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Evaluation of Utility Advanced Distribution Management System (ADMS) and Protection Functions Over Private LTE Communications Network

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SUMMARY

With the continued growth of both the numbers of integrated distributed energy resources (DERs) and the number of attractive utility applications involving grid-edge control of devices of local aggregators, such as home energy management systems, the need for practical and cost-effective communications solutions to enable the control of DERs and other grid-edge devices is evident. Estimates indicate that more than half the total installed photovoltaic (PV) system capacity being added each year is interconnected to the distribution system and yearly additions exceed 5 GW[1]. As PV accounts for the bulk of DER capacity methods to enable the continues integration of large amounts of PV on the distribution system are needed as penetration increases[2]. Much previous work has shown that advanced distribution management systems (ADMS), which are effectively integration platforms for various grid control and visibility applications, can help enable the integration of higher levels of PV while also improving the overall performance and efficiency of the distribution circuit. The addition of greater connectivity and controllability of more and more utility- and customer-owned equipment increases the level of DER integration and overall circuit performance improvement[3]. What has been less studies and often greatly oversimplified in ADMS performance analysis is the required performance of the enabling communications system. The availability of new technologies such as distributed sensors, two-way secure communications, advanced software for data management, and intelligent and autonomous controllers is certainly driving developments to provide the underpinning communications standards and general requirements[4] but the link between expected performance of a utility

[1] Mather, B., Yuan, G., (2018). Going to the Next Level: The Growth of Distributed Energy Resources, IEEE Power and Energy Magazine, v.16 issue 6.
[2] Palmintier, B., et al., (2016). On the Path to SunShot: Emerging Issues and Challenges in Integrating Solar with the Distribution System (NREL Technical Report No. NREL/TP-5D00-65331). Golden, CO.
[3] Palmintier, B., et al., (2016). Feeder Voltage Regulation with High Penetration PV Using Advanced Inverters and a Distribution Management System: A Duke Energy Case Study (NREL Technical Report No. NREL/TP-5D00-65551). Golden, CO.
[4] https://www.nist.gov/programs-projects/smart-grid-communications-0 , updated May 7, 2018

implemented control system (i.e. an ADMS or communications reliant protective function) requires further investigation.

Long-Term Evolution (LTE) is a standardized specification for wireless broadband communication enabling transmissions among various enterprise or public services for users via mobile devices and data terminals. It is based on the 3rd Generation Partnership Project (3GPP) since Release 8 specifications were developed in 2008. Benefits of this technology include[5]:

- Higher bandwidth - 4G LTE provides broadband speeds in comparison to 3G
- Low latency - lower idle-to-active times (improved network responsiveness)
- High spectrum efficiency – higher air-interface capacity, improved cost efficiency
- End-to-end IP network – All IP network means easier integration, improved cost efficiency
- Enhanced security features – 3GPP security architecture for user equipment, access, network, visibility
- Quality of Service – integration onto existing network service layers to corresponding air-interface QoS class identifier (QCI)
- Robust eco-system- LTE, since 3GPP Release 8 (2008) has provided more than 5000 devices from over 400 suppliers.[6]

Given the benefits listed above and the necessity for advanced control of DERs and grid-edge assets, integrating LTE onto such control systems is becoming an intriguing proposition. In this paper, we discuss use of private LTE (P-LTE) for a critical protective application called direct transfer trip (DTT) which is a low-latency, but low bandwidth application of specific interest for the cost-effective integration of DERs at high penetration levels. As P-LTE networks provide the utility full control and visibility using off-the-shelf broad-band communications to their endpoints and applications the use of such systems for DTT, in a non-dedicated fashion but rather as only one of the many utility uses for wireless communications, was evaluated via the integration of a P-LTE system in the National Renewable Energy Laboratory's ADMS Test Bed. This low-latency protective function performance evaluation is only the first utility control application planned to be tested so a discussion of future ADMS application performance with integrated P-LTE is also discussed.

KEYWORDS

Advanced Distribution Management System
Distributed Energy Resources
Distributed Generation
Direct Transfer Trip
Private LTE

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[5] https://www.telecomstechnews.com/news/2016/mar/15/opinion-4g-lte-and-its-benefits-enterprise-networks/ , March 15, 2016
[6] https://gsacom.com/paper/status-lte-ecosystem-report-5614-lte-devices-announced-455-suppliers/ , June 24, 2016

Background

Vendor and Utility Collaboration

Multiple current projects within the National Renewables Energy Laboratory's Power System Engineering Center (NREL) focus on the development and practical implementation of advanced distribution management systems (ADMS) requiring communication capability either between devices or between a centralized ADMS controller and multiple pieces of utility equipment (e.g., capacitor bank controllers, voltage regulator controllers). These communication pathways are often implemented using hardwired connections when completing evaluations in the lab. To develop more realistic ADMS, and other utility communication-reliant functions, performance NREL and Anterix partnered on a project specifically focused on the full hardware integration of utility control and wireless communications in the laboratory environment. This project leverages Anterix's expertise and existing private broadband network solution set to implement a realistic communications network that is utility relevant while also heavily leveraging NREL's ADMS Test Bed and past and current projects related to ADMS testing.

In consultation with a specifically formed industry advisory board (IAB) for the project, the team discussed that all laboratory evaluation activities were to be reflective of real-world utility applications that are in use today and potential future applications as well. The IAB has been instrumental in defining use cases for the test scenarios that carry significance with common utility control procedures and reviewing results and data from the evaluation for refinement and use with individual utilities' network infrastructure plans. Additionally, the IAB has provided invaluable input on the amount, type, and priority of data present in a combined utility communications system as P-LTE is envisioned. Table 1 provides a list of the projects IAB members which consist of seven utilities and one industry expert:

Table 1. Industrial Advisory Board Members for NREL/Anterix Project

Consumers Energy
Evergy
Duke Energy
Eversource
Holy Cross Energy
Hawaiian Electric Company
Xcel Energy
Dots and Bridges

Leveraging existing NREL use-cases and utilities' current and future requirements to enable advanced control of their distribution network, it was determined that use-cases relating to advanced distribution management system (ADMS), a core component of Grid Modernization initiatives throughput the country would be the perfect backdrop for wireless data network testing. Additionally, a low-latency use case representative of the critical communications required to grid-edge equipment during faults or abnormal operating conditions was developed to test the performance limit and trade-offs of P-LTE.

Distributed Generation and its Impact to the Smart Grid

Distributed generation refers to a variety of technologies that generate electricity at or near where it will be used, such as solar panels and combined heat and power. Distributed generation may serve a single structure, such as a home or business, or it may be part of a microgrid (a smaller grid that is also tied into the larger electricity delivery system), such as at a major industrial facility, a military base, or a large college campus. When connected to the electric utility's lower voltage distribution lines, distributed generation can help support delivery of clean, reliable power to additional customers and reduce electricity losses along transmission and distribution lines.[7]

In the residential sector, common distributed generation systems include:

- Solar photovoltaic panels
- Small wind turbines
- Natural-gas-fired fuel cells
- Emergency backup generators, usually fueled by gasoline or diesel fuel

In the commercial and industrial sectors, distributed generation can include resources such as:

- Combined heat and power systems
- Solar photovoltaic panels
- Wind
- Hydropower
- Biomass combustion or cofiring
- Municipal solid waste incineration
- Fuel cells fired by natural gas or biomass
- Reciprocating combustion engines, including backup generators, which are may be fueled by oil

DG typically generate from 1 to 10 MW of power to the electric grid.[8] Distributed generators cannot always power other utility customers when not connected to the utility grid. In times of extreme events (e.g., when lightning strikes a tree and downs a power line), islanding can occur when the electric grid is not adequately designed with appropriate protection to open circuit breakers from power sources such as DG and transmission. Unintentional islanding can be detrimental to the utilities' customers if left to operate and carry the load of the customers. It becomes an unregulated power system and its behaviour is unpredictable due to the power mismatch between the demanded load and the isolated generation.

It is critical to provide protection with resiliency in from both the customer end DG components, at the utility head-end control with resilient communications path. The trend for DERs is continually increasing and calls for evaluation of cost-effective communication solutions.

Generally, DERS and DG usage is becoming increasingly more part of the utilities' Smart Grid and their applications. The follow two data points illustrates the growing demand.

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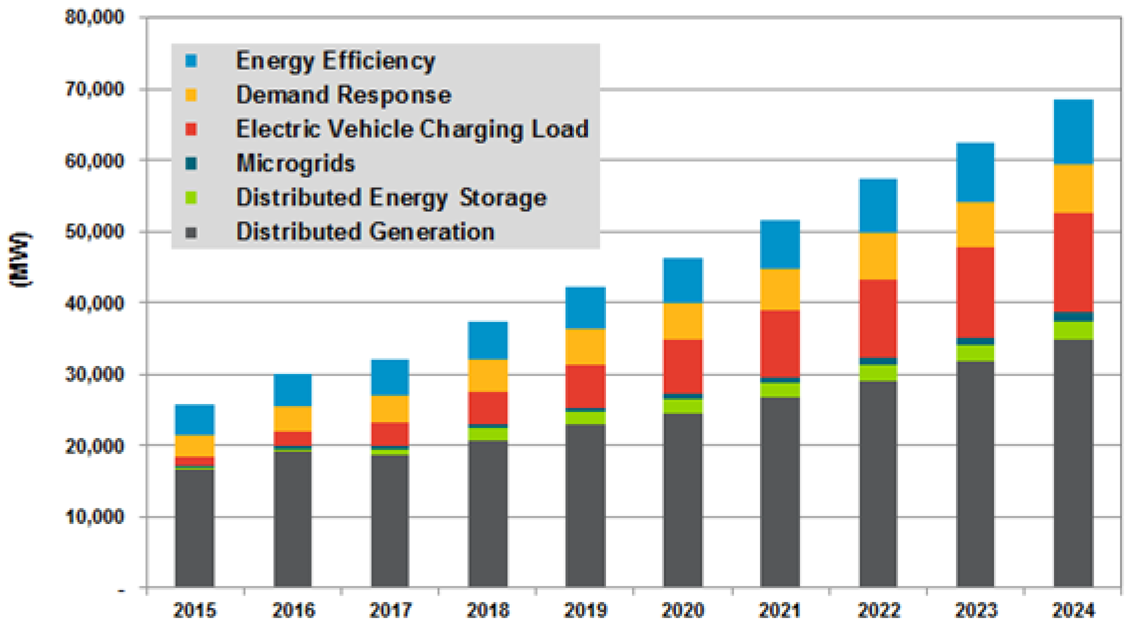
[7] https://www.epa.gov/energy/distributed-generation-electricity-and-its-environmental-impacts , January 19, 2017

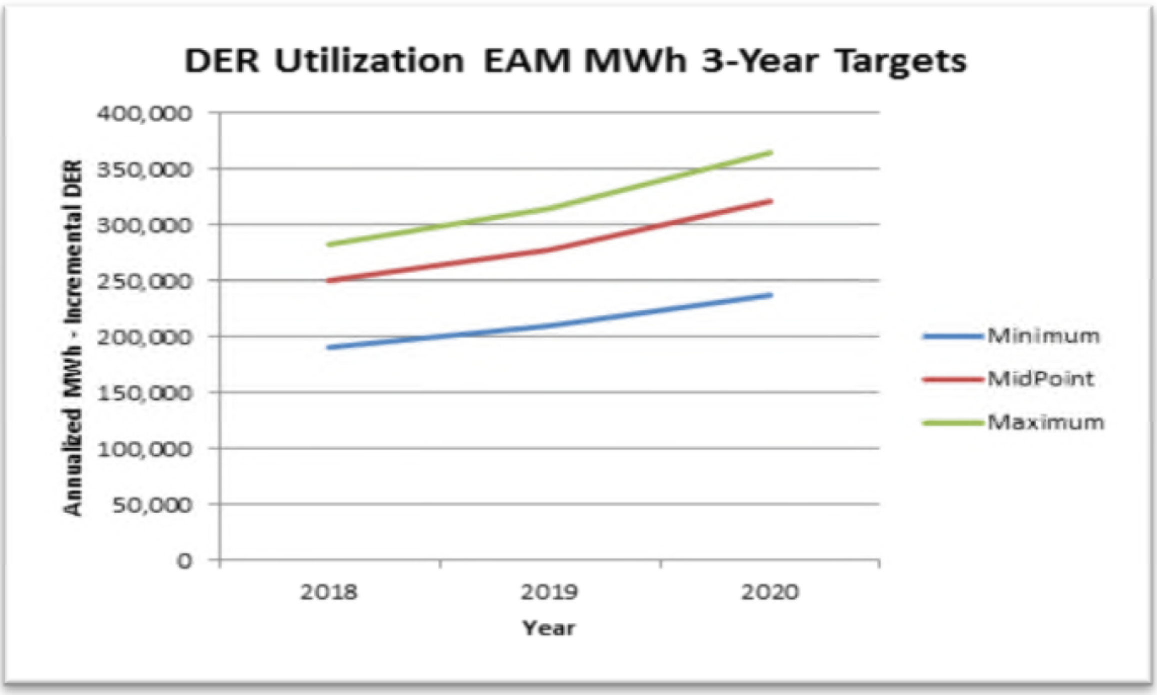
[8] Distributed Generation Direct Transfer Trip (DTT), URI Capstone Project 2016



(Source: Navigant)

Figure 2.10.2 National Grid Interconnection EAM:

MWh Incremental DER Utilization Targets for 2018 - 2020



(Source : National Grid 2018 Distributed System Implementation Plan Update)

Private LTE

P-LTE systems are uniquely positioned to provide the critical communications infrastructure needed by electric utilities and other enterprises to consolidate the many disparate point-to-point and point-to-multipoint communications links that are in use today.[9] Private LTE networks offer several core benefits that make them an ideal solution for the critical needs of electric utilities:

- Licensed spectrum: Operating on licensed spectrum provides the network operator with recourse in the event of interference. Violators must comply with FCC mandates or be prosecuted and fined for non-compliance.
- Private network: A Private LTE network provides a utility the assurance that its traffic traverses only its infrastructure. In the same way applications for critical infrastructure are rarely hosted in public cloud service providers such as Google, utilities will be in control of their infrastructure and their traffic management policies and not subjected to traffic policies implemented by a common carrier.[10]
- Inherent security: Mutual authentication between user equipment (UEs) and base stations (eNBs) and the use of proven encryption schemes are two of the major improvements of LTE[11] over its predecessor mobile wireless technology. Overlaying LTE with accepted security measures such as virtual private network (VPN) tunnels that encrypt and authenticate provides the level of security needed for critical infrastructure.
- Visibility of network elements: A key component of 3GPP cyber-security is to have visibility of the network nodes and element throughout the LTE system. In non-private systems, this function is often left to the service provider who do not share with their users. In privately-owned systems, the user gains this visibility.
- Traffic consolidation by leveraging LTE bearer circuits with assured quality of service (QoS): Combining traffic from multiple applications, which have different requirements for priority, throughput, and latency is exactly what the QoS class identifier (QCI) features of LTE were designed for.
- Broadband technology: Compared to wideband technology, LTE provides greatly improved spectral efficiency to achieve high data rates and permits multiple users to share a common channel.
- LTE Narrowband low power wide area (LPWA) Internet of things (IoT) technology: LTE spectrum can be shared among broadband LTE applications and narrowband IoT (NB-IoT) applications. NB-IoT is ideal for monitoring or controlling very large quantities of devices or equipment that generally require relatively low uplink and downlink data rates.
- Mobility: Within the utility field area network (FAN), instruments or devices used by mobile workers can automatically connect into the private LTE network and provide seamless access to vital backend resources.

Project Timeline

[9] CIGRE US National Committee 2018 Grid of the Future Symposium, Leveraging Private LTE Networks in the Electric Utility, L. Greenstein

[10] ARS Technica. “Fire dept. rejects Verizon’s ‘customer support mistake’ excuse for throttling” https://arstechnica.com/tech-policy/2018/08/fire-dept-rejects-verizons-customer-support-mistake-excuse-for-throttling/ Jon Brodkin August 22, 2018

[11] National Institute of Standards and Technology. US Department of Commerce. “LTE Security – How Good Is It?” https://csrc.nist.gov/CSRC/media/Presentations/LTE-Security-How-Good-is-it/images-media/day2_research_200-250.pdf Michael Bartock, Jeffrey Cichonski, Joshua Franklin

This project started February 2019 and consists of two phases. Phase 1 of the project is completed with the integration of the direct transfer trip of a photovoltaic inverter system over wireless P-LTE. Direct transfer trip (DTT) is a protection function within electric distribution to quickly disconnect or shut-down DERs (typically large MW-scale DERs) on a distribution circuit when that circuits substation breaker or recloser opens. Timing requirements for DTT vary by utility but generally require low-latency in order to ensure that the DER does not sustain an unintentional island (i.e. continues to generate when disconnected from the utility) and that the substation breaker and/or reclosers along the line can operate without the risk of connecting into a powered circuit potentially causing utility and customer equipment damage. Initial testing results of Phase 1 laboratory evaluations are provided in this paper and a more comprehensive set of DTT performance will be collected and reported in the future.

Phase 2 will further develop capabilities for use-cases utilizing NREL's ADMS testbed. The expected outcome of this engagement is a quantified understanding of how the communications portion of an ADMS impacts the overall grid-level performance of such systems when the communication network is a private broadband network leveraging Long Term Evolution (LTE) technology. A report will be published based on this understanding and the results from the evaluation of multiple ADMS/control use cases over a laboratory implementation of an LTE network.

Two sets of measurements will be gathered as part of this project:

- End-to-end ADMS functions and their performance metrics.
- Air-interface performance metrics such as throughput and latency for the LTE system. They will be measured in both uplink and downlink data paths under various signal strength, signal quality, and user traffic profiles.

P-LTE Test Bed

<u>NREL laboratories</u>

NREL's Energy Systems Integration Facility (ESIF) has been utilized for this project. Specifically, ESIFs Power System Integration Laboratories (PSIL), the location of the ADMS test bed, has been augmented with the additions of private LTE testbed. These facilities contribute an elaborate set of resources ranging for the ADMS test bed, grid-edge devices including DER systems, power components for automatic voltage regulation, simulation for real-time control, and realistic electric distribution communications traffic loading profiles. For end-to-end IT networking functions, ESIF provides resources to configuration VLANs, management plane VPN, and integration of network switches, routers to the P-LTE system.

<u>LTE System</u>

The LTE-in-a-box system is an all-inclusive software implementation of LTE core (ePC-HSS/MME/SGW/PGW) elements and the LTE radio access network (eNB) functions. The team implemented the LTE as a private network running in a Linux environment on a stand-alone server rack. The network will allow LTE user equipment or endpoints with appropriate USIM cards to attach on 900 MHz (Band 8). The system is based on 3GPP Release 14 or later functions including the following key features:

- Visibility and monitoring of the air-interface
- Support for NB-IoT, Cat-M1, and LTE technologies
- Air-interface QoS prioritization mapped to specific DSCP/TOS IP tags

- 3GPP security architecture including access and network authentication, air-interface integrity and encryption control
- Access class control with or without pre-emption
- MAC scheduling optimized for traffic loading and RF channel profiles
- MIMO transmission modes

<u>Department of Energy's Guidance and Support</u>

The project undertaken by NREL and Anterix was designated as an ESIF High-Impact Project by the Department of Energy (DOE). This designation provided additional funding to expand the scope of the project and focus of the development of ESIF capabilities related to utility communications systems integration and performance evaluation. It is currently one of seven projects recently presented to the Department of Energy (DOE) as part of their annual review. Two key objectives related to the ESIF High-Impact designation are:

- Ensure ESIF capabilities are relevant to support any communications system (i.e., national scalable): latency communications measurements are relevant to all forms of communications (wired or wireless).
- Carefully consider communications role in utility resiliency: resilience considerations are two-fold – the enabled power system resilience by implementing greater utility control (ADMS, etc.) and the resilience of the communications system itself (poor signal strength, congestion scenarios, etc.)

Demonstration of Direct Transfer Trip of a Photovoltaic Inverter System at NREL

Direct transfer trip (DTT) is when a "trip" command is generated (either autonomously at a substation or via protection equipment vendor specific communications methods) to immediately operate a relay or recloser when an upstream breaker opens within the electric distribution system. As DERs become more and more part of today's Smart Grid, application of DTT potentially needs to be implemented throughout its distribution feeder networks. Due to the remoteness of various relays, recloser, and distributed generation systems, communication to transmit this trip signal is required.

Traditionally, communications to these relays and recloser have been employed using:

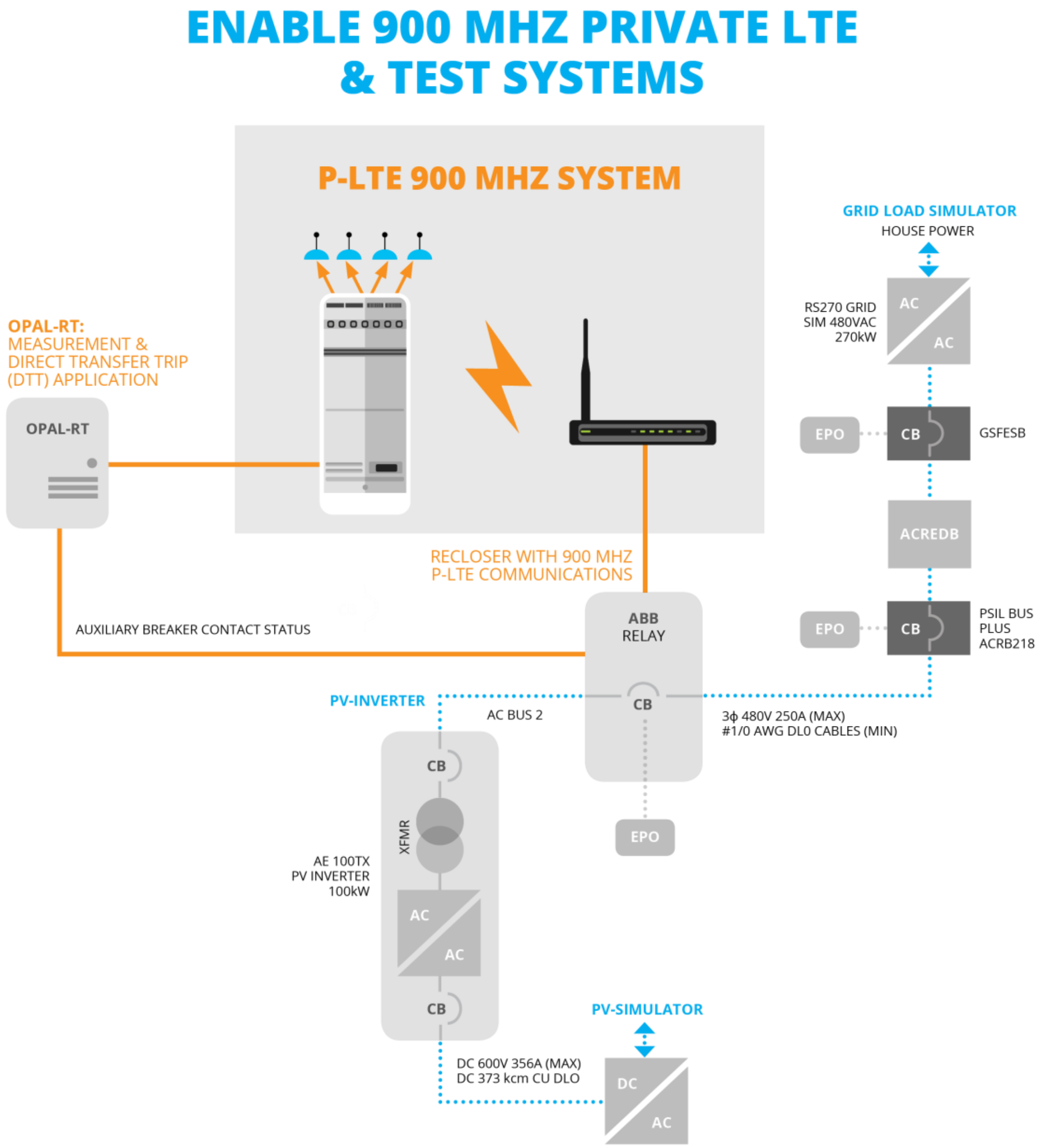
- leased copper line tone circuit with constant connection
- fiber-optics communication with direct connection
- microwave radio with direct channel
- or, serial narrow-band or proprietary radio links with direct channel

In this test, the private LTE system is utilized as the communications link between a command center (i.e. a substation) and the recloser which disconnects a PV generator attached to the distribution circuit. Two air-interface components were evaluated:

- Coverage: impact to performance metrics of throughput and latency for the critical DTT application as signal strength and signal quality vary between strong and weaker levels.
- Capacity: impact to performance metrics of throughput and latency for the critical DTT application under best efforts and prioritized congested traffic levels.

<u>DTT Testbed</u>

A full communications and equipment test of a direct transfer trip (DTT) application where a PV inverter is signalled to trip offline via the LTE communications system has been implemented. The time required to communicate the signal and then actually disconnect the inverter is measured for the various communication system scenarios (congestion, prioritization, etc.). A PV inverter, 100 kW in capacity), was configured for communications via a direct DNP3 signal to trip offline from an accompanying computer. The PV inverter was connected with a PV simulator and AC grid connection to effectively appear connected to a nominal grid and operating under normal conditions other than the communications signal requesting immediate disconnection from the grid.



(Source: NREL / Anterix P-LTE Testbed Configuration)

For the initial demonstration, the round-trip delay between the computer and the communication's module on the recloser attached to the PV inverter system was measured in real-time. The LTE air-interface signal strength and signal quality telemetry were also monitored in real-time.

Table: *Direct Transfer Trip of PV inverter System Initial Test Results*

Test Case	Description	Measured round-trip Delay (ms)	Communication Link Congestion Configuration	Communication Link Signal Strength	Result
1	DTT of PV inverter under strong LTE signal coverage	20 – 40 ms	No congestion	-65 to -75 dBm RSSI	Opened circuit with consistency
2	DTT of PV inverter under weak LTE signal coverage	50 – 90 ms	No congestion	-90 to -100 dBm	Opened circuit with consistency
3	DTT of PV inverter under congested LTE channel (best efforts – no QoS)	80 – 600 ms	Fully loaded downlink resource utilization with background traffic on same cell	-65 to -75 dBm	Inconsistent behaviour ranging from: opened circuit, opened circuit with long delay, opened circuit with no acknowledgement, TCP/IP communications error, and no-trip
4	DTT of PV inverter under congested LTE channel with prioritized traffic (QoS enabled for critical traffic)	20 – 40 ms	Fully loaded downlink resource utilization with background traffic on same cell	-65 to -75 dBm	Opened circuit with consistency

(Source: NREL / DOE High Impact Project Review, September 12, 2019)

Results show that under strong and weaker LTE signal strength and quality, the DTT application still operated with consistency and with relatively low delay. Further characterization of the delay will be tested to formulate an adequate LTE cell edge coverage boundary. Results also show that under heavy downlink congestion, if the command link from server to relay traffic is not prioritized over the LTE air-interface, DTT cannot operate reliably. In order to enable use of DTT, the air-interface and network end-to-end traffic plane must be configured with a dedicated higher QoS compared to other less critical traffic.

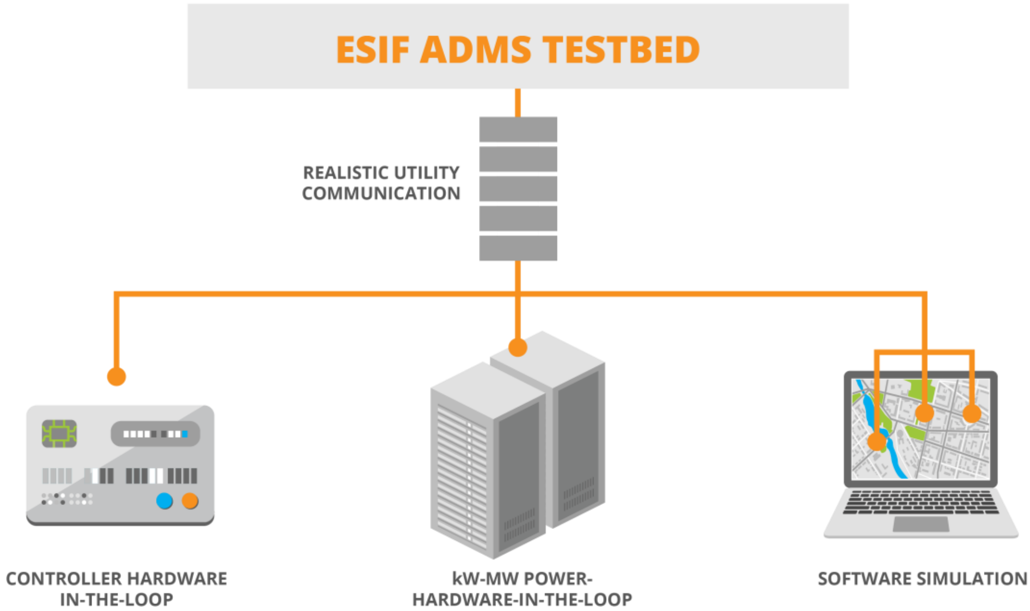
Characterization of additional congestion loads over various LTE signal strength and quality will be quantified in the final report in terms of reliability and performance.

Further refinement of DTT testing will be implemented. One-way latency measurement capabilities will be incorporated into the testbed and will measure the full end-to-end time to trip from command sent (server-side) to circuit open (PV inverter relay). The measurements will be made with external real-time computational resources such as an OPAL-RT using a synchronized timing source.

ADMS Integration

The second stage of testing will utilize NREL's Advanced Distribution Management Systems (ADMS) Testbed. The ADMS Testbed will be configured with the Holy Cross Energy (HC) ADMS Use Case and multiple experiments with various communications settings/congestion levels will be evaluated using this specific use case. The HCE Use Case consists of simulation data for two days of utility operation; one day is the system peak loading day (which occurs in the wintertime) and the other is the peak PV generation day. One hour from each of these days, during which a large amount of communications and control actions occur, will be selected and will be used for evaluation on the real-time ADMS Testbed. Both time points selected are representative of critical operational periods for utilities and thus latency and/or dropped packets within the communications system will have a noticeable impact. The control implemented during these two hours of real-time simulation include a comprehensive DERMS control which controls roof-top PV systems, batteries, EV loads, HVAC loads, and electrical water heaters using a previously developed real-time optimal power-flow algorithm. The developed DERMS interfaces with Survalent ADMS using only the SCADA module through which the DERMS control receives voltage and feeder head (start-of-circuit) power measurements). The DERMS can control up to 6 hardware devices including a 3-phase PV inverter, two single-phase inverters with a battery as well, and one EV charger. Within the ADMS Use Case there are 161 residential loads which are also controllable which include a rooftop PV system, HVAC system, and water heater. Some loads also have a battery energy storage system and EV chargers. For this project a simplified version of the HCE Use Case will be made by slight modifications by limiting the use case to include a limited number of real hardware end points to make lab evaluation and scheduling easier.

Testing will include characterization of the air-interface performance in terms of coverage and congestion scenarios.



(Source: NREL / Anterix P-LTE Testbed Configuration Phase 2)

Follow-on Work

Data collected on this project will further opportunities not only in distribution protection methods, but also enables other potentially cost-effectives measures for ADMS, and distribution automation (DA) applications. The IAB will review these findings, and hopefully propose new use-cases for grid operations.

There have been numerous trials with utilities using P-LTE in 900 MHz with a focus on existing DA applications. Development on this project proves that P-LTE can enable low-latency application such as DTT on a PV inverter system and similar applications. Further enhancement could be to optimize and improve protection applications for electric distribution.

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