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Requirements and Capabilities Needed for Robust DERMS Control Verification

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1. Introduction

1.1 Background

A Distribution Management System (DMS) is responsible for monitoring and maintaining the health of a distribution grid. Common DMS applications include fault location isolation and service restoration, on-line power flow (OLPF), volt/VAR optimization (VVO), and switch order management. These systems were developed primarily in the area of top-down, unidirectional power flow, with large centralized generating plants moving electricity through the transmission grid and into the distribution grid from and thence to consumers. The recent and ongoing addition of distributed energy resources (DER) to the grid, including rooftop and community solar and wind, means that power is now flowing into the distribution grid from the edge, which complicates the functioning of the DMS.

To ameliorate this problem, DMS use distributed energy resource management systems (DERMS) to control DER such as solar inverters. DERMS comprise software management tools that allow management and near real-time control of an array of DER. DERMS control devices and grid services including smart inverters, capacitor banks, on-load tap changes, voltage regulators, and customer loads [1]. DERMS may be either deterministic—initiating an action after an event occurs—or predictive—using analytics to forecast voltage or power flow violations. Predictive actions can use weather forecasts, historical loading, and known distributed resource protocols [2].

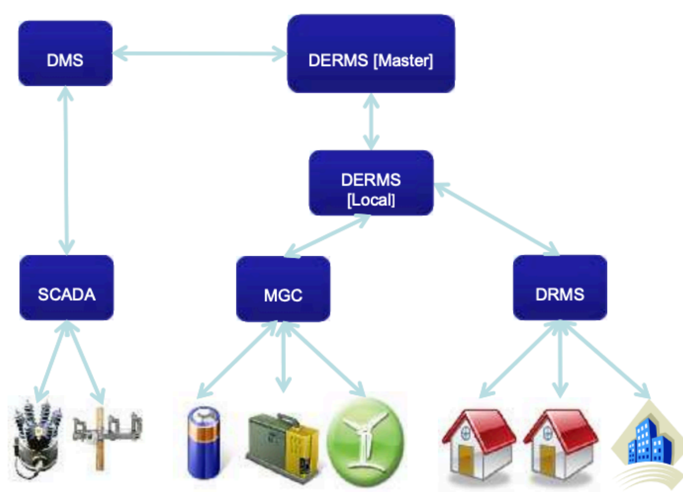

Figure 1. Information flow for DERMS and DER devices [3].

An overview of the information flow involving DERMS is shown in Figure 1. The DMS exchanges information with supervisory control and data acquisition (SCADA) systems. The DMS then uses that information to send signals to the master DERMS, which then determines how to transmit the information to local DERMS. The local DERMS sends commands to microgrid controllers (MGC) and demand response management systems (DRMS). Then, information from the MGC and DRMS transmit information on monitoring back up through the DERMS and to the DMS [3].

1.2 Motivation

A grave security concern is that the DMS or DERMS represent single points of vulnerability that could be compromised by attackers, and thus issue commands that could destabilize the grid, causing power outages, equipment damage, and loss of life. Distributed energy devices, like the protective equipment in Ukraine attacks, implicitly trust the commands sent by the DERMS and blindly execute them without validation [4, 5].

While to date there have been no cyber-attacks on DER devices, a fault event from 2016 demonstrated that simultaneously manipulating multiple inverters can cause grid instability. In this case, fire damage to a set of transmission lines in California resulted in a series of transient voltage changes on the lines. The duration of the transients was short, so while the instantaneous frequency exhibited large changes, the average frequency on the lines remained within operational tolerances. However, the device management software in one brand of solar inverter was mistakenly programmed to monitor instantaneous frequency rather than average frequency, causing large numbers of inverters to switch into a protection mode. This resulted in 1200 MW loss of distributed photovoltaic power production; it did not cause any blackouts, but the sudden loss of that much power put the grid into an unsafe state [6]. While this event was result of a faulty firmware, similar effects can be achieved if a cyber-attack compromised DERMS and issued commands that would simultaneously disconnect/connect multiple inverters.

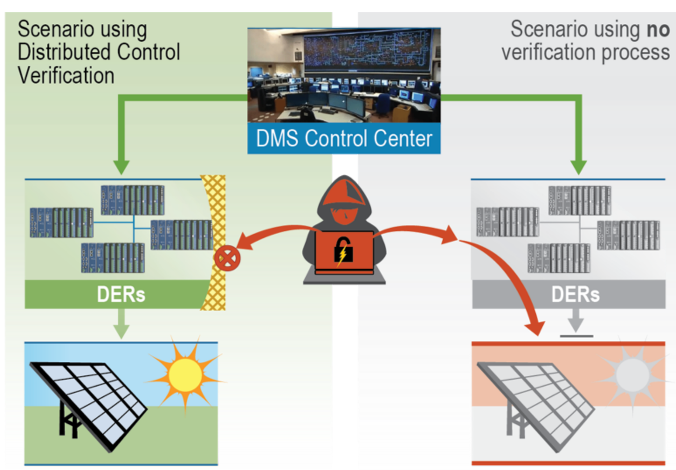

Figure 2. On the left, commands that are sent from the DMS control center are verified at DER such as inverters, and cyber-attacks are unable to adversely influence the system. In the current status quo, right, an attacker can convince DER to carry out malicious commands.

The Red Cave[1] system will add defense-in-depth by performing verification of state-change commands at the edges, using a device within a microgrid called a real-time automation controller (RTAC) that manages a suite of 6-10 endpoints such as solar inverters, loads, and battery storage (see Figure 2 and Figure 3). The microgrid might comprise hundreds of neighborhoods, each with its own RTAC.

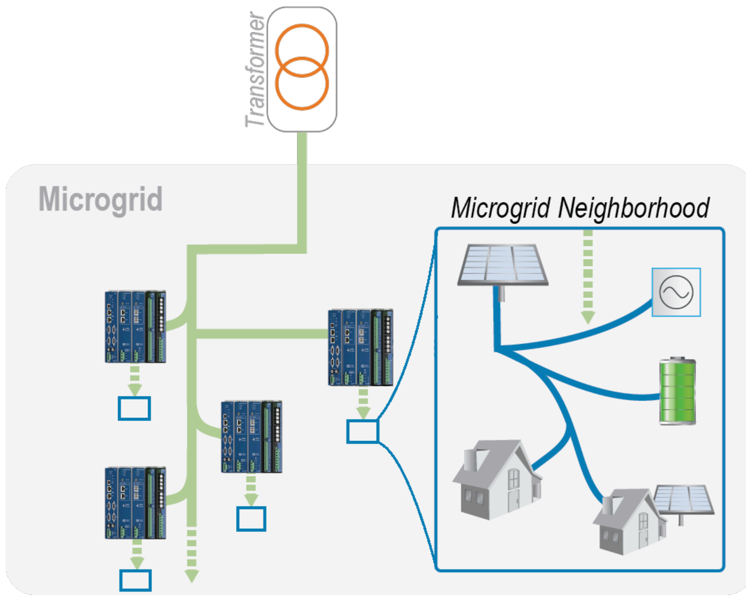

Figure 3. Structure of an RTAC-based microgrid. An RTAC is a type of DER that controls individual devices in a microgrid neighborhood.

1.3 Overview of Requirements and Capabilities Needed

To create algorithms and technology that can be used by DERMS, we must ensure that the algorithms do not perturb normal operations of DERMS for the distribution grid—the power grid equivalent of the medical maxim, "First, do no harm." Thus, we have derived the following operational, technical, and performance requirements for Red Cave to operate within the constraints imposed by the current communications, hardware, and software environment that exist in DMS, DERMS, and DER:

1. Command verification must be completed within the normal response time of a DERMS running without Red Cave. This time will depend on the nature of the application (e.g., demand response vs. frequency regulation).
2. The algorithms must be implemented using the computational and storage resources of a typical RTAC.
3. The technology must use existing communication channels provided by RTAC, and must not interfere with normal DERMS use of these channels.

[1] Derived from RDCV, Robust DERMS Control Verification.

1.4 Approach for Collecting Requirements and Capabilities

Section 2 provides an overview of hardware capabilities of DERMS and related devices, including the latency and bandwidth in distribution communications infrastructure, the computational capabilities of current and future resources, and the space and power capabilities of inverters and DER hardware. We performed literature review to gain an understanding of the hardware requirements of DERMS—specifically latency and bandwidth requirements for several DER applications. Section 2 also lays out the communications media that currently exist and potentially will exist in the future around DER. We have estimated the number of messages that can be transferred by each communications medium as well as provided estimated bandwidth based on review of literature. Upon discussion with our subcontractors, we will refine these requirements to account for specific control message paths and communications.

in Section 3. This includes a discussion of algorithms that are currently used in the transmission system that may be adaptable to the distribution grid as well as other potential algorithms that can be applied for state estimation. We are evaluating which of these algorithms are appropriate for our control verification development and will make decisions based on discussions with our subcontractors. We will not be implementing full algorithms as it is likely to resource-intensive to do so at remote controllers. Rather, we will use heuristics based on these state estimation algorithms to approximate the state of the system.

In our statement of work, we discussed developing a set of cyber-attack scenarios with Southern California Edison and Schweitzer Engineering Laboratories that demonstrate microgrid controller vulnerabilities. As this document focuses on the development requirements of our algorithms and cyber-attack scenarios will be used to validate those future algorithms, we will be submitting a second document with these scenarios once we have completed development with our subcontractors.

2. Hardware Requirements and Capabilities

DERMS utilize data from DERMS-enabled devices, smart meters, and distributed grid sensors. Optimization algorithms are then used to send out control signals to adjust, turn on, or turn off devices connected to the DERMS networks [1].

To ensure that the algorithms we create can be applied to grid devices and meet the performance, operational, and technical requirements of message control paths, we assess the communications, computational, and storage capacities of common devices, which include DERMS, smart inverters, and RTAC. In this section, we outline the latency and bandwidth capabilities of distributed communications infrastructure, including the requirements of DER devices and controllers, the computational capabilities of current and futures resources, and the space and power requirements of inverters and DER hardware. We then describe the potential communications media that do or may exist in microgrid now and in the future. For each medium, we describe the message latency, bandwidth, and the implications of those things for our algorithm development. These requirements metrics are outlined to determine the required response times of our algorithms.

2.1 Communications Requirements of Distributed Communications Infrastructure

Latency and bandwidth requirements will vary based on applications but will be critical in transferring messages from a DMS to a DERMS and eventually to DER devices. Communications technology will allow utilities to allocate energy flowing both from the grid to loads and from DERS back to the grid. Communications will be required to allow islanding, where microgrids can operate independently of the power grid [7]. The requirements are summarized in Table 1 and expanded upon in the following sections.

Table 1. Communications Requirements for DER and DERMS.

Latency	Bandwidth
20 ms – 30 minutes	100 kbps – 1 Gbps

2.1.1 Latency

The US Department of Energy recommends a latency between 20 ms and 15 s for DERs, demand response, and distributed storage in the distribution system [7]. Latency calculations must also include the time taken to measure and process system voltage. This time varies with different sensors but can take 0.5 seconds to measure and process the voltage, and then can take up to a second to reach a new setpoint [8]. Sandia National Labs recommends a response time of less than 1 second as a communications metric for smart inverters [9].

Latency will vary based on the response parameter needed. Required response times for some demand response activities are shown in Table 2 [10]. Other potential response times include 4 seconds for frequency regulation, around 20 ms for real-time monitoring and control, and around 20 ms during faults and switching on and off of protection devices [7].

Table 2. Characteristics of response services to manage distribution system challenges (adapted from [10]).

System Requirement	Advanced Notice	Response Time	Duration of Response	Frequency	Geographic Specificity
Maximum Capacity Relief	Day-ahead	10 – 30 minutes	< 4 hours	Seasonal but > 1 time / day	One level below overloaded equipment
Emergency Load Transfer	30 minutes – 4 hours	≤ 30 minutes	< 4 hours	Infrequent	Substation to transformer
Steady State Voltage Mgmt.	< 1 minute	Seconds – minutes	Continuous	Continuous	Close proximity to affected area
Power Quality	< 1 minute	< 1 second	Continuous	Continuous	Substation to transformer
Phase Balancing	Day-ahead	Seconds – minutes	Continuous	Continuous	Substation to secondary feeder
Outage Recovery	< 1 minute	Seconds – minutes	< 1 hour	Infrequent	Substation to transformer

To calculate the latency metric for the potential communications media in Section 2.2 in microgrids, we assume that a 15-second time window is available for an RTAC to receive and implement a command from a DERMS; this is the time window within which we must verify the DERMS command, and would support all but one of the applications in Table 2. We then assume that half of the time window is used for computation and the other half is used for the communications. We finally calculate the number of messages that can be sent based on the message latency for each medium. This upper bound on the number of messages we can send will limit the number of nodes we can include in our decentralized verification model (the precise upper bound on scaling is not yet known, but will be derived experimentally when we design and implement our algorithms). When we have more information from subcontractors on the number of messages required to issue a command and how large those messages are, we will update this document to discuss the required communications times.

2.1.2 Bandwidth

The bandwidth required for DER applications is estimated to be between 9.6 kbps and 56 kbps allocated per individual DER device [7]. Since many DER devices will likely utilize the same communications paths to reach controllers, sufficient bandwidth is required to provide effective communications. This bandwidth can range from 100 kbps to 10 Mbps for neighborhood area network operations and from 10 Mbps to 1 Gbps for wide area network applications [11].

2.2 Expected Communications Infrastructure Around DERs

Communications systems are vital to the operation of DERs and DERMS in the microgrid. In this section, we review the likely communications systems that will exist around microgrids and how each of these communications systems meet the requirements of DERs and DERMS. These metrics can be used both to determine parameters in our algorithm development, modeling, and simulation and to determine how realistic a communication medium is for DER applications. Some communications media have a wide range in a metric, for example, a range in bandwidth ranges from the order of bps to Mbps. Each medium has a section on implications for DERs and DERMS that describes when requirements may or may not be met. It is noted that the upper limit on latency and bandwidth parameters for each of the communications media are likely to only exist in ideal network conditions.

2.2.1 Wired Communications

Table 3 summarizes the wired communications media assessed in this report and how well they meet requirements of DER and DERMS communications.

Table 3. Summary of Wired Communications Media.

Media	DSL	Fiber	PLC
Message Capacity	250 – 600 messages	500 – 1500 messages	75 – 1500 messages
Bandwidth	1 – 100 Mbps	50 Mbps – 1 Gbps	100 bps – 3 Mbps

2.2.1.1 Digital Subscriber Line

Broadband communications systems are provided by cable companies to offer internet connectivity using cable infrastructure. Service is offered with use of a Digital Subscriber Line (DSL) or cable modem to a customer's location. Broadband is advertised as a high-speed internet provider. DSL transmits a digital data signal over high frequency to allow fast throughput and high bandwidth. Utilities are currently using DSL and broadband for automated meter reading, SCADA, and IT communications [13]. DSL has previously been used for advanced metering management and metering, such as by Eandis and Infrax in Belgium. In this project, two-way communication systems between central systems and meters were installed along with 36,000 smart communication gateways. DSL was combined with power line communication and mobile networks to make these communication gateways [11]. Table 4 summarizes the capabilities metrics identified for DSL.

Table 4. Capabilities Metrics for DSL.

Media	DSL
Message Capacity	250 – 600 messages
Bandwidth	1 – 100 Mbps

2.2.1.1.1 DSL Latency
Message latency of Broadband and DSL cables ranges from around 25 to 60 ms for common DSL and broadband providers [14]. This latency translates to a message capacity of 250 to 600 messages in a 15 second time period.

2.2.1.1.2 DSL Bandwidth
The bandwidth for DSL ranges from 1 Mbps to 100 Mbps, depending on the protocol used and the coverage range expected. Using the ADSL (asymmetric digital subscriber line) protocol, for example, covers up to 5 km of coverage and has a maximum theoretical data rate from 1 to 8 Mbps. Using the VDSL (very-high-bit-rate digital subscriber line) has a bandwidth range of 15-100 Mbps but the coverage is only up to 1.5 km [11].

2.2.1.2 Fiber
Fiber optic communications support long distance communication for monitoring and control applications [15]. EPB, a municipal electric utility in Chattanooga, Tennessee, has installed a fiber network to support its smart grid electricity upgrades for power reliability, operation efficiency, and customer-focused power-management [16]. Fiber networks are single-mode (carry data in one direction) or multi-mode (carry data upstream and downstream). Multi-mode fiber would be necessary in DER applications because of the need to transfer information both from microgrid controllers to DERs and from DERs to the microgrid controllers. The message capacity and bandwidth of fiber are shown in Table 5 and expanded upon in the following sections.

Table 5. Capabilities Metrics for Fiber.

Media	Fiber
Message Capacity	500 – 1500 messages
Bandwidth	50 Mbps – 1 Gbps

2.2.1.2.1 Fiber Latency
Latency of commercial providers of fiber communications range from around 10 to 30 ms [14]. This latency range relates to a message capacity between 500 and 1500 messages in 15 seconds.

2.2.1.2.2 Fiber Bandwidth
Fiber communications offer bandwidth between 50 Mbps to 1 Gbps, which can be partitioned for PMU applications as well as secondary services throughout a utility’s distribution system, such as internet access [15].

2.2.1.3 Power Line Carrier
Power Line Carrier (PLC) encompasses the communication technologies that allow communication signal to propagate through power lines. PLC has been applied for smart metering in the distribution grid [17]. PLC utilizes the 50 or 60 Hz power system infrastructure maintained by distribution companies to inject data onto power lines and receive the data with data detection

equipment. Data is modulated at a higher frequency than the electrical system frequency [13]. Table 6 summarizes the capabilities metrics for PLC.

Table 6. Capabilities Metrics for PLC.

Media	PLC
Message Capacity	75 – 1500 messages
Bandwidth	100 bps – 3 Mbps

2.2.1.3.1 PLC Latency

Latency of PLC can range based on the class deployed. One estimate of the latency of broadband PLC ranges from 10 to 200 ms per hop [18]. This latency is likely higher for narrowband PLC, but estimates were not found in literature. The message capacity of PLC ranges from 75 to 1500 messages in 15 seconds.

2.2.1.3.2 PLC Bandwidth

There are three classes of PLC that operate in different frequency ranges, and therefore have varying data rates. The Ultra Narrow Band operates from 300 to 3000 Hz and has data rates on the order of 100 bps. Narrow Band PLC operates between 3 and 500 kHz and have a bandwidth from 2 to 500 kbps. The highest bandwidth is offered by broadband over the power line, which ranges from 2 to 80 MHz and has data rates from 1 to 3 Mbps [13].

2.2.2 Wireless Communications

Table 7 summarizes the wireless communications media we have assessed and how well each of the media meets the needs of DERs and DERMS.

Table 7. Summary of Wireless Communications Media

Media	Microwave	Satellite		ZigBee	WiFi	LTE
		Traditional	*Starlink*			
Message Capacity	< 150 messages	15 – 37.5 messages	430 – 600 Messages	75 – 750 messages	250 – 15000 messages	150 – 15000 messages
Bandwidth	2 Mbps – 1 Gbps	1 kbps – 10 Mbps	~ 1 Gbps	20 – 250 kbps	5.5 Mbps – 1.3 Gbps	2 Mbps – 10 Gbps

2.2.2.1 Microwave

Microwave communications involves using local loop technology that allows microwave receivers to receive broadcast radio waves. Worldwide Interoperability for Microwave Access (WiMAX) is the standard for microwave communications. There is both licensed and unlicensed spectrum of microwave communications and can generally provide high distance coverage and data rates [19]. The capabilities metrics for microwave are shown in Table 8.

Table 8. Capabilities Metrics for Microwave.

Media	Microwave
Message Capacity	< 150 messages
Bandwidth	2 Mbps – 1 Gbps

2.2.2.1.1 Microwave Latency

Latency of WiMAX communications varies based on the type of communications being transmitted. The latency typically is less than 100 ms round trip [20]. As the latency varies widely based on the distance covered by a microwave link, the technology used, and spectrum, and interference, latency estimates are not readily available. However, some microwave links will easily meet latency requirements of DERs while others will not be able to access the speed necessary. This latency relates to a message capacity of less than 150 messages in 15 seconds.

2.2.2.1.2 Microwave Bandwidth

There are several bands of microwave communications. Licensed bands operate at 2.3, 2.5, and 3.5 GHz and the unlicensed band operates at 5.8 GHz [19]. These range in bandwidth, but advanced unlicensed microwave link technology can carry up to 400 Mbps and advance licensed technology can reach bandwidth on the order of 1 Gbps [21]. However, line-of-sight is required to implement licensed links, which prohibits implementation for remote DERs [22].

2.2.2.2 Satellite

Developments in satellite communications technologies have led to a decrease in prices of equipment and services and an increase in the efficiency of satellite communications. Satellite communications are most applicable to areas with no terrestrial communications infrastructure. Satellite communications are currently used to provide IP services for machine-to-machine applications [23]. SpaceX's Starlink is one potential technology that could provide more widespread satellite communications. Starlink is expected to be a constellation of 4,425 low earth orbit satellites that would have lower latency and higher bandwidth than traditional satellite communications. Low earth orbit is defined by satellites orbiting at approximately 500 km above earth, compared to other satellite communications at approximately 35,000 km above earth [24, 25]. Satellite communications are likely to only be used in rural or geographically remote locations with no existing telecommunications infrastructure [26]. Table 9 outlines the message capacity and bandwidth of satellite communications.

Table 9. Capabilities Metrics for Satellite.

Media	Satellite	
	Traditional	*Starlink*
Message Capacity	15 – 37.5 messages	430 – 600 messages
Bandwidth	1 kbps – 10 Mbps	~ 1 Gbps

2.2.2.2.1 Satellite Latency

Traditional satellite communications systems have latencies between 400 ms and 1 s, resulting in a message capacity of 15 to 27.5 messages in 15 seconds. The low end of the latency is a minimum based on the speed of information exchange between a geostationary satellite and a receiver. Achieving latencies at this minimum would require advanced and likely expensive technologies. Recently released technologies have latencies of around 1 s [23]. Starlink communications is expected to have latencies of 25 to 35 ms, made possible because of the satellites' low earth orbit [25]. This translates to a message capacity of between 430 and 600 messages in 15 seconds.

2.2.2.2.2 Satellite Bandwidth

Traditionally, satellite communications have data rates from the order of 1 kbps to 10 Mbps. This bandwidth is affected by the distance of the satellite from earth [23]. Starlink is expected to have bandwidth on the order of 1 Gbps when released [25].

2.2.2.3 ZigBee

ZigBee is a wireless communications technology that uses low-power digital radios based on the IEEE 802.15.4 standard. This technology has low power usage, data rates and cost. ZigBee operates on three frequency bands ranging from 868 MHz to 2.4 GHz with relatively small ranges, on the order of 10 km [26, 19]. Table 10 summarizes the message capacity and bandwidth of ZigBee.

Table 10. Capabilities Metrics for ZigBee.

Media	ZigBee
Message Capacity	75 – 750 messages
Bandwidth	20 – 250 kbps

2.2.2.3.1 ZigBee Latency

ZigBee communications range in latency from 20 ms to 200 ms [27, 28]. This translates to a message capacity ranging from 75 to 750 messages per 15 seconds.

2.2.2.3.2 ZigBee Bandwidth

Data rates range from 20 kbps to 250 kbps, depending on the frequency band utilized [12].

2.2.2.4 WiFi

Wireless Fidelity (WiFi) is a useful communications technology for the local area network and is based on the IEEE 802.11 standard. WiFi uses unlicensed radio spectrum and operates at 2.4 GHz and 5 GHz. There are several variants of the 802.11 standard which have ranges from 27 to 70 meters indoors and 75 to 250 meters outdoors [29]. The capabilities metrics are shown in Table 11.

Table 11. Capabilities Metrics for WiFi.

Media	WiFi
Message Capacity	250 – 15000 messages
Bandwidth	5.5 Mbps – 1.3 Gbps

2.2.2.4.1 WiFi Latency

Latency of WiFi networks varies widely with the equipment used. While no consensus on the range of latency in WiFi networks was found in on the open internet, the latency is estimated to range from approximately 1 ms to 60 ms [30], meaning the message capacity ranges from 250 to 15000 messages in 15 seconds.

2.2.2.4.2 WiFi Bandwidth

WiFi bandwidth ranges from 5.5 Mbps to 1.5 Gbps depending on the variant of the 802.11 standard implemented. However, these speeds are theoretical and actual networks range from around 5.5 Mbps to 200 Mbps [31].

2.2.2.5 LTE

Cellular telecommunications were introduced in the early 1980s to transmit voice communications and now allows access to high-speed internet. Cellular networks, such as 3G, Long Term Evolution (LTE), 4G, and 5G, are potential technologies that can be applied for smart grid communications [32]. Cellular networks are currently utilized in smart meter deployments to provide end-to-end connectivity in metering infrastructure as well as in metering communication hubs [33].

5G LTE networks are currently in development to support industry needs including the smart grid. The evolving network is targeting advanced features such as high bandwidth, low latency, high availability, 100% coverage, and a reduction in energy usage [34]. 5G is still in development, so all metrics are estimates for what is expected for the future network. Table 12 shows the capabilities metrics for LTE.

Table 12. Capabilities Metrics for LTE.

Media	LTE
Message Capacity	150 – 15000 messages
Bandwidth	2 Mbps – 10 Gbps

2.2.2.5.1 LTE Latency

Cellular latency for LTE is close to 100 ms. [35]. The 5G system is being built to support 10 ms latency end-to-end, and 1 ms over-the-air for ultra-low latency design [36]. This relates to a message capacity between 150 and 15000 messages per 15 seconds.

2.2.2.5.2 LTE Bandwidth

Bandwidth for cellular networks ranges from 2 Mbps for 3G to 50-100 Mbps for 4G and estimates up to 10 Gbps for 5G [34, 32].

2.3 Space and Power Capabilities of Inverters and DER Hardware

For future implementation of our algorithms, we must ensure that they are able to meet space and power constraints on RTAC. One example of a RTAC, is the SEL-3530. This device integrates IEC 61850, contains 1024 MB of memory and 2 GB of storage, and has a 533 MHz processor speed [37].

In this section, we will add information gained from subcontractors with information on the space and hardware capabilities for implementing our algorithms on their devices. This will inform the requirements of our algorithms, including the amount of computing capacity we will be able to utilize and the amount of storage we will have access to.

3. State Estimation Algorithms

The DMS can be used to perform state estimation in the distribution system. State estimation is commonly performed in the transmission grid to detect bad data measurements, smooth out small errors, detect topology errors, provide estimates for unmonitored parts of the system, and to estimate network parameters based on redundant measurements. State estimation has not commonly been used in the distribution grid because distribution systems have had unidirectional and relatively passive flows. An overview of the conventional state estimation process is shown in Figure 4, where RTU stands for remote terminal unit and PDC represents a phasor data concentrator [38].

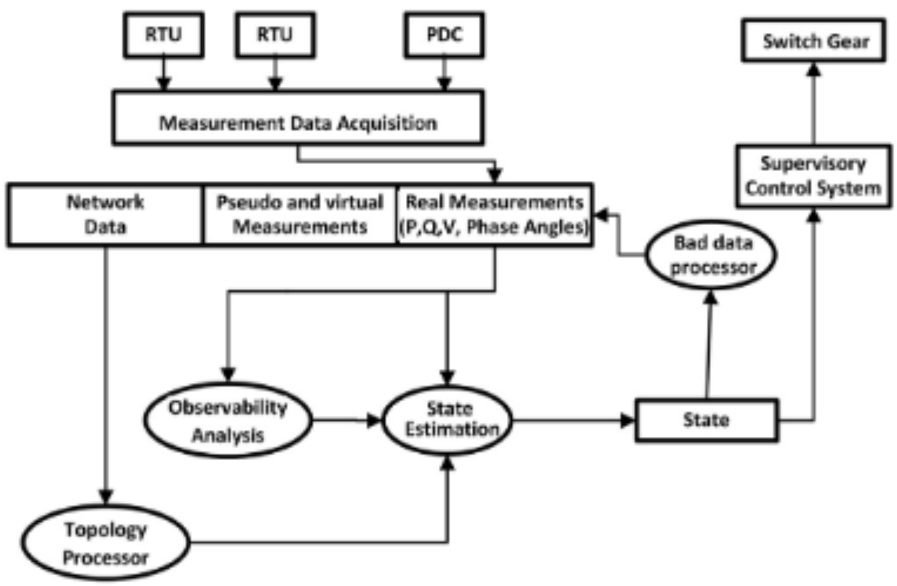

Figure 4. Overview of state estimation [38].

The distribution system has different requirements for state estimation because of the high resistant-to-reactance ratios, low availability of real-time measurements, scale and complexity, complexity of measurement functions, and unbalanced phases [38].

3.1 Algorithms and Software Used at DMS

Currently there are algorithms that are used in the transmission system for state estimation. These can be adapted to work for distribution system state estimation, as described in Section 3.1.1, or there are other algorithms that can be used for distribution system state estimation, as described in Section 3.1.2.

3.1.1 Algorithms Building on Transmission System State Estimation

Several approaches to performing state estimation in the distribution system by updating transmission system state estimation have been proposed, as reviewed in Ahmad, et al. 2018. One proposed methodology involves updating weighted least squares used for the transmission system to apply to the distribution system [39, 40, 41, 42, 43].

A second approach is to use load estimation for distribution state estimation because the lack of metered measurements is not sufficient for observability. The existing measurements consider the three-phase details or incorporate voltage measurements and meshed network topologies [44, 45, 46].

The phase imbalance problem exists in practice that must be considered to perform accurate state estimation. Some examples of this methodology are used to treat each phase as an independent state estimation problem [44, 47, 48].

Another challenge to modifying transmission state estimation to the distribution system is incorporating DERs. Methodologies have been developing to perform state estimation in a microgrid and to take into account quickly-changing topologies introduced by DERs [49, 50, 51, 52].

3.1.2 Algorithms Separate from Transmission System State Estimation

Other approaches for distribution system state estimation include node-voltage-based state estimation (NV-DSSE) and branch-current-based state estimation (BC-DSSE. NV-DSSE considers complex node-voltages as state variables that represent real-time non-synchronized measurement, real-time synchronized measurements, or pseudo-measurements from statistical load profiles. These measurements can be used to perform a weighted least squares approach to calculate voltage drops at every node [44, 53, 54, 55].

BC-DSSE involves using complex branch-currents as state variables. In this methodology, power measurements are converted to equivalent current measurements, branch currents are estimated, the state vector is updated, and then the network node voltages are calculated using a forward sweep through the network graph [44, 56, 57, 58].

3.2 Challenges of Distributing Algorithms

After conferring with our subcontractors, we will gain an understanding of the challenges of performing state estimation in a distributed context. We will then outline the requirements for our algorithms based on these challenges.

4. Conclusion

The Red Cave system is being developed to verify the validity of commands sent by DERMS, allowing DER to ensure that a DERMS command will not unduly stress or destabilize the grid. Algorithms that we develop as part of this system must meet the hardware and software requirements of real-world solar deployments to confirm that Red Cave will not adversely affect the functional performance of solar deployments.

We defined three performance requirements for Red Cave to operate within DERMS communications constraints. To meet the first requirement—command verification must be completed within the normal response time of a DERMS running without Red Cave—we analyzed the latency and bandwidth required by demand response and DER applications through literature review. The latency required ranges from 20 ms for real-time monitoring and during faults to 30 minutes for emergency load transfer and maximum capacity relief. We then outlined the wired and wireless communications media that are likely to and currently exist around DERMS and microgrids. For each of the media, we estimated the number of messages that can be transmitted in a 15-second time frame and the bandwidth provided by each medium.

To assess the second performance requirement—the algorithms must be implemented using the computational and storage resources of a typical RTAC—we have introduced the space and power constraints of one example RTAC. We will expand this section to discuss the available storage and power that we will be able to utilize for algorithm implementation upon discussion with our subcontractors.

The final performance requirement outlined is that the technology must use existing communication channels provided by RTAC, and must not interfere with normal DERMS use of these channels. To address this performance requirement, we outlined the communication channels that will be used to connects RTAC to DERMS and provided an overview of state estimation algorithms that are used for state estimation in the grid.

In section 2, we gave an overview of distribution system state estimation methods, and focused on the most widely used method, Weighted Least Squares, which also is the type of method that will most directly map onto our ADMM-based collaborative autonomy system. Selection of a specific WLS algorithm will depend on the state information available. We will select a specific algorithm after consulting with our subcontractors, particularly SoCal Edison.

As this is a living document, we have provided an initial bounding of the applicability of our approach to verifying DERMS commands. We will modify this document as the project progresses to include input from out subcontractors and to assess how assumptions we make in our algorithm development meet the requirements outlined in this document.

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