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CIGRE US National Committee
2012 Grid of the Future Symposium

Technology Options for Distribution Communications Infrastructure to Support Advanced Smart Grid Applications

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SUMMARY

Advanced smart grid applications bring a unique set of requirements to distribution communications systems. The ability to support multiple applications concurrently improves the overall value of the network by spreading the costs and enabling more benefits. In addition, more advanced communication standards such as 4G technologies can enable more demanding grid applications that have not been practical to support in the past.
A variety of standards-based communications technologies are available for use as distribution communications infrastructure. Cellular architecture standards such as IEEE 802.16 (WiMAX) and 3GPP LTE are often chosen to implement high reliability, broadband, multi-functional communications infrastructure using licensed spectrum. These technologies are being successfully deployed by both commercial carriers and utilities around the world. Although they are quite similar in many ways, there are some notable differences. Unlicensed standards such as 802.11 (Wi-Fi), and emerging standards for TV White Space provide additional options for utility communications.
In addition to the technical considerations, business model considerations strongly influence the process of selecting the optimum choices for distribution communication infrastructure. In addition to the application set, factors such as coverage area, spectrum availability, and the service and capabilities offered by commercial wireless operators factor into the evaluation process.
The complex set of options and technologies can present a daunting challenge to utilities in the process of designing or deploying communications systems to support advanced applications. Collaborative research in to this area is being conducted, which will result in the creation of new industry resources.

KEYWORDS
Distribution Automation Communications Infrastructure WiMAX LTE Wi-Fi Field Area Network

Introduction

Utility communications engineers find themselves at the convergence of several trends. First, new grid applications demand high performance and high reliability data communications over a wider geographic area. Second, suitable radio spectrum is in short supply in much of the world, and is subject to strong competitive pressures for commercial mobile wireless services. Third, the effect of global economic challenges on utilities continues to constrain available funds for capital investment and operational expenses.
These trends are contradictory, and preclude a universal solution for distribution communications infrastructure. The good news is that wireless communication technologies and standards are continually evolving and improving, driven by the mass market for smartphones and other devices

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with wireless broadband capabilities. The newer "4G" standards have been optimized to maximize range and data throughput while making the most efficient use of spectrum. This paper will explore the technology options for implementing communications networks capable of supporting advanced distribution automation, as well as the business factors that influence that selection. These wireless technologies are applicable to networks operated by mobile broadband carriers, as well as utility-owned private networks.

Applications driving the need for distribution communications infrastructure

In most cases, utilities have networks in place to support SCADA at substation locations. These networks use a combination of fiber, microwave, leased lines, and narrowband VHF radios. These technologies are generally point-to-point, which makes it costly to extend connectivity to new locations. New applications that require higher data throughput and lower latency, as well as nearly universal coverage along feeders and the surrounding territory, fall into several broad classes.

The first application class supports distribution operations. Distribution Feeder Automation is a prime example. Extending communications out to remote devices improves the ability to monitor and control the distribution system. Typical DA functions such as control and monitoring of fault sensors, line sensors, reclosers, and switches do not require significant bandwidth individually, but in aggregate, the data load can exceed the capabilities of existing SCADA systems. Advanced applications such as Fault Location, Isolation, and Service Restoration (FLISR) can significantly reduce outage duration, but requires low latency communications to sense the outage area and reconfigure sectionalizers. Implementation of Volt/VAR optimization and Conservation Voltage Reduction throughout distribution also requires additional communications, but can provide significant payback from the efficiency gained resulting from reduced line losses and peak load reduction.

The second class of applications takes advantage of the broadband capacity of the Field Area Network to do things that were never possible before. Video surveillance of critical assets is a becoming a priority application in many areas. Enabling the field force with high bandwidth data can provide real-time data and documentation, support situational awareness, and enable new applications such as augmented reality data visualization. Field worker devices can directly connect to the FAN, or utility vehicles can bridge to the FAN and create Wi-Fi hotspots at the work site.

The third class of applications relates to migrating existing devices onto the FAN to improve the overall cost benefit balance of the FAN. This typically involves migration of the AMI system's backhaul onto the FAN, but other types of legacy systems can be migrated as well. Cost benefits may come from eliminating expenses for 3rd party backhaul providers. Benefits may also be realized by enabling the retirement of older legacy communications systems that have become expensive to maintain as their devices are moved onto the FAN.

State of FAN Technology Standards and Ecosystems

These smart grid applications are a subset of those that are driving some utilities to consider a broadband Field Area Network for their distribution communications infrastructure. This doesn't mean that a high performance FAN is required in every situation. Some distribution applications can be adequately supported by an AMI system, for example. For the applications where a FAN is needed, a variety of wireless communications solutions are available. WiMAX (based on IEEE 802.16) and LTE (based on 3GPP standards) are the leading candidates for high performance, high reliability networks that can support multiple applications. Both of these standards are true 4G technologies.

Although WiMAX was the first 4G standard to be published, and the first to be widely deployed, the commercial operators' direction is changing. In the past two years, many operators have decided to implement LTE as their upgrade path from 3G to 4G technology. Sprint and Clearwire (who operate commercial WiMAX networks today) have also decided to migrate to LTE. This direction among carriers can be somewhat attributed to the origins of LTE as part of the 3GPP family. These standards evolved from their origins in GSM in the 1990s, and they have been designed and architected with the needs of mobile wireless operators in mind. This design philosophy allows handover of calls between the 2G, 3G, and 4G generations of the network, and supports billing, inter-network roaming of users, and many other functions required by mobile operators.

In contrast, the standardization for WiMAX takes place in the IEEE 802 LAN/MAN Standards Committee. The 802.16 Working Group (WG) is one of ten currently active WGs and technical advisory groups (TAGs) in IEEE 802. The shared IEEE 802 architecture provides a degree of unification between the individual 802 standards. Therefore, the architecture and interfaces to higher layers of 802.16 have more in common with standards like 802.3 (Ethernet) and 802.11 (Wi-Fi) than telecom standards such as the 3GPP family. This "LAN" orientation can enable easier integration of WiMAX with enterprise IT networks and systems.

The origins and architectural "leanings" of the respective standards do not mean that each standard is only suitable for a single purpose. There are many WiMAX networks deployed globally that provide mobile voice and data services, and are fully integrated into the mobile operator's existing voice networks. Likewise, it is possible to integrate an LTE network into the enterprise LAN architecture.

Both standards will continue to evolve over time. Currently there are two sets of amendments to the 802.16 standards underway. GRIDMAN (802.16n and 802.16.1a)) defines improvements to support higher reliability and resilience, enabling the network to reconfigure in case of disruption. M2M (802.16p and 802.16.1b) defines changes to better support Machine to Machine applications. This includes support of larger numbers of devices connected to a base station, and improvements in multicast, security, and power saving modes. The LTE Advanced standards have been completed, but have not been rolled out, since the first deployments of Release 8 LTE are still underway.

Distribution Communication Infrastructure Technology Options

A variety of communication technologies are able to meet the requirements of the grid applications previously outlined. The appropriate technology must be evaluated based on a number of factors, including the specific requirements of all the applications to be supported (throughput, latency, and reliability), the available spectrum options, and the financial aspects of capital investment vs. operational expenses.

In most cases, a private Field Area Network is built out from a utility's existing Wide Area Network (WAN), which is typically implemented with a combination of fiber and point-to-point microwave. If needed, the FAN can serve to extend the WAN, in addition to supporting other applications.

Standards-based wireless technologies used for a FAN generally fall into three categories: 4G networks operating in licensed spectrum (WiMAX and LTE), technologies for unlicensed spectrum, and emerging "cognitive radio" technologies for TV White Space.

4G Licensed Technologies: WiMAX and LTE

These wireless technologies are the latest incarnation of what is often called the cellular architecture, which is able to provide continuous coverage over an arbitrarily large geographic area. Multiple base stations provide regions, or "cells", of coverage. The base stations are located so that any point in the service area falls within the coverage area of at least one base station. The connected devices implement a "handover" function, which allows a device to move from one base station to another while maintaining a connection. This is essential for mobile devices like phones, but can also increase reliability of fixed devices. Cellular networks may be range limited or capacity limited. Distribution communications infrastructure tends to be range limited, since the required coverage areas tend to be large, but the number of devices and the data requirements per device are relatively low. Commercial cellular operators are often capacity limited, due to their large numbers of data-hungry users.

At the radio link level, 802.16 (WiMAX) and LTE have more similarities than differences. They are both based on OFDMA (Orthogonal Frequency Division Multiple Access), and support MIMO (Multiple Input Multiple Output). They support a variety of frequency bands and channel widths. They both provide an efficiency-optimized MAC layer with advanced QoS (Quality of Service) and scheduling control.

One of the significant differences is the orientation towards paired spectrum (FDD or Frequency Division Duplexing) or unpaired spectrum (TDD or Time Division Duplexing). Mobile telephony systems have historically used paired spectrum (FDD). One frequency range is used for the downlink (DL - from base station to user device), and another frequency band is used for the uplink (UL from user device to base station). The LTE standard continued this orientation to match the paired spectrum allocations owned by commercial operators. WiMAX was designed to operate in a single block of spectrum using TDD. Aside from the ability to take advantage of spectrum that would be otherwise unsuitable for an operator's FDD system, TDD systems can also provide more flexibility in allocating bandwidth to the UL or DL direction. Since the TDD radio link alternates between functioning as UL and DL, the amount of time allocated to each is adjustable based the data flow. An FDD system has a fixed amount of spectrum allocated to UL and DL channels. Differences in capacity (from MIMO and/or base station antennas) are used to optimize the DL to serve the needs of mobile phones. However, grid applications such as sensors and video require more bandwidth on the UL. A TDD system is better able to accommodate imbalances in the UL and DL data flows.

LTE and WiMAX are not limited to FDD and TDD, respectively. A TDD variety of LTE (TD-LTE) has been developed and is starting to be deployed, particularly in China. Likewise, WiMAX includes options that support FDD operation, although that capability has not been widely used.

Another significant difference between WiMAX and LTE is in the ability to provide connectivity for layer 2 messages (Layer 2 of the protocol stack). As an IEEE 802 standard, 802.16 uses the same layer 2 addressing format as Ethernet. Some protocols, such as IEC 61850 GOOSE messages [1] rely on multicast at layer 2. LTE provides an IP-only network, and does not support layer 2 connectivity. Although protocols exist to tunnel layer 2 through IP networks, they add overhead and complexity. WiMAX supports layer 2 directly, although some system configuration may be necessary.

The third difference between WiMAX and LTE relates to the forwarding of messages between peer devices on the network. LTE's design does not support direct forwarding of packets between devices within the radio access network. All packets must pass through the Enhanced Packet Core (EPC), which may be in a different city for large networks. The EPC typically serves as a gateway to the Internet, so for a mobile phone the EPC is on the normal path. However, for grid applications (such as FLISR) that require direct device-to-device communications, the added latency of routing packets to the EPC and back could be an issue. WiMAX provides the capability for local routing through a single base station, or along the shortest route between base stations.

These examples should not be taken as an endorsement of WiMAX over LTE for grid applications, but are meant to highlight some relatively subtle differences that can have an effect on system implementations.

While WiMAX and LTE are designed for licensed spectrum, there are some licensed bands that are more easily accessed. For example, the 3.65 GHz band is considered "lightly licensed" [2] in the US. The license can be obtained for an administrative fee rather than through a competitive auction. However, licenses are not exclusive and users may have to cooperate with other users in the same band to avoid interference. The relatively low power limits and higher frequency will require more base stations (compared to lower frequency licensed bands), so this option is not a panacea.

Wireless Technologies for Unlicensed Spectrum

The strength and weakness of the ISM (industrial, scientific, and medical) bands are a direct result of their unlicensed nature. The strength is the availability of hundreds of MHz of RF spectrum in various bands at no cost for licenses. Compared to the billions of dollars that small slices of spectrum are auctioned for in the US and elsewhere, this seems like an incredible value. The flip side of the low cost of entry is the shared use of the band. All users have equal access and rights, and there is no limit to the number of users. As the number of users in the same band and geographic area increases, the available network throughput per user decreases. Some bands, such as the 915 MHz band (frequently used for RF-Mesh AMI systems) and the 2.4GHz band (used for Wi-Fi and ZigBee HANs) are crowded in many urban areas.

The relatively new IEEE 802.15.4g standard [3] supports operation in the 915MHz ISM band in the US, and comparable unlicensed bands in other countries. Compared to LTE, Wi-Fi, and WiMAX, the data rates are relatively slow, but the standard is designed for different applications. This standard is designed to be capable of supporting AMI networks, as well as some less demanding distribution automation applications. An 802.15.4g network typically uses meshing between its nodes, and employs collectors to bridge data from a number of meters and devices to a higher bandwidth backhaul network.

The 802.11 standard (Wi-Fi) presents some interesting options for a higher performance distribution communications and/or backhaul network using unlicensed spectrum. Several vendors offer meshed 802.11 systems that can cover a metropolitan area with high bandwidth Wi-Fi access. These types of systems are used for distribution applications as well as supporting real-time video. The mesh algorithms make it possible for the system to "route around" failed nodes and/or areas experiencing high interference or congestion. With all meshing technologies, the ability of the system to compensate for disruptions requires a relatively large number of nodes in the mesh in a topological arrangement that provides a variety of routes between any two nodes. Furthermore, the benefits of the flexible routing come at the cost of higher latency, since each packet requires multiple hops to traverse the mesh.

Emerging Technologies – TV White Space

TV White Space refers to the use of unused TV channels for purposes other than television broadcasting by licensed TV stations. The UHF television frequency band has desirable propagation characteristics in terms of range and building/foliage penetration. In the US, the FCC has made these channels available for unlicensed radio devices operating under specific rules. There are limitations on antenna height and output power, and devices must avoid licensed users through a combination of geo-location, database access, and interference sensing. The availability of unused channels varies widely from urban to rural areas in the US. Many large metropolitan areas have no available channels while rural areas may have as many as 40. For a system to take advantage of frequency agility (moving the network to avoid interference and other users) multiple vacant channels should be available. Exactly how many are actually needed is a question for further research.

The IEEE 802.22 [4] standard for TVWS has been completed, and others (802.11af and 802.15.4m) are in development. Commercial devices operating in this spectrum are becoming available. There are some concerns that the FCC regulations may not adequately protect all types of TV broadcast receivers from TVWS systems under all conditions, which could lead to complaints against the system owner. This is another topic to be explored in future research and testing.

The interest in TV White Space is international. Regulations in various countries are often linked to their digital TV transitions, as it happened in the US. The CEPT in Europe and OFCOM in the UK are in the process of establishing TVWS regulations in their respective areas. Within the constraints of shared use, possible interference, and allowable power levels, TV White space may provide a useful option (primarily in rural locations) for distribution communication applications.

Distribution Communication Infrastructure Business Model Issues

Leveraging Private Network Investment

Deploying a private distribution communication infrastructure can require a significant capital investment. Many factors will influence the total cost. The most important is the size of the geographic area to be covered, which drives the number of base stations or access nodes required. For licensed cellular architecture systems, the cost of the spectrum itself may be a significant factor. Utilities have successfully purchased blocks of spectrum for their own territories, but the cost is quite high – potentially in the millions of US dollars. The frequency of the spectrum is also a key factor. Lower frequency bands have better propagation characteristics, and can enable a lower number of base stations (for a range limited network). Another factor that influences the cost is the utility's existing wide-area network infrastructure. An existing fiber WAN can support wireless base stations and provide major savings compared to installing new backhaul connections at each base station.

The benefits component of the cost/benefit analysis will derive from the operational cost savings and new applications enabled by the network. The distribution communications infrastructure will enable new applications that will provide positive benefits in terms of efficiency in power delivery, reduction in outages and their duration, and better management of peak loads. Each application will provide an ongoing financial return on the investment. Leveraging multiple applications on one network often makes the difference in providing a positive return on the network investment.

Public Carrier Infrastructure

As an alternative to (or in addition to) private networks, most utilities use public carriers' wireless networks in some way. Commercial wireless networks have been globally deployed by a number of operators to support the demand for mobile voice and data services. These operators are seeking utilities as customers, and the rates they charge for utility-oriented services have dropped substantially over the past decade. This is partly because of the efficiency improvements enabled by 3G and 4G technologies. The carriers own large amounts of spectrum in various bands. Understanding which frequency bands a carrier uses for their specific technologies (3G or 4G) should be part of the evaluation process, since they have differing propagation and coverage characteristics. Other than the cost for the services, network reliability is the most frequent concern of utilities considering commercial networks for distribution communications. The carriers have made substantial progress in term of managing service outages due to storm damage, from backup power at cell sites to mobile base stations that can be deployed to affected areas. Some carriers are also implementing redundancy in their network core. Utilities must evaluate and verify each carrier's specific capabilities in the context of their own business needs and reliability requirements. Many times, they conclude that redundancy is still necessary. That could mean a private utility communication system serves as the backup for the carrier, or conversely, the carrier may function as a backup to a utility communication system.

Public Safety Sharing

Recent policy changes in the US have opened a new opportunity for utilities to share an LTE network in the 700MHz bands with the primary public safety users [5]. There are a number of unresolved open issues at the time of this writing. One of the biggest is the lack of a precise definition of what "secondary user" status means. Exactly what happens to utility access to the network in the case of an event that involves a large number of public safety users? Utilities that are interested in investigating public safety network sharing partnerships need to open a dialog with their state as soon as possible. After a window of approximately two years, this one time opportunity will longer be available.

Ongoing Research on Distribution Communication Infrastructure

This paper highlights a subset of the complex group of inter-related factors that influence the selection of distribution communication infrastructure. The choices are ultimately driven by the combination of application requirements that define the limits of bandwidth and latency that the network must provide. The availability and frequency of appropriate spectrum (along with financial and business model factors) can tip the balance between a private utility network deployment and the use of commercial wireless operators. Hybrid combinations of private infrastructure and commercial operators' networks are also commonplace, introducing another range of options along that continuum. The set of available standards and technologies is continually evolving and improving their capabilities and performance. The integration of these new networks, devices, and applications into the enterprise also requires careful attention to the aspects of cybersecurity to prevent the introduction of vulnerabilities.

To develop a resource that integrates research and experience from all aspects of this complex landscape, EPRI is developing a Field Area Network Demo program [6]. The program will enable collaboration between utility members that are implementing Field Area Networks, each with a unique approach and solution, and integrate the best practices and analysis into a single guidebook document. The guidebook, and the collaboration it represents, will provide an ongoing resource for the members as their networks continue to grow and evolve.

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