protection function of distribution systems that quickly disconnects, or de-energizes, a live conductor when an affected circuit opens. The objective is to avoid an event in which live conductors on the ground cause a short circuit because of unintended local arcing conductivity during a falling conductor event, resulting in a fire hazard. This function requires the highest level of resilient transmission of the signaling to and from the participating protection IEDs. Moreover, the triggering of relays and controls with low latency, even under congested or low-signal quality channel conditions, is required. This is a critical test of advanced SCADA operations for a utility's protection use case using a dependable wireless communications solution.

In contrast to uplink PMUs that require high bandwidth, downlink command signaling requires low latency and low bandwidth analogous to other system protection-related functions. It requires the transmission of signaling to multiple remote IEDs using 900 MHz LTE gateways on a distribution system (e.g., recloser controller or relay) with low latency. It also requires signaling of PMU/phasor measurement information to and from multiple remote IEDs using the additional 900 MHz LTE gateways to an aggregation point, where tripping decisions can be actively made and transmitted to the IEDs for opening the associated breakers. IEC 61850 and IEEE C37.118 protocols are the transport layer signaling used by the application's signaling and PMU functions. This paper provides the results of using PLTE-enabling communications for the FCP application.



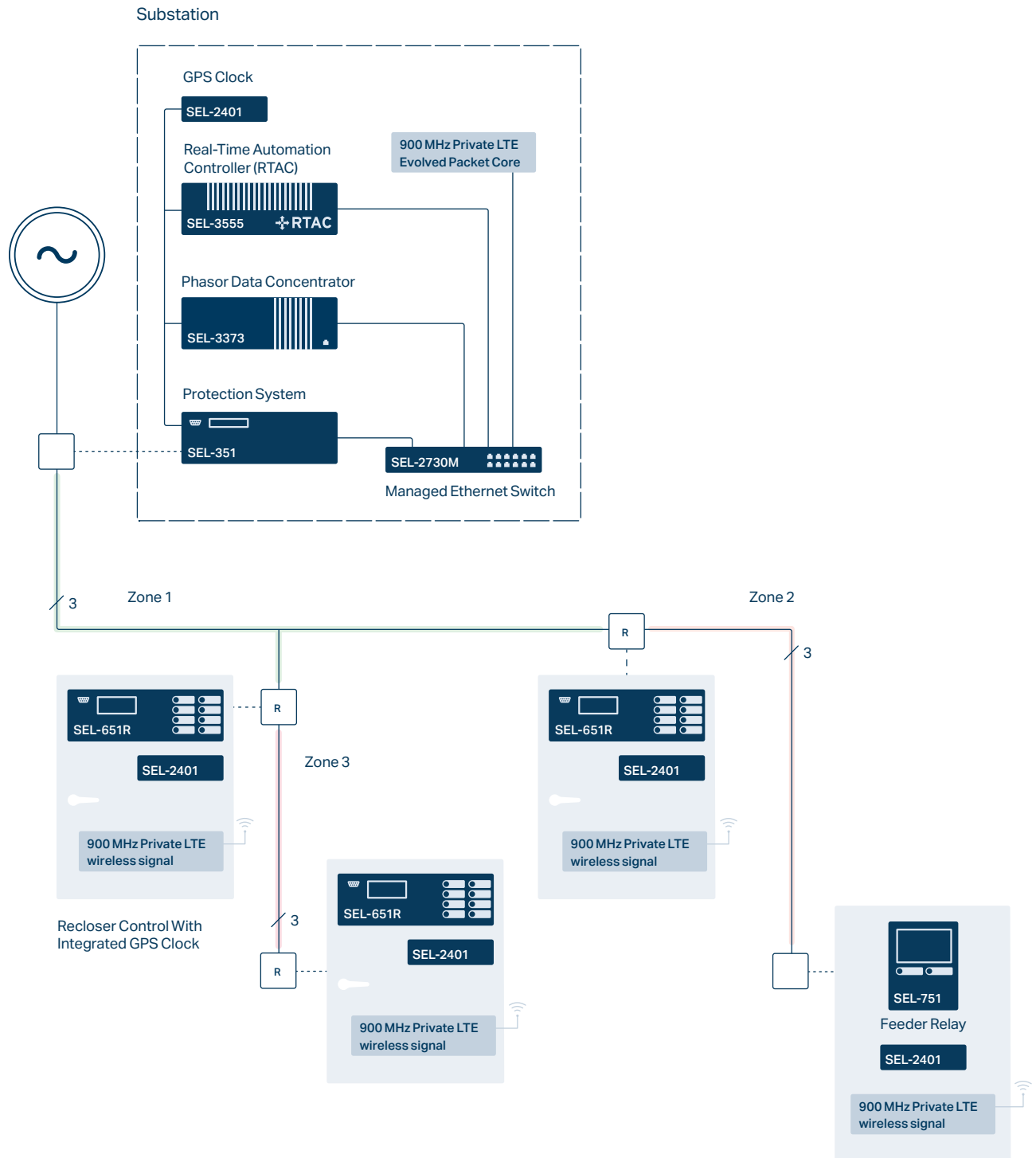


Figure 2—FCP one-line architecture system under test.

Figure 2 shows the system with one line used for testing the 900 MHz PLTE system. It is a standard 12 kV distribution circuit with an SEL-351 Protection System at the substation and an SEL-651R-2 Advanced Recloser Control and SEL-751 Feeder Protection Relay in the field. A real-time digital simulator (RTDS) is used in the test setup to model the distribution circuit. This testing involves the hardware-in-the-loop (HIL) feature. The physical test rack consists of the following equipment:

- SEL-351 Protection System
- SEL-651R-2 Advanced Recloser Control
- SEL-751 Feeder Protection Relay
- SEL-3373 Station Phasor Data Concentrator (PDC)
- SEL-3555 Real-Time Automation Controller (RTAC)
- SEL-2407® Satellite-Synchronized Clock
- 900 MHz PLTE system—Full EPC/RAN 3GPP Release 13
- Cisco unmanaged switch

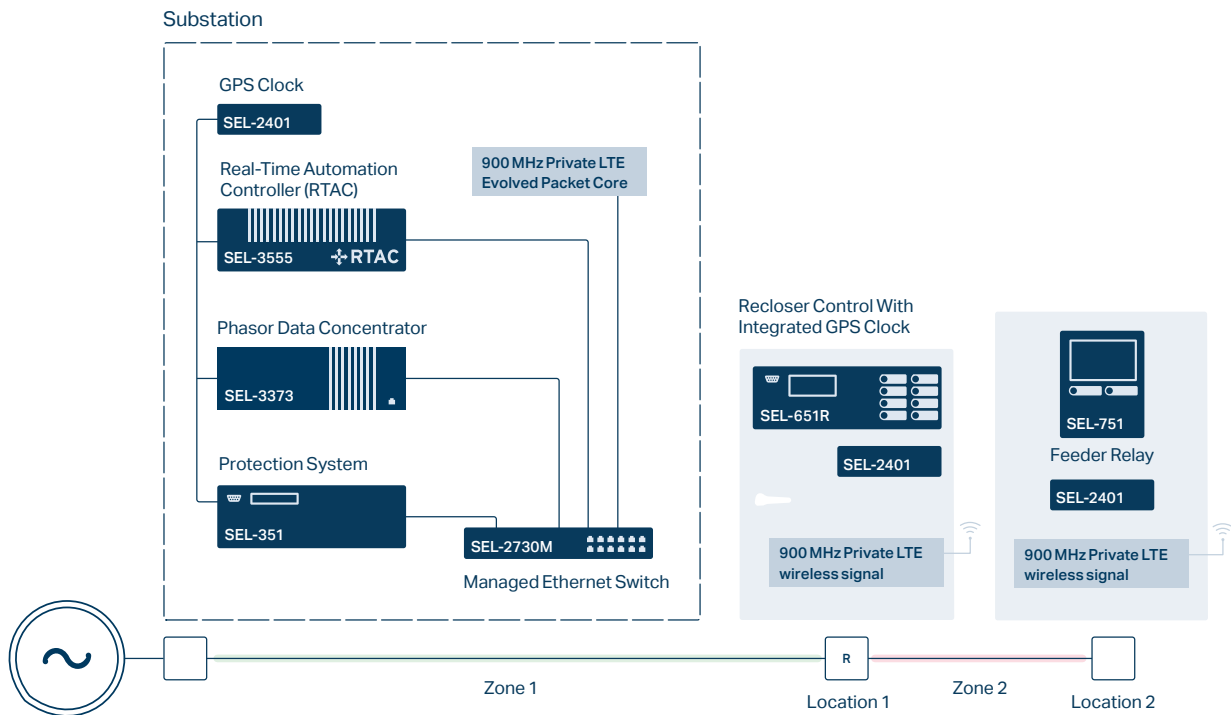


Figure 3—Test system scenarios with falling conductor events at remote Locations 1 and 2.

For the testing using PLTE, a falling conductor event is simulated at either Location 1 or Location (see Figure 3). Once the event occurs, the PMU data from protection equipment on each end of the line segment with the broken conductor will begin to show the signature waveforms of the conductor break. The falling conductor detection algorithm is continuously monitoring each phase of every line segment, looking for changes in system voltage over time (dV/dt) or for differences in sequence voltage magnitude or angles between the measurements on each end of every line segment. If any of these measurement methods exceeds the system thresholds, the algorithm indicates a falling conductor event and the RTAC sends trip signals to the appropriate protective devices. For a broken conductor in Location 1, trip signals are sent to the SEL-351 and SEL-651R-2 to isolate that line segment. For a broken conductor in Location 2, the trip signals are sent to the SEL-651R-2 and the SEL-751 to isolate that line segment.

An initial calibration scenario was implemented with a wired connection to and from the PDC and the protection equipment using an unmanaged switch and IP targets within the same subnet. The objective of this test was to establish the baseline for latency measurements in the test bed and to qualify necessary signaling between the various SEL equipment using IEC 61850 and IEEE C37.118 protocols.

#### INITIAL CALIBRATION RESULTS

Synchrophasor data quality between the IEDs and the PDC was verified using SEL PDC Assistant software. Healthy IEC 61850 communications quality was verified between the RTAC and all the relays in the test set up.

The following is a summary of IEEE C37.118 and IEC 61850 communications checks between various points in the test system shown in Figure 2:

##### 1. IEEE C37.118 communications data:

Transmit	Receive	Status
SEL-351	PDC	OK
SEL-651R-2	PDC	OK
SEL-751	PDC	OK
PDC	RTAC (for SEL-351)	OK
PDC	RTAC (for SEL-651R-2)	OK
PDC	RTAC (for SEL-751)	OK

##### 2. IEC 61850 communications signaling (communications confirmed with packet capture [PCAP] logs):

Transmit	Receive	Status
RTAC	SEL-351	OK
RTAC	SEL-651R-2	OK
RTAC	SEL-751	OK

The system acted as expected in response to falling conductor simulations at Locations 1 and 2.

The average communications latency from the RTAC for five iterations of falling conductor events at both locations is:

- 11 ms for the SEL-351
- 10.2 ms for the SEL-651R-2
- 12.6 ms for the SEL-751

The average falling conductor initiation-to-trip time for five iterations of falling conductors at Locations 1 and 2 is:

- 274.4 ms for the SEL-351 at the substation location (no wireless in Network Architecture 1)
- 273.7 ms for the SEL-651R-2 at Location 1
- 276.2 ms for the SEL-751 at Location 2

These latency (falling conductor initiation-to-trip time) results are well within the limits of this FCP application with an operational target requirement of approximately one second for a 25-foot-tall distribution line. This is expected since the baseline results were established with wired connectivity between the various SEL protection equipment elements in the test bed.

#### **SYSTEM ARCHITECTURE USING PLTE**

The PLTE communications system uses off-the-shelf 3GPP Release 13 standardized LTE hardware and software implementations from Amarisoft. The components include an EPC, eNB, and multiple LTE gateway access points. Two access points provide the wireless connectivity to the two protective IEDs on the test bed. An additional access point generates traffic loads to simulate various resource utilization conditions on the LTE air interface. These access points operate at 900 MHz and were procured off the shelf from GE and Encore Networks. A private enterprise server was also implemented with various quality of service (QoS) tiers. Since the underlying SEL FCP application operations network requires the same subnet connectivity, a frame relay topology was employed. See Figure 4 for the PLTE architecture. The experiment was performed indoor in a controlled test environment.

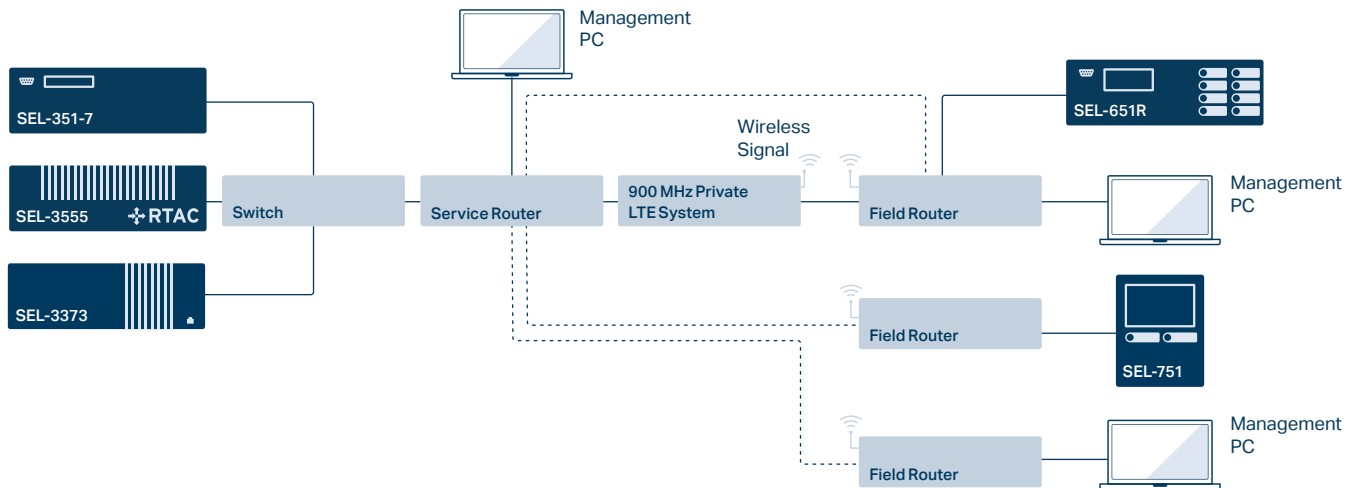


Figure 4—PLTE architecture diagram for Network Architecture 1 enabling wireless connectivity for SEL FCP test bed.

Three segments of VLANs were implemented to segregate traffic based on the priority of their payloads. Prioritization is possible because the LTE system is a private network using licensed spectrum. Implementation of QoS Class Identifier (QCI) tagging was configured for bidirectional wireless traffic. QoS tagging was further implemented using various service tiers defined in both the router, on the server side, and on each of the LTE gateway access points, on the field equipment side. In a practical end-to-end scenario, protection signaling and commands would typically be set to traverse wirelessly over the LTE with higher priority than other traffic, e.g., AMI or other SCADA traffic.

There are two potential network topologies to be supported. In Network Architecture 1 (Figure 4), the substation location is treated as an edge PDC point where the wireless PLTE eNB would terminate an air-interface link from the various LTE gateway access points connected to SEL relays and controllers. In this scenario, the PDC is directly connected via wired interfaces at the edge (e.g., via fiber or Ethernet backhaul to the utility's data center application server), providing ultra-low-latency communications performance.

In Network Architecture 2, the substation and the PLTE eNB are not colocated with the edge PDC. In this scenario, added wireless links are required to interface not only with the various LTE gateway access points, but also with the interface between the PDC and the utility's data center application server. In this scenario, the PDC's communications link adds additional LTE air-interface latency. In practice, when it is cost-effective, this situation can occur in remote feeders in rural areas. See Figure 5 for the Network Architecture 2 structure.

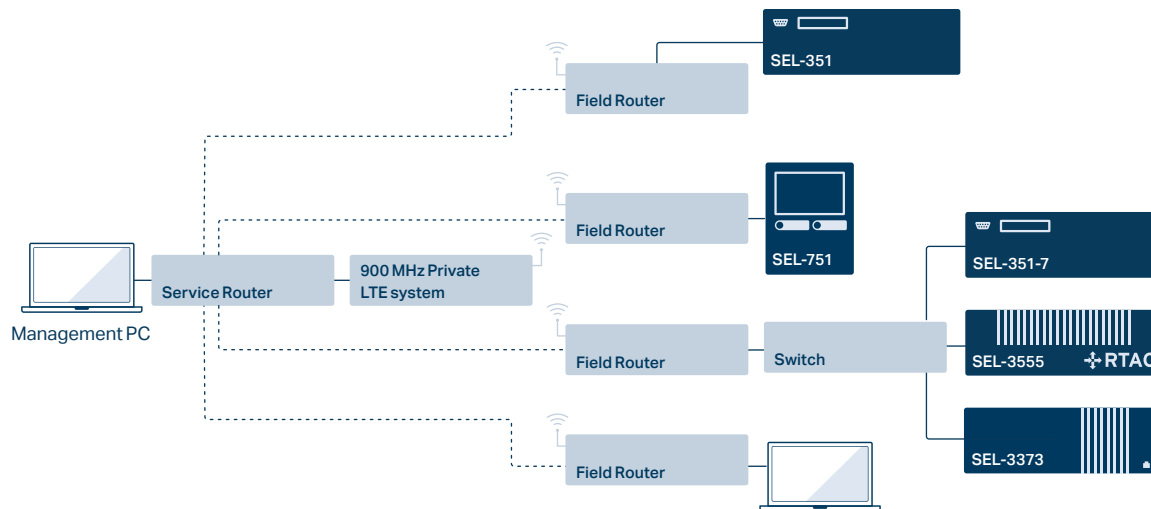


Figure 5—PLTE architecture diagram for Network Architecture 2 enabling wireless connectivity for SEL FCP test bed.

## RESULTS

In Network Architecture 1, an implementation of PLTE connecting various protection hardware was tested, as illustrated in Figure 3. Six different wireless scenarios were tested. In these tests, latency is calculated based on the difference in time between the PDC and various protection equipment locations in the simulated SCADA system.

Test ID	LTE signal condition	Traffic load	QoS priority
1	Medium	Medium	Low
2	Medium	High	Low
3	Medium	High	High
4	Low	High	Low
5	Low	High	High
6	Low	Medium	High

Table 1—List of tested scenarios using Network Architecture 1.

## SIGNAL CONDITIONS

Implementing broadband wireless using LTE is advantageous since it can service a wide coverage range for LTE IEDs wherever a signal is available. The signal is provided in the downlink direction by an LTE eNB at a tower location for traffic sent to LTE IEDs. This is key for RTAC trip commands. Each LTE IED also transmits its signal in the uplink direction to the LTE eNB receiver on the tower. LTE IEDs near a base station have strong signal strength and signal quality in both downlink and uplink directions. In general, LTE IEDs farther from an LTE eNB tower or base station have weaker signal strength and signal quality in noise-limited areas. In these tests, typical wireless coverage refers to wireless signal strength in the medium signal range of an eNB. In general, medium signal quality is afforded 16-quadrature amplitude modulation (QAM) bitrates per LTE Channel Quality Indicator (CQI) scheduling in the downlink direction.

The following operating points were implemented during the testing of various signal strengths and quality of the LTE air interface.

Signal condition	Typical signal strength— measured as reference signal received power by the LTE access point	Typical signal quality in the downlink direction (reference signal SNR)	Per antenna attenuator setting on the PLTE test bed
High	-70 to -80 dBm	>25 dB	~30 dB
Medium	-100 to -115 (noise-limited test environment) dBm	10 to 20 dB	~50 dB
Low	-120 to -125 dBm	<=5 dB	~60 dB

Table 2—LTE signal condition test parameters.

### TRAFFIC LOAD CONDITIONS

As noted in previous sections, the PLTE implementation prioritizes user traffic. The benefit of prioritization is to reduce the latency of time-critical traffic when the network becomes congested with other, lower-priority traffic. The private LTE system can implement priority queuing for both synchrophasor telemetry payloads and the command to relay traffic. Since the messages use IEC 61850 and IEEE C37.118 protocols, any associated acknowledgments and retransmissions are also treated with the same priority levels compared to other traffic.

Without implementing traffic load on the PLTE air interface via the Encore LTE access point, the only traffic generated over the wireless interface is from the protection equipment payloads. If a traffic load on the Encore LTE access point is generated, then the additional wireless resources are utilized within the LTE air interface. Specifically, LTE resource block (RB) traffic utilization is measured. In a scenario where an uplink or downlink LTE air interface is fully loaded (i.e, greater than 90 percent traffic utilization), lower-priority traffic can be impacted. Conversely, the highest-priority traffic would not be impacted if an active LTE connection is maintained between the LTE eNB and the LTE access points. The percentage of utilization is defined as the traffic resources used compared to the total available traffic resources. In the LTE downlink direction, this is mainly measured over traffic resource elements offered within the physical downlink shared channel (PDSCH).

In the uplink direction, this is mainly measured over traffic resource elements offered within the physical uplink shared channel (PUSCH).

In practice, SEL protection equipment traffic is configured for higher traffic prioritization service. Hence, this traffic, in general, traverses with lower latency and higher reliability compared to traffic with lower-priority service. For this test, a typical load is arbitrarily defined as 50 percent of target utilization for a wireless link. For an LTE eNB cell, target utilization of resources in protection applications is generally limited by the uplink direction due to the bandwidth performance requirements of IEEE C37.118 data payloads. The targeted uplink utilization is 80 percent of uplink traffic resource utilization. Hence, a medium load is considered to be 40 percent of total resource utilization, while a high load is greater than 90 percent of total resource utilization.

## MEASURED RESULTS

An example of measurements for an initial calibration test (high LTE signal quality with no traffic load at lower QoS priority) from one PDC-triggered event is shown in the following table. For every scenario, the application was repeated five times in both downlink and uplink directions to provide statistic relevance to the results.

Table 3 shows the time delta (ms) between falling conductor initiation (the instant the relay sees a falling conductor event) and the instant the relay receives a trip command from the RTAC.

Test Location	FC Initiate (ss.ms)	RTAC Outgoing Trip Command (ss.ms)	FC Initiate to RTAC Trip Cmmnd (ms)	SEL-351 Incoming Trip (ss.ms)	RTAC to SEL-351 Delta (ms)	Init to SEL-351 Trip Delta (ms)	SEL-651R Trip Incoming Trip (ss.ms)	RTAC to SEL-651R Delta (ms)	Init to SEL-651R Trip Delta (ms)	SEL-751 Trip Incoming Trip (ss.ms)	RTAC to SEL-751 Delta (ms)	Init to SEL-751 Trip Delta (ms)
1	18.384	18.648	264	18.659	11	275	18.667	19	283			
1	10.136	10.408	272	10.42	12	284	10.43	22	294			
1	28.579	28.848	269	28.859	11	280	28.867	19	288			
1	0.112	.408	296	.42	12	308	.427	19	315			
1	47.898	48.168	270	48.177	9	279	48.19	22	292			
2	18.475	18.768	293				18.787	19	312	18.789	21	314
2	34.743	35.048	305				35.068	20	325	35.072	24	329
2	5.872	6.168	296				6.188	20	316	6.19	22	318
2	42.855	43.168	313				43.188	20	333	43.189	21	334
2	32.919	33.208	289				33.227	19	308	33.231	23	312

Table 3—Initial calibration test results for latency using 900 MHz PLTE.

The average communications latency from the RTAC for five iterations of falling conductor events at Locations 1 and 2 is:

- 11 ms for the SEL-351 with no significant increase in ms compared to the wired network.
- 19.9 ms for the SEL-651R-2 with an average increase in latency of 9.7 ms compared to the wired network.
- 22.2 ms for the SEL-751 with an average increase in latency of 9.6 ms compared to the wired network.

The average falling conductor initiation-to-trip time for five iterations of falling conductors at Locations 1 and 2 is:

- 285.2 ms for the SEL-351 at the substation location (no wireless in Network Architecture 1).
- 306.6 ms for the SEL-651R-2 at Location 1.
- 321.1 ms for the SEL-751 at Location 2.

These results are well within the limit of one second for a 25-foot-high distribution tower.



Table 4 summarizes the results over various network conditions.

Test ID	PLTE Air- Interface Path	Average RTAC/Trip Latency to SEL-351 (ms)	Average FC Initiation-to-Trip Time at Substation (ms)	Average RTAC/Trip Latency to SEL-651R-2 (ms)	Average FC Initiation-to-Trip Time at Location 1 (ms)	Average RTAC/Trip Latency to SEL-751 (ms)	Average FC Initiation-to-Trip Time at Location 2 (ms)	Observations
1	Downlink	12.0	388.6	19.0	340.3	24.6	342.0	Suggested operation condition
	Uplink	12.0	416.6	26.8	385.9	25.2	338.8	Suggested operation condition
2	Downlink	12.6	325.2	20.7	343.7	26.6	354.6	Suggested operation condition
	Uplink	11.4	317.0	19.4	327.6	25.4	336.2	Suggested operation condition
3	Downlink	12.0	412.4	20.1	385.1	24.4	354.0	Intermittent "No Protection"
	Uplink	No Protection	No Protection	No Protection	No Protection	No Protection	No Protection	"Ping Timeouts, No Protection" per system due to testing condition of higher-priority traffic load—expected
4	Downlink	11.2	418.6	26.2	396.3	30.6	363.4	Suggested operating condition; higher latencies observed due to weak signal conditions; PDC time-out window can be expanded for further evaluation
	Uplink	11.8	350.2	25.9	349.5	30.4	359.2	Suggested operating condition; higher latencies observed due to weak signal conditions; PDC time-out window can be expanded for further evaluation
5	Downlink	12.0	490.4	45.4	504.8	27.6	487.8	Intermittent "No Protection" under loaded condition; in no-load condition, observed doubling of FC-to-trip times in 4 cases; PDC time-out windows can be expanded for further evaluation
	Uplink	No Protection	No Protection	No Protection	No Protection	No Protection	No Protection	"Ping Timeouts, No Protection" per system due to testing condition of low signal and higher-priority traffic load—expected
6	Downlink	11.4	341.7	25.3	358.5	28.2	362.4	System can operate when cell traffic is not full
	Uplink	10.8	354.2	28.5	377.3	29.0	383.2	System can operate when cell traffic is not full

Table 4—Summary of trip time latency results for various test configurations.

Results affirm the functionality of FCP using PLTE. The application operates appropriately with high, medium, and low LTE coverage. The range of falling conductor initiation-to-trip times are well within the one second target for Locations 1 and 2 in all properly configured test scenarios (Test ID 1, 2, and 4). The application also operates robustly when high end-to-end QoS prioritization is employed for its messaging payloads.

Outlier scenarios (Test ID 3, 5, and 6) were also tested to affirm adverse impacts if QCI settings are not set correctly or not available to be configured. For example, configuring the protection equipment traffic using a low QCI priority leads to adverse effects of intermittent or full “No Protection” function for falling conductors.

Further, comparing the payloads between downlink and uplink messages, we observe that under loaded conditions with low coverage, the uplink direction is more adversely impacted. It is therefore critical that the design of the PLTE communications link is limited by the uplink traffic direction. Per SEL, the user payload requirement for the IEEE C37.118 payload is, at a minimum, 60 kbps. The PLTE downlink under a noise-limited situation offers more payload capacity under a balanced signal link design. Further refinement for the link should include a confidence level of signal availability. Typically, wireless links are designed to have 90 to 95 percent area availability.

#### **FUTURE ARCHITECTURE AND OPTIMIZATION**

This experiment demonstrates the function of FCP and its latency performance over PLTE under different congestion and signal scenarios. Prioritization allows for reliability of application traffic. Based on the above results, we recommend operating FCP traffic over higher-priority service.

With high, medium, and low LTE signal strength and quality, FCP also performs within protection limits. It is notable that the function of FCP still performs within the limits of the application metric, even under lower signal condition. This indicates the robust design of LTE to achieve low latency.

The opportunity to optimize FCP parameters may further enhance operation under low-signal conditions. In Test ID 4 and 5, where the LTE signal condition is low, we assess that the trip time to the SEL 651R-2 can be increased by two, or potentially three, times. We expect that further evaluation can be made to analyze the read time-out window size parameter, which will allow for the RTAC to make decisions on valid synchrophasor message content.

Network Architecture 2 can also be analyzed and assessed with future testing.

## Acknowledgments

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