# Emerging Communications and Sensor Technologies That Advance Distribution Automation

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# Emerging Communications and Sensor Technologies That Advance Distribution Automation

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***Abstract*—Today, power utilities are integrating intelligent sensors and advanced communications into their distribution systems that go beyond substations to include downstream feeder intelligent electronic devices (IEDs). This integration of advanced technologies provides several benefits. It increases system efficiency and cost-effectiveness, and it improves reliability, power quality, and resiliency. It also enables easy integration of new technologies such as renewables, energy storage, and plug-in electric vehicles.**

**Reliable two-way communications and sensors enable advanced distribution automation (DA) applications that require minimal human interaction. This paper describes applications of DA, with a focus on emerging communications technologies and advanced line sensors that provide distribution utilities faster fault detection, isolation, and restoration. It also describes communications sensor network architectures and how these sensor networks integrate into the existing utility infrastructure to provide insights into the distribution system. The essential requirements of these communicating sensor networks, including energy harvesting, accuracy, and cybersecurity, are covered in detail. The paper also shows how sensor networks, when combined with communications technologies, can improve reliability indices like the System Average Interruption Frequency Index (SAIFI), the Customer Average Interruption Duration Index (CAIDI), the System Average Interruption Duration Index (SAIDI), and the Momentary Average Interruption Frequency Index (MAIFI) for distribution utilities.**

## I. Introduction

The world's energy consumption is expected to increase 28 percent by the year 2040 [1]. Aging infrastructure will not be able to support the increased energy demand. By applying innovative technology and communications, however, utilities can maximize efficiency, deliver more energy using the existing grid, and keep up with global energy demand. This transition will require updating existing utility practices and using automation to unlock new applications that will enable efficient energy delivery.

## II. Distribution Automation (DA)

Power utilities are investing in new technologies across their operations and infrastructure. The fundamental objective for technology investments is to improve the efficiency of existing infrastructure. Some utilities are working on large initiatives to overhaul information technology/operation technology (IT/OT) network infrastructure and are building intelligence into their assets to support new and emerging applications. With an increasing number of field devices capable of two-way communications, tremendous amounts of sensor and intelligent electronic device (IED) data are available. Utilities can use these data to continuously monitor the performance of assets to improve reliability and efficiency.

Today's active distribution networks need adaptive protection and control, automatic reconfiguration, advanced sensors and measurements, network management of apparatus, and two-way communications networks. DA is a system that enables electric utilities to monitor, coordinate, and operate distribution systems in real time from remote locations. Key drivers for DA include:

- An increase in worldwide energy consumption.
- An increased emphasis by utilities on system efficiency, reliability, and quality.
- A focus on renewable energy and the integration of distributed energy resources (DERs) to reduce carbon footprints.
- The availability of real-time information and tools from field devices for faster decision-making.

DA applications and control capabilities typically include:

- Overload mitigation and load shedding.
- Cold-load pickup.
- Load reconfiguration and transfer.
- Fault location, isolation, and service restoration.
- Voltage regulation.
- Volt and volt-ampere reactive (VAR) control.
- Distributed generation control.
- Loss-of-source detection and open-phase detection.
- Miscoordination detection and mitigation.

## III. Reliability Indices

The most important metrics for distribution utilities are reliability indices. Reliable power delivery is critical to the success of any distribution utility and is assessed in terms of the frequency and duration of outages. There are four reliability indices commonly used by electric power utilities.

The System Average Interruption Frequency Index (SAIFI) is calculated as total number of customer interruptions divided by number of customers served. In (1), $N_i$ is the number of interrupted customers for each interruption event during the reporting period and $N_T$ is the total number of customers served in the area being indexed.

$$\text{SAIFI} = \frac{\sum N_i}{N_T} \quad (1)$$

The System Average Interruption Duration Index (SAIDI) is commonly known as "customer minutes of interruption" and is a measure of the average time customers have their electric power interrupted. In (2), $r_i$ is the restoration time for each interruption event.

$$\text{SAIDI} = \frac{\sum r_i N_i}{N_T} \quad (2)$$

This calculation assumes that as soon as service is interrupted, crews are dispatched and restoration work starts immediately. Hence, the duration of an outage or interruption is the same as restoration time.

The Customer Average Interruption Duration Index (CAIDI) represents the average time required to restore service for each outage or interruption. Note that in (3), CAIDI = SAIDI/SAIFI.

$$\text{CAIDI} = \frac{\sum r_i N_i}{\sum N_i} \quad (3)$$

The Momentary Average Interruption Frequency Index (MAIFI) is similar to SAIFI but is used to track the average frequency of momentary (short-duration) outages. MAIFI equals the total number of customer momentary interruptions divided by the total number of customers served. In (4), $ID_i$ is the number of interrupting device operations (e.g., breakers reclosing to clear possible temporary faults on the system).

$$\text{MAIFI} = \frac{\sum ID_i N_i}{N_T} \quad (4)$$

Tracking some or all of these reliability indices can help utilities understand the behavior of their distribution systems to better plan for future investments in infrastructure and technology [2].

## IV. Emerging Communications

Existing DA architectures were developed using standards that satisfied specific requirements of centralized generation, transmission, and distribution systems. With the integration of DERs such as solar and wind farms, DA systems face a new set of communications requirements. To improve DA and leverage the capabilities of installed field IEDs and sensors, utilities must choose communications technologies that bind these devices together. Therefore, it is important for utilities to understand the emerging communications technologies that are available for their needs and the communications systems requirements for their applications.

According to the National Institute of Standards and Technology (NIST) Framework and Road Map for Smart Grid Interoperability, the communications network for distribution power systems is known as the field-area network (FAN). This network is dedicated to DA and the integration of DERs. A FAN allows utilities to communicate with DA devices such as IEDs, voltage regulators, capacitor banks, sensors, faulted circuit indicators (FCIs), and remote controller switches, as well as a large array of newer technologies such as DERs and microgrids.

Some utilities have two or more independent networks. For example, a utility might have one network used for DA and one advanced metering infrastructure network used for smart meters installed at residential and small commercial locations. Each of these networks relies on different mechanisms to backhaul its aggregated data to a common data control center. Instead of expanding and maintaining these separate networks, it would be helpful to utilities if the next generation of FANs integrates these networks so that end devices can exchange data more seamlessly. This integration would provide many communications system benefits, such as bandwidth efficiency, latency, reliability, and security.

The communications network for DA is typically a three-tier architecture that consists of a wide-area network (WAN), a FAN, and a neighbor-area network (NAN), which is a FAN subnetwork. The WAN forms the communications backbone of the network, linking distribution systems to core utility systems. The WAN consists of two types of networks: the core network that connects the substations and the utility, and the backhaul network that connects FANs to the core network.

There are essentially two types of FANs: low-latency networks, which support time-stringent applications such as teleprotection, and latency-tolerant networks, which do not have stringent latency requirements. A NAN facilitates data flow between customer premises and a data concentrator or a substation. In some cases, it is desirable for the FAN to support interfaces with NANs to facilitate communication through the FAN to endpoints. The next generation of FAN is expected to use FAN backhaul to transport both DA data and NAN data, such as advanced metering infrastructure data. In this paper, we concentrate on FANs.

## V. Emerging Communications Requirements for DA

Emerging communications requirements are designed to meet the evolving needs of DA. Today, a wide range of wireless communications systems and technologies is available. The systems that meet the majority of the key requirements for DA applications are the ones that will likely be adopted in the near future.

### *A. Latency*

Latency is the time duration for a message to reach its destination when passing through the communications network. Different types of DA applications have different latency requirements. For example, protection and control data exchanged between IEDs require lower latency than the latency for supervisory control and data acquisition (SCADA) data exchanged among field devices, sensors, and data control centers. Acceptable latencies can range from milliseconds to minutes.

Another factor to consider is latency variation. Deterministic latency is required for high-speed control applications such as load shedding. Typically, a list of prioritized loads is expected to shed under certain abnormal conditions, for example a fault or loss of generation [3]. If the latency of the communications network is indeterministic, the system might not achieve the correct balance between generation and demand (load). This could lead to unintended consequences, such as blackouts or equipment damage. It is important to know the minimum and maximum latency variations of a communications system to determine whether it is suitable for an application.

Network design and architecture are also important for latency and its variation because they affect the way that data move through the network. For example, latency is proportional to the number of hops in a mesh network. That architecture directly impacts the latency of communications systems.

### *B. Availability*

According to ISO/IEC 2382:2015, availability is the "ability of a functional unit to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided."

Applying this definition to a communications network, availability is the network's ability to successfully transfer data from one point to another. This includes successful connectivity at the physical layer, the link layer, and the network layer. The time that a communications network is not delivering this service is referred to as downtime.

Radio link availability is the ratio of the time a radio link provides good data to the total time the radio transmits data [4]. A 95 percent availability implies 438 hours of outage time per year, and a 99.95 percent availability implies 263 minutes of outage time per year. For distribution system applications, a radio link availability requirement of 95 to 99.95 percent is widely accepted [5]. Availability and latency are key metrics used to calculate the overall system performance.

### *C. Interoperability*

Interoperability is the ability of different communications systems to exchange information and work cooperatively to perform specific tasks. Interoperability makes integration easier and seamless. It enables two-way communications among the different interconnected elements of distribution systems.

Two key elements of interoperability for emerging communications are standard protocols and the supported physical interface. While different communications systems can have over-the-air protocols that are incompatible, it is critical that output interfaces use standardized protocols. Harmonized protocols simplify collecting and aggregating data because data from multiple systems can be easily integrated into common applications.

### *D. Scalability*

Communications systems must support present and future DA functions. Infrastructures need to accommodate additional device deployment, which occurs with modernization of the electric grid. Communications systems must also deal with large network topologies and accommodate network expansion without increasing complexity. Emerging communications systems could scale millions of field devices over the next few decades. The cost of deployment and maintenance is reduced significantly for scalable communications.

### *E. Cybersecurity*

Cybersecurity is a critical issue for utility infrastructure because more and more devices are interconnected. The security of emerging communications systems depends strongly on authentication, authorization, and encryption mechanisms. These mechanisms must be included in all layers of the protocol stack, from physical to application layers. Utilities can increase the security of emerging communications systems by using wired communications technologies such as firewalls, virtual private networks, and Internet Protocol Security (IPsec). They should also include higher-layer security mechanisms such as Secure Shell (SSH) and Transport Layer Security (TLS).

It is critical for communications devices to prevent tampering. Devices should lock unused ports, whitelist device software and firmware, and use memory encryption. They should also alert operators to physical tampering with the equipment.

User authentication must be integrated with a utility's central active directory using standard protocols such as Lightweight Directory Access Control (LDAP) or Remote Authentication Dial-In User Service (RADIUS). This ensures nonrepudiation of activity on network devices for role-based accounts.

### *F. Time Synchronization*

Coordinating system time between devices exchanging information over a communications network is as important as the information itself. Time synchronization accuracy requirements between devices on a network are dictated by the application. For example, phasor measurement units have strict time synchronization requirements because they provide real-time measurements of distribution systems.

Time synchronization can be obtained in many ways. Clocks that are satellite-synchronized using the Global Positioning System (GPS) or Global Navigation Satellite System (GNSS) produce a local serial time code signal, IRIG-B. IRIG-B provides time synchronization with better than 100-nanosecond accuracy to devices using this signal.

Satellite-synchronized clocks also use the IEEE 1588 Precision Time Protocol (PTP) to distribute precise time with better than 1-microsecond accuracy over Ethernet networks. It is a message-based time transfer protocol, and its synchronization accuracy and precision are dependent on device-specific characteristics and network design [6]. Network Time Protocol (NTP) is the most widely used time synchronization method. NTP uses a client-server model to communicate time information between devices and can achieve a synchronization accuracy of between 1 and 100 ms.

## VI. DA Applications and Requirements

Wireless communications technology is appealing for utilities adding or updating DA applications. Table I shows a

TABLE I
DA APPLICATIONS AND REQUIREMENTS

| Application | End-to-end Communications Latency | Message Characteristics |
|---|---|---|
| Overload mitigation | Slow; seconds | Small data packets with commands when circuit overloading occurs |
| Traditional load reconfiguration, isolation, and service restoration | Slow; seconds | Small data packets with commands when a fault occurs |
| High-speed load reconfiguration, isolation, and service restoration | Fast; ~50 ms | Very small data packets with commands when a fault occurs |
| FCIs and wireless line sensors | Slow; ~seconds | Periodic, medium-sized data packets with load status information or small data packets with fault information when a fault occurs |
| Remote devices to substation | Slow; ~seconds | Periodic data packets with variable sizes |
| SCADA to control center | Slow; ~seconds | Periodic data packets with variable sizes and occasionally large sizes for file transfers |
| High-speed load shedding | Fast; ~100 ms | Very small data packets with commands when loads need to be shed |
| Volt/VAR control | Slow; seconds | Small data packets with commands when voltage and reactive power need to be adjusted |
| Teleprotection | Fast; 4–40 ms | Very small data packets with commands |
| Voltage control (capacitor banks and voltage regulators) | Slow; seconds to minutes | Small data packets with commands when voltage needs to be adjusted |
| Distribution generation control | Slow; seconds | Small data packets with commands to control generation |
| Distribution generation interconnection control | Fast; ~100 ms | Very small data packets with commands when a distribution generation site connects or disconnects from the distribution network |
| Meter reading | Very slow; minutes to hours | Periodic data packets with variable sizes |
| Remote personnel access | Slow; ~seconds | Data packets with variable sizes for command response and occasionally large sizes for file transfers |

list of typical DA applications and their requirements [7]. The advantages of adding a wireless communications system instead of traditionally wired or fiber-optic cable communications are twofold: a lower installation cost and a faster installation process.

One disadvantage of wireless communications systems is that these systems are subject to interference. Interference can cause longer delays (latency) because of the need to retransmit data. Interference can also lead to data loss and subsequently reduced data availability.

Latency, availability, and reliability are the key parameters typically used to determine whether a wireless technology is suitable for a particular DA application.

## VII. EXISTING AND EMERGING COMMUNICATIONS TECHNOLOGIES FOR DA

This subsection presents a list of emerging communications systems that could come to define DA. It is unlikely that any one emerging technology will dominate in all areas of DA. Rather, utilities will select the emerging communications systems that suit their specific application needs.

### *A. Licensed Networks*

The shared nature of the unlicensed radio frequency spectrum leads to a high potential for interference. Some utilities acquire a slice of a licensed spectrum for distribution system communications. The main advantages of licensed networks are low interference and high transmit power. Utilities can use the allocated frequency band exclusively and avoid radio frequency interference altogether. Transmit power, usually higher for licensed bands, improves link budgets and increases the propagation distance.

The two main disadvantages of licensed networks are the reduced spectrum size and the high upfront cost of spectrum acquisition. The reduced spectrum size leads to lower bandwidth and data rates. Lower data rates impede the scalability of large networks and limit bandwidth-intensive applications (e.g., streaming synchrophasors). The cost of spectrum acquisition is substantial because of the scarcity of available spectrum: many utilities and other industries, such as the oil and gas industries, are competing to acquire small slices of licensed spectrum. Additionally, the time to obtain license approval can be long enough to impact the network development time.

## B. Unlicensed Networks

Unlike licensed networks, unlicensed band networks do not require licenses to use frequency bands. Unlicensed bands are available in Europe at 863 to 870 MHz, in North America at 902 to 928 MHz, and worldwide at 2.4 to 2.5 GHz.

Unlicensed networks are appealing for communications technologies because they are available worldwide and utilities do not have the upfront costs of spectrum acquisition. However, because the bands are shared and utilities do not have exclusive rights to use them, devices must deal with interference and background noise. For reliable communications, system designs for unlicensed radio frequency bands must ensure that information is not lost due to interference. This is done using purpose-built systems that have error detection, correction at the link layer, and acknowledgment or negative-acknowledgment retransmit at higher layers. All of these design choices come with latency tradeoffs, but as long as the applications can function with that caveat, networks that use unlicensed bands are a good choice because of the high bandwidth available. High bandwidth translates to better scalability and coverage for more applications.

## C. Public Cellular Networks

Over the last ten years, an increase in mobile traffic caused by the proliferation of smartphones has caused cellular networks to transition from voice-centered to data-centered services. Applications requiring high data rates, global access to the Internet, and seamless mobility have been the drivers of cellular technology advancements in the last decade.

A major benefit of cellular technology is that there is no network to set up because devices use the existing public network infrastructure. Utilities only need to deploy relatively inexpensive end devices to create functioning networks. They then can easily scale these networks. However, there are recurring monthly service fees that vary depending on data usage and the number of included devices. For some applications, service level agreements are needed between the utility and the carrier company to guarantee performance, and those can increase costs.

### 1) 4G LTE

4G LTE cellular technology is used for DA because of its high data rate and throughput. It can be used for both backhaul, where a high data rate is needed, and sensor networks, where low rates are often acceptable.

### 2) Machine-to-Machine (M2M) Cellular Technology

Today, the need for Internet of Things (IoT) and M2M communications poses a new set of requirements that are not supported or optimized by current cellular technologies, such as LTE. M2M requirements are one of the major drivers for next-generation cellular networks. There is a clear divergence between human-to-human communications and M2M communications. Human-to-human communications are voice and data services (such as multimedia) that do not have energy consumption constraints. M2M communications are technologies that enable networked devices to exchange information and perform actions without human intervention. The data rate for M2M communications can be low, periodic, or sporadic. Energy consumption can also be low. Some battery-powered M2M communications devices are required to last for 10 years.

Cellular technology has three uses in M2M communications for distribution systems: as the backhaul of FAN aggregation points (such as data concentrators) to the data center; as the backhaul of FAN aggregation points to a substation that is part of the backbone network; and as a direct connection between two FAN aggregation points.

Recently, a new set of standards focusing on M2M communications has emerged for low-data-rate and low-power devices. The new set includes LTE categories Cat-1, Cat-0, and Cat-M, as well as narrow-band IoT (NB-IoT). Table II shows LTE evolution toward M2M communications.

#### a) Cat-M

Although Cat-1 and Cat-0 are listed in Table II as part of M2M communications systems, they do not meet some main requirements of network emerging communications such as low power consumption and low cost. However, Cat-M (officially known as LTE Cat M1) meets these requirements and is often viewed as the LTE technology built specifically for IoT and M2M applications. Cat-M meets most of the emerging communications requirements by reducing its performance (see transmit power and bandwidth in Table II) to reduce cost and power consumption, key drivers for M2M end-device use.

The advantage of Cat-M technology over competing cellular technologies is its compatibility with the existing LTE network. Because Cat-M was developed to use LTE infrastructure, cellular operators simply need to upgrade software to enable Cat-M devices to operate within the LTE network. Cat-M is suitable for sensor networks and medium-data-rate DA

TABLE II
COMPARISON OF LTE CELLULAR TECHNOLOGY

| Release | Category | Downlink Speed (Mbps) | Uplink Speed (Mbps) | Number of Antennas | Duplex | Bandwidth (MHz) | Transmit Power (dBm) |
|---|---|---|---|---|---|---|---|
| 8 | Cat-4 | 150 | 50 | 2 | Full | 20 | 23 |
| 11 | Cat-1 | 10 | 5 | 2 | Full | 20 | 23 |
| 12 | Cat-0 | 1 | 1 | 1 | Half | 20 | 23 |
| 13 | Cat-M | 1 | 1 | 1 | Half | 1.4 | 20 |
| 13 | NB-IoT | 0.2 | 0.144 | 1 | Half | 0.2 | 23 |

suitable for sensor networks and medium-data-rate DA applications. Cat-M is likely to emerge as a short-term winner for DA applications that use cellular technology.

*b) NB-IoT*

NB-IoT is a new narrow-band communications technology that was built on top of existing LTE networks. The technology standard was completed by the 3rd Generation Partnership Project (3GPP) in 2016. It was designed to provide improved coverage for a large number of low-throughput, low-cost devices with low power consumption in delay-tolerant applications.

NB-IoT uses narrow-band channels to provide higher sensitivity and a long range, but it has a limited data rate. The demodulated spectrum can be much wider than individual transmissions so that multiple links can occur simultaneously. The base station bears the complexity of decoding multiple narrow-band channels simultaneously. One advantage of NB-IoT is its ability to connect many low-throughput devices with variable data rates. As indicated in 3GPP guidelines, the design objectives include low cost, high coverage, long battery life, and large capacity. The latency can be as long as 10 seconds. NB-IoT enabled devices can be ideal for wireless sensor networks and very low-data-rate DA applications.

*3) 5G*

Increasing demand for broadband services and services for IoT and M2M applications are driving the development of 5G. The evolution of cellular technology has allowed users to experience faster data speeds, prompting an increase in data-driven applications and services. While existing cellular technology has coped with the rising data demand so far, it is clear that more capacity and new technology are needed.

5G distinguishes two classes of IoT-based M2M applications: massive and mission-critical. Massive M2M applications are characterized by a large volume of end devices. This volume can consist of billions of connections, including low-cost and low-power devices for wireless sensor networks, smart metering, connected homes, and so on. Although current 4G LTE technology can accommodate some M2M application needs, the technology was not designed to handle a very large number of connections efficiently.

Mission-critical applications require high reliability, low latency, strong security, and availability. 5G provides a highly reliable connection to support both massive and mission-critical DA applications.

At the time of this writing, there are several efforts underway to define 5G technical specifications. Some carriers have already made public announcements about plans for 5G networks. Two large wireless carriers in the United States have stated that they intend to deploy 5G technology in major cities beginning in Q4 of 2018.

Because 5G technology is designed to address IoT and M2M applications, it could be an important communications technology emerging in the next 5 to 10 years. Table III shows some key features of 5G technology.

TABLE III
5G FEATURES

| Feature | Specification |
|---|---|
| Latency-in-the-air interface | 1 ms |
| Average end-to-end device latency | 10 ms |
| Maximum data rate per connection | 10 Gbps |
| Area capacity density | 1 $\text{Tbps/km}^2$ |
| Availability | 99.999% |
| Coverage | 100% |
| Battery life | 10 years for low-power IoT devices |

## D. Private LTE Networks

Private LTE is based on LTE standards and a scaled-down version of the LTE technology designed specifically for enterprise business, government, and educational purposes. Private LTE networks use dedicated equipment to serve a geographic area and to fulfill the requirements of specific applications. The use of dedicated equipment allows a private LTE network to tailor its network for optimized performance, e.g., a lower latency.

A private LTE network can be deployed in a shared spectrum, an unlicensed spectrum, or a licensed spectrum. The following three subsections describe each of these options.

*1) 3.5 GHz Citizens Broadband Radio Service (CBRS)*

In 2015, the United States Federal Communications Commission (FCC) authorized the use of the 3.5 GHz radio band, 3550 to 3700 MHz, for shared wireless access. This band was previously a protected spectrum used by members of the U.S. Navy and U.S. Department of Defense, with part of the band licensed to wireless Internet service providers (ISPs).

The FCC is planning to make this spectrum available under a new set of licensing rules that protects incumbents while making the spectrum broadly available for a wide set of users. The CBRS band rules are still being finalized, but the FCC has established a three-tiered, spectrum-sharing framework for the band.

*a) Tier 1: Incumbents*

The first tier of the CBRS band is for incumbents, which include the federal government and satellite providers. These existing users get permanent priority as well as site-specific protection for registered sites, which are also known as "exclusion zones." The systems of this tier are protected from interference by lower tier users at all times.

*b) Tier 2: Priority Access Licenses (PALs)*

PALs are offered within the 3550 to 3650 MHz portion of the spectrum and are assigned based on spectrum auctions. They cover seven 10 MHz bands within that lower 100 MHz of the CBRS band. The licenses are for 10 MHz channels and are valid for three years. The cost of PALs is expected to be much lower than the cost of licensed bands used by public LTE operators.

PAL availability will be determined by census tracts, areas defined by the U.S. Census Bureau as neighborhoods encompassing roughly 2,500 to 8,000 residents. A single census tract can have up to four PALs within a limited geographic area. Each PAL can be renewed only once.

*c) Tier 3: General Authorized Access (GAA)*

GAA users are allowed to use any portion of the CBRS band that has not be assigned to a higher-tier user. GAA provides free access to the spectrum, which makes it similar to an unlicensed spectrum. Since PALs are limited to a maximum of 70 MHz in any given census tract, the remaining 80 MHz of the total CBRS band are available for GAA use (when not occupied by Tier 1 users). The 3650 to 3700 MHz bands are used by the incumbents and GAA users exclusively.

*d) CBRS Implementation*

Fig. 1 shows how the three tiers share the CBRS band in the spectrum-sharing framework.

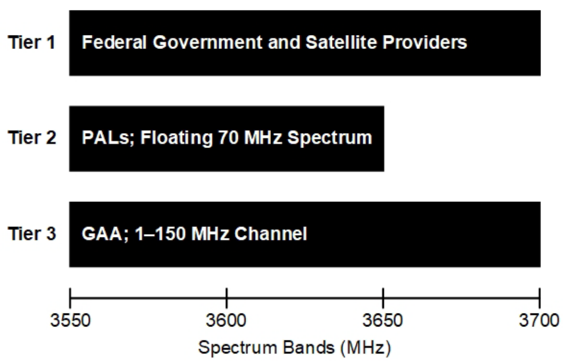


Fig. 1. Overview of the CBRS Spectrum-Sharing Framework

To make this three-tiered spectrum work, a key element of the CBRS sharing architecture is the Spectrum Access System (SAS). The SAS is a cloud-based server that maintains a database of all base stations in a region. It enforces the sharing mechanism based on FCC rules, creating centralized, dynamic coordination of spectrum assignments across all base stations in a region.

Any end device that supports the new 3GPP band for CBRS (Band 48) can be used in a private LTE network. A utility will be able to self-provision its end devices on its private LTE network without involving a mobile operator. The utility can install its own SIM card on the devices. If a utility wants end devices to work on both private LTE and a public mobile network, the devices need to be dual-SIM devices that have two SIM cards installed.

*2) 5 GHz Band*

In recent years, the FCC has made a portion of the 5 GHz band available for unlicensed use. A portion of this unlicensed band can be used for private LTE communications: U-NII-1 (5150 to 5250 MHz) and U-NII-3 (5725 to 5850 MHz). These bands are available to users today, as long as the equipment being deployed has been approved by the FCC for commercial use. The group of companies that started promoting this technology is now known as the MulteFire Alliance.

In principle, MulteFire technology is suitable for any spectrum band that requires over-the-air contention, such as the global 5 GHz unlicensed spectrum band or the shared spectrum in the 3.5 GHz CBRS band in the U.S. It builds on elements of the 3GPP Release 13 and 14 standards for Licensed Assisted Access (LAA) and Enhanced Licensed Assisted Access (eLAA), which modify standard LTE to operate in a global unlicensed spectrum. Enhancements, including Listen-Before-Talk (LBT), have been designed to let MulteFire technology users efficiently coexist with other spectrum users, such as Wi-Fi.

LBT and dynamic sub-band selection simplify and avoid the need for radio frequency planning. Like LAA and eLAA, MulteFire can dynamically detect and select the least-used bands to avoid other spectrum users. It will also use LBT to ensure fair coexistence when bands have to be shared with other users.

A MulteFire network can issue its own SIM cards for use with its own services. It is also possible for standalone networks to allow open access from devices without a SIM card by allowing them to automatically self-provision a local identity.

*3) Licensed Spectrum Bands*

As a final option, organizations may use any of the already licensed spectrum for private LTE. While the majority of the licensed spectrum has been licensed over broad geographic regions, the FCC allows "secondary" market activities including the partition and disaggregation of the spectrum. If a utility has already purchased a license to operate in a band that is wide enough for LTE technology, it is feasible to find a set of LTE-enabled equipment that allows the utility to build a private LTE in that band.

## *E. Wireless Smart Ubiquitous Network (Wi-SUN)*

Wi-SUN is a wireless mesh network in which each network element is a repeater. Because of this configuration, each node can be accessed either directly from an access point or from another network node through one or multiple hops, as shown in Fig. 2.

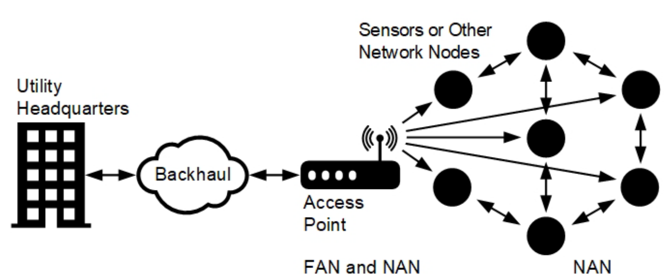


Fig. 2. Wi-SUN System Architecture

Wi-SUN topology is based on the IEEE 802.15.4g standard for the physical layer, the IEEE 802.15.4e standard for the link layer and media access control (MAC) sublayer, and the Internet Engineering Task Force (IETF) IPv6 Over Low-Power Wireless Personal Area Network (6LoWPAN) protocol for the logical link control sublayer. Its key characteristics are presented in Table IV.

TABLE IV
WI-SUN FEATURES

| Feature | Specification |
|---|---|
| Frequency bands | Europe: 863–876 and 915–921 MHz<br>India: 865–867 MHz<br>North America and Brazil: 902–928 MHz<br>China: 470–510 MHz<br>Japan: 902–928 MHz<br>Korea: 917–923.5 MHz |
| Maximum data rate per terminal | Up to 300 kbps |
| Average latency | 20 ms/hop |
| Maximum aggregation per concentrator | 10,000 terminals |
| Urban range (without repetition) | 1.86–3.1 mi (3–5 km) |
| Rural range (without repetition) | 6.2–9.3 mi (10–15 km) |

Wi-SUN latency is related to the mesh topology. This topology offers advantages in range extension and self-healing capability (alternative routes are created automatically), but this can increase the latency of the network. This does not present a problem for low-data-rate DA applications, but it could have a negative impact on high-data-rate DA applications. To overcome this restriction, Wi-SUN designers can build specific predetermined paths in the network that can achieve near-deterministic network latency.

### *F. Low-Power Wide-Area Network (LPWAN) and Long Range (LoRa) Technology*

LPWAN is an emerging wireless solution that helps integrate wireless sensors and other low-data-rate field devices. This network can cover long distances with minimal power consumption and maintenance. LPWAN has the potential to serve as a communications infrastructure for distribution systems in the future.

Two representative technologies of LPWAN are LoRa technology and NB-IoT (discussed previously). Although NB-IoT is a competitor of LoRa, the two can complement each other. LoRa technology is perfect for utilities to incorporate into regions without cellular network coverage. It can also be used to establish private networks with specific requirements for specific applications. LPWAN may provide a practical and economical DA solution.

LoRa operates in the unlicensed bands of 433, 868, and 915 MHz. The main improvement of LoRa technology over existing technologies is its modulation technique. LoRa modulation is based on chirp spread-spectrum (CSS) technology. This technique uses broadband linear pulses to encode information. The frequency of the pulses increases or decreases based on the encoded information. CSS, which has been used for radar applications since the 1940s, provides robustness to combat channel-degrading effects such as multipath fading, the Doppler effect, and in-band jamming interference. As a result, LoRa technology can achieve a receive sensitivity of –148 dBm, about a 20 dB improvement in receiver sensitivity compared with other leading sub-gigahertz technologies. The link budget can be as much as 157 dB over the link budgets of traditional communications media.

LoRaWAN is a communications protocol that resides in the Layer 2 data link layer and is based on open standards. LoRaWAN includes LoRa technology devices. It uses a star topology, as shown in Fig. 3. LoRaWAN receives data packets from end nodes, and then forwards the packets through a gateway to an application by a backhaul such as a cellular or Ethernet network.

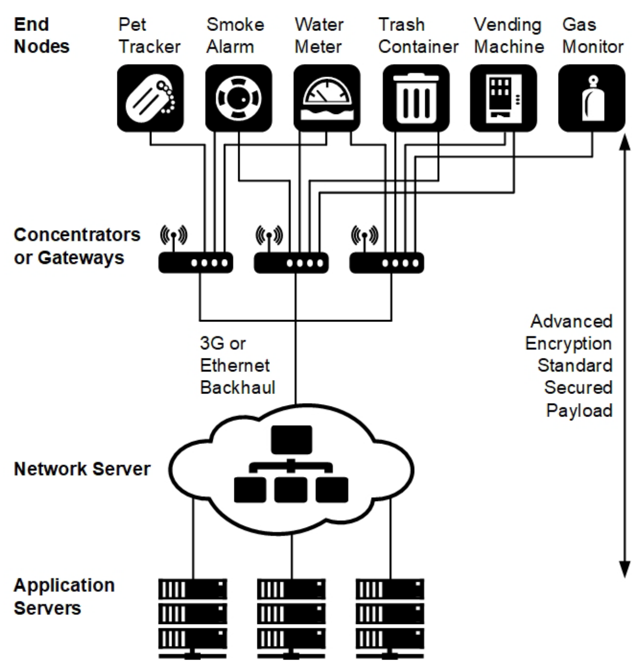


Fig. 3. LoRaWAN Overview

LoRaWAN has many benefits: a long range, a low cost, low power consumption, and the ability to register devices over the air using highly secure key exchange mechanisms. The extremely low power consumption allows devices to operate from 10 to 20 years using a battery. This could be ideal for wireless sensor networks. Table V shows key characteristics of LoRaWAN.

TABLE V
LORAWAN FEATURES

| Feature | Specification |
|---|---|
| Frequency range | Europe and India: 867–869 MHz<br>North America and Brazil: 902–928 MHz<br>China: 470–510 MHz<br>Japan and Korea: 920–925 MHz |
| Maximum data rate per terminal | 50 kbps |
| Average latency | 1 second |
| Maximum aggregation per concentrator | 15,000 terminals |
| Urban range | 1.2–3.1 mi (2–5 km) |
| Rural range | 6.2–9.3 mi (10–15 km) |

Although the theoretical data rates suggest that LoRaWAN can support most DA applications, further studies are needed to verify that this technology accurately meets DA requirements.

# VIII. EMERGING WIRELESS TECHNOLOGIES SUITABLE FOR DA APPLICATIONS

Table VI summarizes the emerging communications technologies discussed in this paper and their suitability for use in DA applications.

# IX. WIRELESS LINE SENSORS

## A. *Wireless Sensor Technology*

This section provides details on wireless sensor technology that is being used to enhance distribution reliability. The technology and device features vary depending on the type of wireless line sensor. Wireless distribution sensors fall within one of three categories:

- Wireless FCIs.
- Fault and load transmitters (FLTs).
- Advanced line sensors.

Wireless FCIs are the simplest overhead distribution sensors, and only report fault or no fault statuses. These inexpensive devices are used in large quantities across distribution power systems and are only used to identify fault locations. Wireless FCIs are replacing noncommunicating FCIs, which include targets (mechanical or LED) that require visual checks.

FLTs go beyond basic fault detection and include additional fault metrics such as fault magnitude, event type, and fault direction. Devices in this category also include load-reporting capabilities.

Advanced line sensors contain the same fault and loading capabilities of the wireless FCIs and FLTs. They also have a richer feature set that can include advanced functionality such as event reporting. The exact features and capabilities of advanced line sensors vary between manufacturers.

TABLE VI
SUITABILITY OF EMERGING TECHNOLOGIES FOR DA

| Application | 4G LTE | Cat-M | NB-IoT | 5G | Private LTE | Wi-SUN | LoRa |
|---|---|---|---|---|---|---|---|
| Overload mitigation | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Traditional load reconfiguration, isolation, and service restoration | Yes | Yes | No | Yes | Yes | Yes | Yes |
| High-speed load reconfiguration, isolation, and service restoration | No | No | No | Possibly | Possibly | No | No |
| FCIs and wireless line sensors | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Remote devices to substation | Yes | Yes | No | Yes | Yes | Yes | Yes |
| SCADA to control center | Yes | Yes | No | Yes | Yes | Yes | No |
| High-speed load shedding | No | No | No | Possibly | Possibly | No | No |
| Volt/VAR control | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Teleprotection | No | No | No | No | No | No | No |
| Voltage control (capacitor banks and voltage regulators) | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Distribution generation control | Yes | Yes | No | Yes | Yes | Yes | Yes |
| Distribution generation interconnection control | No | No | No | Possibly | Possibly | No | No |
| Meter reading | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| Remote personnel access | Yes | Yes | No | Yes | Yes | Yes | No |

### B. *Requirements for Wireless Line Sensors*

#### 1) *Accuracy*

The most application-crucial requirement for line sensors is the ability to accurately detect fault conditions and measure load current. Inaccurate or unreliable fault information can present confusing fault reports and guide line crews to incorrect fault locations, increasing the time needed to isolate faults and restore service. Any delay caused by a line sensor can offset its benefits and ultimately cause a lack of trust in the device. The line sensor must send accurate fault information every time.

Accuracy requirements for monitoring load and detecting faults vary depending on the application. Devices that only detect fault currents, such as wireless FCIs, have less-stringent requirements: around 95 percent fault detection accuracy is sufficient. Line sensors used in load-reporting applications need more precision and have an accuracy requirement of greater than 99 percent.

#### 2) *Power*

All wireless line sensor devices consume power and thus require power sources to operate. Line sensors are low-power devices. Radio communications and LED displays are typically the two biggest consumers of the power budget. The rate at which radio transmissions occur affects the power consumption. A continuous two-way communications link is not viable for present technology, assuming a ten-year device life. As such, the radios in line sensors cannot be powered all the time. Typically, a line sensor only turns on the radio when a message is ready to be transmitted. Messages are sent periodically about loading information or by exception after a fault or outage occurs.

A nonrechargeable lithium battery is one option for providing power to line sensors. A primary lithium battery has a high charge density and a long lifespan, so it is ideal for a line sensor application. The energy that a lithium battery provides is always available over the life of the battery. Because the sensor is completely self-reliant for power, system outages do not affect the radio communications or LEDs. However, after the lithium battery is depleted, maintenance is required to either replace the battery or replace the line sensor. This requires truck rolls and increases the overall cost of ownership of these devices.

Another way to power line sensors is to use energy-harvesting technology. This method uses a current transformer (CT) coupled to the overhead conductor to charge a supercapacitor or other rechargeable energy storage components. Fig. 4 shows a simple block diagram of an energy-harvesting implementation. The signal from the CT is rectified and then regulated before charging the reusable power source. Energy-harvesting technology excels at extending the life of the device and reducing maintenance for battery replacements. However, the sensor is almost completely reliant on the power system for the energy to operate. The supercapacitor holds a small amount of energy to provide power to the device during brief system outages. Extended outages that last several hours or more will deplete that energy and cause the device to suspend operations until power is restored.

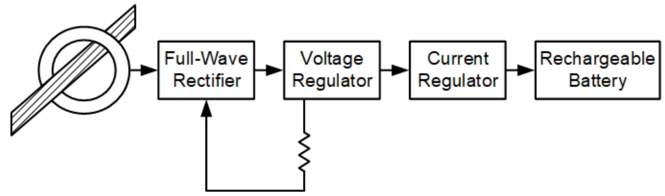


Fig. 4. Energy Harvesting Implementation

A hybrid powering option combines both battery and energy-harvesting technologies, as shown in Fig. 5. The hybrid method uses energy harvesting to power the line sensor and recharge a supercapacitor during most of the operating time of the device. A small backup battery source is also embedded in each device and is used to power it during extended outages. When the battery is only used in periods of extended outages, its lifespan is much longer than that of a battery installed in a device that uses the battery as its only power source. Extending battery life minimizes maintenance. A backup battery option also eliminates any sensor downtime caused by supercapacitor depletion during extended outages.

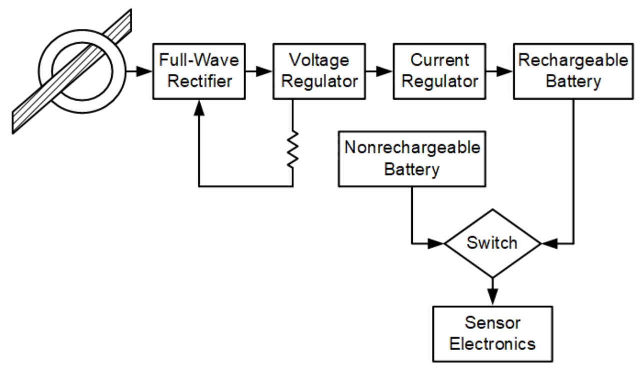


Fig. 5. Hybrid Powering Implementation

#### 3) *Physical Requirements*

Line sensors monitor currents on overhead power conductors through a coupled split-core CT. A split-core CT provides a practical means for installing line sensors on live conductors.

Line sensors are installed on overhead distribution conductors using shotgun-style hot sticks, so these sensors need to be easy to install. The sensor should install in less than five minutes and require no special tools (other than the hot stick).

The weight of the sensor must also be balanced with its performance. As features are added to the device, its weight increases. A sensor that is heavier than four pounds is difficult to manage at the end of a 20-foot hot stick, making installation challenging.

Overhead line sensors are installed and operate in harsh outdoor environments that affect performance and can reduce their lifespan. Outdoor applications are demanding on both internal and external components of line sensors. Durability is essential because these devices must withstand wide temperature ranges, daily and seasonal thermal cycling, rain, snow, and sunlight.

Line sensors should meet the requirements of IEEE 495-2007 to ensure suitability for installation in harsh environments. Although this standard does not explicitly cover wireless line sensors, noncommunicating FCIs are installed in the same environments. Thus, the environmental tests covered in the standard are also applicable to wireless line sensors. Temperature, ultraviolet light, rain, electrical effects, and phase immunity are all covered under the IEEE 495 standard. Additional testing is also needed beyond the standard to further develop ruggedness and reliability for wireless line sensors. These tests can include physical drops, ingresses from dust or water, and ice buildups (see Fig. 6 for one example).


Fig. 6. Ice Buildup Test on Wireless FCI

### *C. Wireless Line Sensor Features*

Features for wireless line sensors vary to fit individual applications. As advances continue in small low-power component technology, new features and capabilities for wireless sensors advance as well. New line sensor capabilities allow for applications that were previously impossible.

#### *1) Loading Information*

Wireless line sensors that monitor load current send loading data (e.g., average and peak loading) at regular update intervals. Accurate loading information from line sensors provides insight into the entire distribution system beyond the substation. They can also report power factor and load direction. Data usually present in periodic loading reports include, but are not limited to:

- Average load data.
- Peak load data.
- Power factor.
- Load direction.
- Load alarms.

#### *2) Fault Information*

Wireless line sensors have evolved beyond simple "fault" and "no fault" indicators. Precise identification of fault locations from distributed wireless sensors improves system awareness and fault response times. Sensors can also now detect and report fault current magnitudes.

At a minimum, a line sensor should detect the fault current magnitude and precisely time-stamp the event for coordination with other IEDs. Fault direction is necessary for identifying the fault location when there are DERs. Data present in fault messages typically include, but are not limited to:

- Fault magnitude.
- Fault direction.
- Fault type.
- Event time stamp.
- LED display.
- Event report.

#### *3) Wireless Sensor Architecture*

The network architecture can determine the performance of any sensor network and its fit for various DA applications. Sensor device manufacturers should keep applications in mind before selecting the architecture for a sensor network.

## X. Example Wireless Sensor System Designed for DA

The FLT system discussed in this section was designed for DA, is collector-based, and operates in an unlicensed radio band. It uses a star network topology in which wireless sensors communicate to a fault and load receiver, also known as a concentrator. The concentrator is responsible for collecting data from the sensors on the network, including event messages and data messages.

Event messages consist of small packets of data, such as average load current, peak load current, fault indication, fault type (momentary, permanent, or disturbance), display indication, wireless receive signal strength, and various other data on the health of the sensor. Data messages include settings and configurations sent to the sensors from the concentrator as well as software upgrades sent out to the sensors. Over-the-air firmware upgrade capability is an important feature because once the sensors are deployed, it is hard to access them to apply upgrades using software.

A star network topology, like the one in this example system, has better response determinism and is simpler than complex mesh networks. Further, purpose-built wireless protocols, such as time-division multiple access (TDMA) protocols, provide equal and dedicated time slots for all of the sensor nodes on the network. This helps to avoid collisions in the wireless network and reduces delays due to noisy nodes. Another important attribute of a purpose-built TDMA protocol is that it provides more time slots for event messages generated on a periodic basis than for data messages that do not occur on a regular basis (e.g., settings changes or firmware upgrades).

In this system, the concentrator aggregates sensor data using a wireless protocol and communicates via DNP3 over Internet

Protocol (IP) to utility back office systems such as SCADA systems, outage management systems, or other distribution management systems. DNP3 communication is desired for DA equipment because of its simple interoperability with other network systems, as described in Section V, Subsection C. Because the concentrator is a DNP3 server, this approach significantly simplifies deployment and integration of the sensor network into existing utility systems. The wireless technology for this system uses the unlicensed 900 MHz ISM band, which provides adequate bandwidth for sending load data in near real-time fashion from the sensors. Fig. 7 shows the system overview and illustrates various communications options for sending sensor data to utility applications.

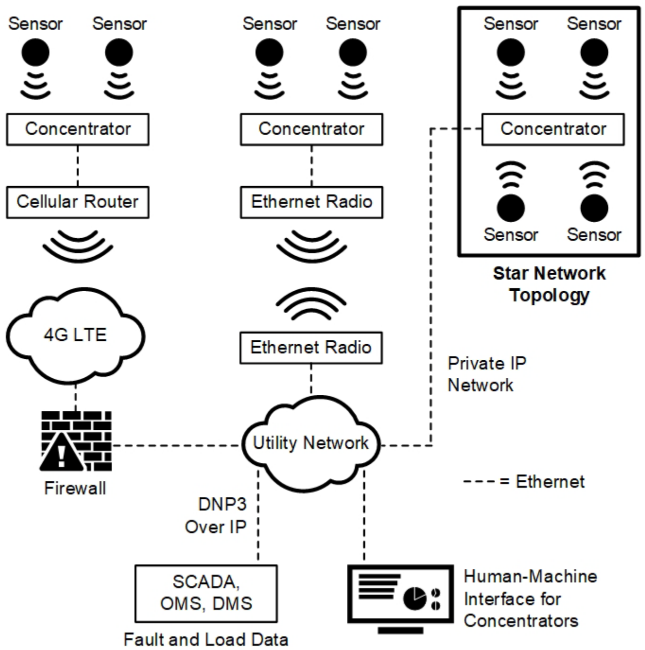


Fig. 7. Overview of an FLT System

## XI. Conclusions

Today, there are several wireless communications options available and even more emerging wireless technologies for DA applications. With a wide variety of applications and performance requirements for DA, there is no clear winner or a one-size-fits-all solution when it comes to choosing a wireless technology. Utilities must pick technologies based on "fit for use" and attempt to cover most use cases to minimize the number of different wireless technologies.

Similar evaluation is needed for the wireless line sensors occupying these networks. Utilities must balance sensor DA application requirements and product features in order to make the implementation of wireless line sensors worthwhile and practical. A well-considered system will reduce operational expenses, improve reliability metrics, and increase efficiency in delivering energy to end users.

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## XIII. Biographies

**Shankar V. Achanta** received his M.S. in electrical engineering from Arizona State University in 2002. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2002 as a hardware engineer, developing hardware for power utility products. Shankar currently holds 14 SEL patents, and he is an inventor on several patents that are pending in the field of distribution sensors, precise timing, and wireless communications. He currently holds the position of engineering director for the distribution controls and sensors group at SEL.

**Kei Hao**, P.E. (M 2011), received his Ph.D. in electrical engineering from the University of Wisconsin–Madison, his M.S.E.E. from the University of Wisconsin–Milwaukee, and his B.S.E.E. from La Universidad de la Republica, Uruguay. He joined Schweitzer Engineering Laboratories, Inc. in 2010 as an automation and protection engineer. He is presently a development lead engineer in research and development. He has experience in control and automation systems, wireless communications systems, and power system automation and protection. He is a member of IEEE and a registered professional engineer in the state of California.

**Jakob Fowler** received his B.S. degree in electrical engineering from Northern Illinois University in 2011. He joined Schweitzer Engineering Laboratories, Inc. in 2011 as an associate field application engineer in the fault indicator and sensor division. He focused primarily on support for faulted circuit indicators used on distribution circuits. In 2014, Jakob transferred to the research and development division to work on the development of faulted circuit indicators and sensors.


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