

# *Lines of Communication*

Architecture and Solutions for  
Linking the Elements of the  
Smart Distribution Grid

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<AU: WOULD YOU PROVIDE AN INTRODUCTORY SENTENCE SO THE ARTICL DOESN'T START WITH FIGURE 1?> FIGURE 1 SHOWS A CROSS SECTION OF A MODERN power system that includes elements ranging all the way from traditional generation and transmission down to customer-owned generation. Also shown are multiple emerging advanced automation and control systems. Significantly, every part of this power system either contains information required by other entities or needs to interact from a control perspective with other parts of the system. The emerging power system communication requirements are not just traditional "home-run" SCADA requirements; they are more like a mesh in which any point in the system may need to communicate with any other point in the system. The speed and latency requirements for this communication range all the way from milliseconds to hours. Picture the communications equivalent of a duplex power outlet, in which communication services are provided from anywhere to anywhere with a quality of service that meets the needs of any particular application, all of which must be accomplished while maintaining adequate security and without adversely affecting communication system performance.

Energy distribution systems are at a crossroads due to significant imbalances of various kinds on present networks. Not only is the overall gap between demand and supply continuing to increase due to global population growth, there is also a geographic imbalance in energy production and consumption patterns resulting from the escalating energy demands of newly industrializing nations (Brazil, China, India, and Russia). Clearly, while incorporating a wide variety of renewable (non-fossil-fuel) sources will be an inevitable part of the solution, the possibility of significant changes aimed at improving the overall power delivery network will in itself be a significant driver. Of these, the more radical changes will occur at the distribution level, in terms of making the grid "smart." These future "smart grids" will be significantly affected by digital systems and power electronics. Smart distribution grids (SDGs) will be markedly different from their legacy counterparts due to the infusion of these new technologies on multiple fronts. Table 1 characterizes the salient differences between today's distribution systems and those anticipated in the future. An essential ingredient in these future distribution systems is a new generation of communication technologies. These topics are further explored below.

Legacy distribution system deficiencies are characterized by low flexibility and intelligence, outdated networks, unacceptable performance measures, increased consumer cost of service issues, and environmental issues. The U.S. Department of Energy (DOE) has defined a smart grid as "the electricity delivery system (from point of generation to point of consumption) integrated with communication and information technology for enhanced grid operations, customer services, and environmental benefits." Certain characteristic features of a smart grid have been identified. Among them are:

- ✓ self-healing from power disturbance events

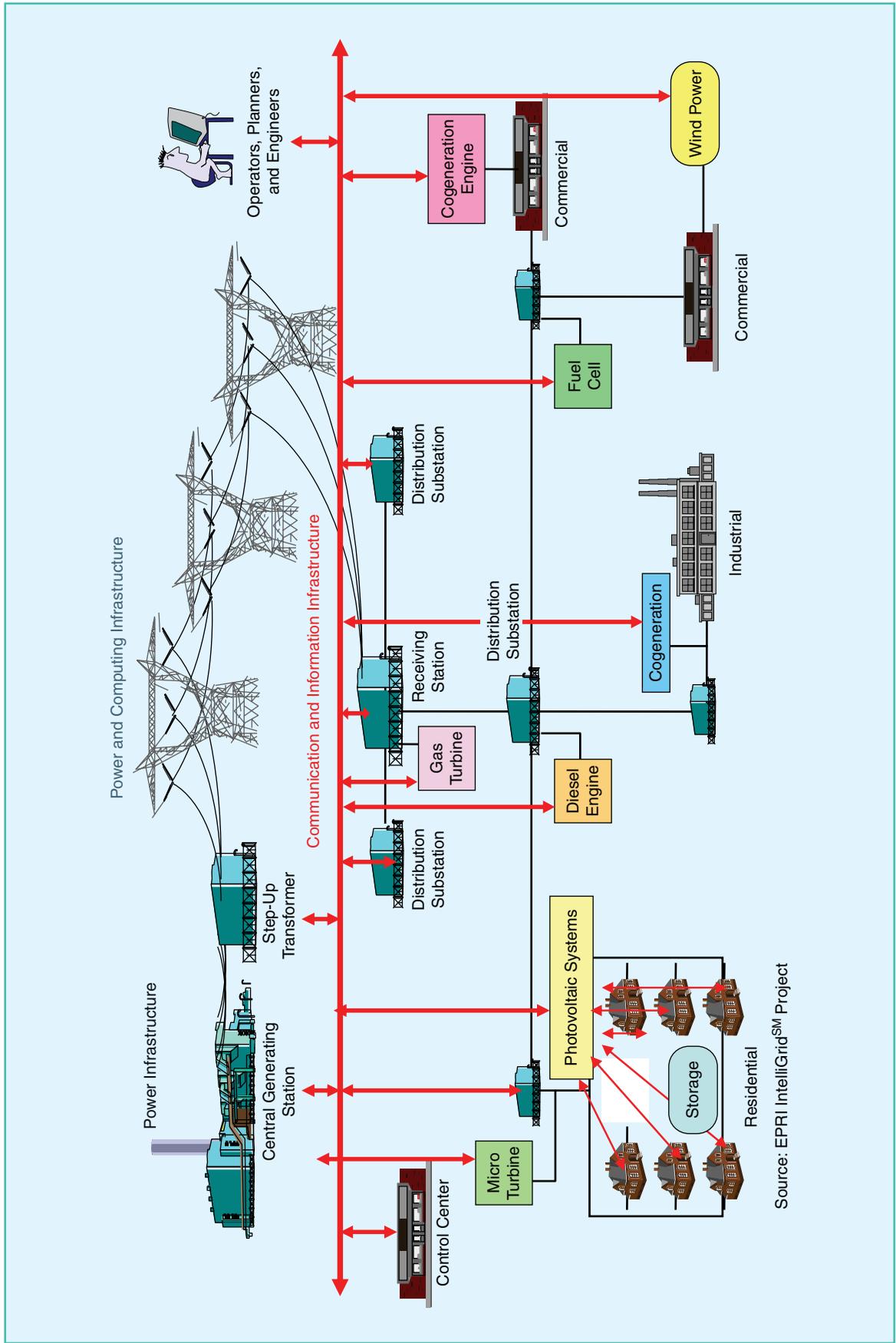
- ✓ enabling active participation by consumers in demand response
- ✓ operating resiliently against physical and cyber attack
- ✓ providing power quality for 21st-century needs
- ✓ accommodating all generation and storage options
- ✓ enabling new products, services, and markets
- ✓ optimizing assets and operating efficiently.

## Communication Network Standards for Smart Grids

The Energy Independence and Security Act (EISA) of 2007 passed by the U.S. Congress brought the term *smart grid* into the public vocabulary. The law assigned the National Institute of Standards and Technology (NIST) "primary responsibility to coordinate development of a framework that includes protocols and model standards for information management to achieve interoperability of Smart Grid devices and systems" (EISA Title XIII, Section 1305). To carry out its EISA-assigned responsibilities, NIST devised a three-phase plan to rapidly identify an initial set of standards while providing a robust process for continued development and implementation of standards as needs and opportunities arise and as technology advances. The three phases were as follows:

- 1) **NIST was to engage stakeholders in a participatory public process to identify applicable standards and requirements as well as gaps in currently available standards and priorities for additional standardization activities.** With the support of outside technical experts working under contract, NIST has compiled and incorporated stakeholder input from three public workshops, as well as technical contributions from working groups and a cyber security coordination task group, into the NIST-coordinated standards road-mapping effort.
- 2) **NIST was to establish a smart grid interoperability panel (SGIP) forum to drive longer-term progress.** A representative, reliable, and responsive organizational forum was needed in order to sustain continued development of interoperability standards. On 19 November 2009, the Smart Grid Interoperability Panel was launched to serve this function.
- 3) **NIST was to develop and implement a framework for conformity testing and certification.** Testing and certification of how standards are implemented in smart grid devices, systems, and processes are essential to ensure interoperability and security under realistic operating conditions. NIST, in consultation with stakeholders, plans to develop an overall framework for testing and certification. The initial steps were completed by early 2010 <AU: edits OK?>.

Significant SGIP deliverables to date include the "NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 1.0" and a NIST Interagency Report entitled "Guidelines for Smart Grid Cyber Security." The



Source: EPRI IntelliGrid<sup>SM</sup> Project

**figure 1.** Power system profile. <AU: Do you have permission from the source to use this image? We cannot publish it without permission >

**Table 1. Distribution system characteristics.**

Characterization	Existing	Future (Smart)
Topology	Radial except downtown networks	Loop and meshed
Generation	None or sporadic	Microgrids; green technologies
Devices	Old and aging	New and evolving
Operation	Slow	Near real-time
Planning	Less than 30 years	Less than ten years
Power flow	Unidirectional	Bidirectional

first of these establishes a conceptual smart grid communication framework and identifies numbered communication interfaces for further study. The second provides recommendations for establishing a secure communication environment. Continuing work aims to produce a series of priority action plans (PAPs) that will contain recommendations for enhancements to existing standards work to fill gaps in their interoperability. The SGIP will also publish a list of “recommended” interoperable standards.

## Smart Infrastructure

### Key Technology Areas

The National Energy Technology Laboratory (NETL) has identified five foundational “key technology areas” (KTAs) that will provide the needed impetus to characterize and meet the new challenges and opportunities of the smart distribution grid:

- 1) **Sensing and measurements:** These will include massively deployed smart sensors, smart meters integrated with an advanced metering infrastructure (AMI), and low-cost phasor measurement units.
- 2) **Advanced components:** These will appear in several forms: as flexible control devices and new generation and storage technologies; solid-state, digitally and remotely controlled elements such as switches and relays; and intelligent static transformers, to name a few.
- 3) **Advanced control schemes:** These will encompass new, robust, digital closed-loop methods using distributed intelligence that will respond to control signals to achieve advanced distribution automation. Advanced protection schemes are part of this KTA. These will include differential line and adaptive protection devices that rely on low-latency communications.
- 4) **Improved interfaces and decision support systems:** These include information management systems for key functions such as data management, fusion, mining, and control.
- 5) **Integrated communications:** A new communication infrastructure will form an overlay over the power grid for efficient communication of data and control to support the items listed above. It will operate at multiple levels, connecting end users (customers) to other net-

work elements (distribution transformers, substations, and control centers) (see Figure 1). This infrastructure will need to support moderately high-speed secure data transfers with predictable and controllable latencies specified through the use of quality of service (QoS) parameters at the message level.

## Communication Requirements for Smart Grids

There will be a significantly increased emphasis on *real-time* monitoring and control for the purposes of enhanced operational reliability in the era of distributed generation and increased customer participation in the energy marketplace. Frequent and accurate sensing of network status and appropriate use of this information for real-time control actions are the drivers for the new, networked decision and controls architecture that will be required to achieve the desired levels of grid stability, efficiency, and reliability. The communication network and the associated protocol stack will be charged with transporting sensory information reliably.

The new grid will add thousands of distributed but intermittent generators, turning one-time pure energy consumers into part-time producers as well. These renewable energy sources are known to be more stochastically time-varying, however. As a consequence, the future grid will need to send a great deal of control information to end nodes (consumers) for the purposes of applications such as demand response. This implies a more symmetrical, two-way flow of information, at least in some segments of the future smart grid, as energy flows from the consumer with spare energy resources towards grid control centers. This is quite different from the present-day scenario, where information flows largely in one direction only. The evolution from one-way communication (strongly asymmetrical) to two-way communication (more symmetrical) calls for a fundamentally new end-to-end communication architecture that is cognizant of the requirements of the new data flows that must be supported. For example, an independently operating energy microgrid of, say, a few hundred premises will require an architecture that supports relatively frequent information exchange among them. The latency constraints required for such communications to enable demand response and energy trading suggest the desirability of a distributed protocol suite and a more fully connected network topology (i.e., with multiple paths between the end points). On the other hand, applications such as monitoring power quality over a wide area may be consistent with a hierarchical network topology that allows convenient intermediate nodes for data aggregation; typically, these will require multiple hops between the source (where data are generated) and the destination (where the information is processed to generate decision and control actions) and hence must be latency-tolerant. A classification of some of the new SDG functionalities and their network requirements is provided in Table 2. Note that most monitoring and control applications require low to moderate bandwidths

**table 2. Classification of SDG functionalities and network requirements.**

Applications	Properties	
	Bandwidth	Latency
Power quality monitoring	Low	Low
Distribution automation (voltage/var control)	Low	Low
Advanced metering	Moderate	High
Protective relaying	Low	Low
Demand response (pricing, load control)	Low	High
Rural broadband access	High	Low

(other than the proposition to support broadband Internet access for rural and other underserved areas <AU: is this a monitoring/control application? how so?>). Finally, while the average data rates at individual smart meters or other sensor nodes will in general be low, the rate required at links within the network hierarchy will increase due to aggregation at intermediate points. Only for deployments intended to support high-speed Internet access (such as for access to rural or underserved areas) will the anticipated link rates reach those for broadband (10 Mb/s or greater). In most cases, less than 1 Mb/s (and typically on the order of 100 Kb/s) will suffice for the foreseeable future. Applications that will require relatively low latency include any that support real-time or near real-time monitoring and control.

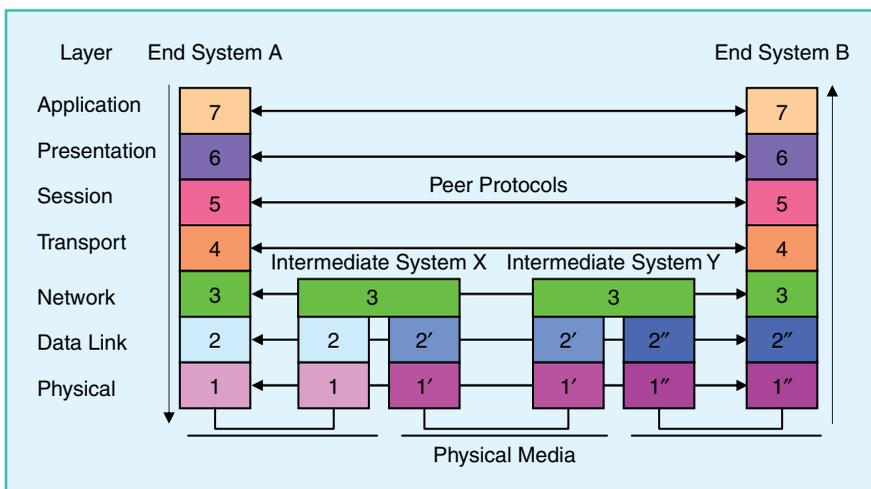
It is useful to view the end-to-end SDG communication infrastructure as consisting of multiple zones—beginning with the subscriber end points (homes and businesses), extending through the meters and the low-voltage distribution network, and terminating at the distribution substations. Such a multizone architecture gives the operator control over its devices and a secure domain environment for its applications. It is logical to partition the ensuing discussion into the following three zones of a smart distribution management system (DMS):

- ✓ a customer area (inside customer premises, up to the smart meter) that constitutes the *smart microscale DMS*
- ✓ a secondary distribution area (low-voltage, between the customer area and the distribution transformer) that constitutes the *smart miniscale DMS*
- ✓ a primary distribution area (medium-voltage, from the distribution transformer to the substation).

### Characteristics of a Smart Communication Infrastructure

Several design considerations are essential for a communication infrastructure to successfully serve an emerging SDG. These include the following:

- ✓ Communication protocols must be “layered,” as in the open system interconnect (OSI) and Internet Engineering Task Force (IETF) RFC 1122 and 1123 communication models. This allows the separation of physical media, addressing, security features, and application specification (see Figure 2). Importantly, such a network can mix multiple physical media to meet application needs without sacrificing interoperability. It can also share common addressing methods to simultaneously transport messages from multiple application layer protocols. Transparent application layer support allows end-to-end interoperability without requiring the use of application gateways to repackage information. Best practice in today’s world is to use IPv4 addressing at the transport layer while pointing the way to IPv6 as it becomes available. IPv6 will offer an expanded address space as well as other advantages, including QoS controls <AU: OK?>.
- ✓ Security must be “designed in” rather than “bolted on.” Best practice is to use upper-layer security, which protects the information rather than wrapping security around every link in the communication chain (see Figure 3).



**figure 2.** The OSI protocol stack.

- ✓ QOS controls <AU: OK?> should be included, so that the infrastructure can support both high- and low-priority messages on the same network. IPv6 offers QoS services “built in.”
- ✓ Upper-layer protocol selection is important for interoperability. Major players in the distribution automation (DA) arena include ANSI C12.22 for meter communication, DNP3 over IP to support legacy DA devices, and IEC61850, which supports self-describing devices and provides interoperability with emerging substation devices.
- ✓ Physical layer selec-

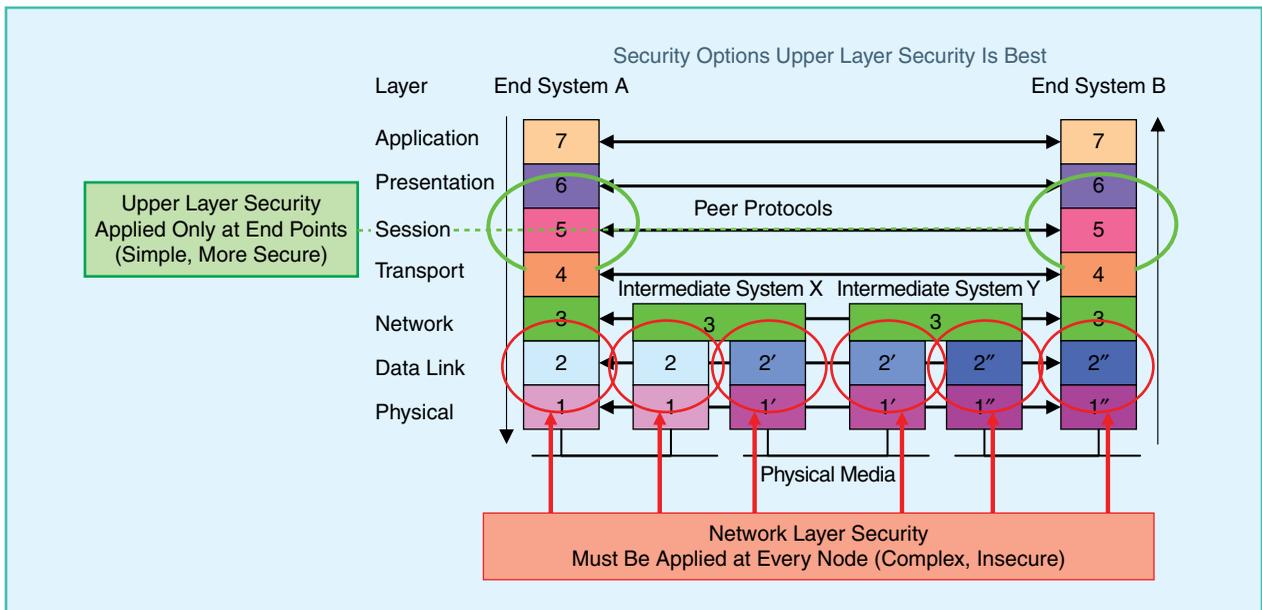


figure 3. Security options.

tion will depend on local application constraints but can be used “mix and match” if part of a layered architecture. Possible solutions include a variety of both wired and wireless common carrier digital services, both licensed and unlicensed radio technologies, and private “wired” facilities such as fiber optics and power line carrier (PLC) solutions. Fiber installed as part of the transmission- or distribution-line construction is a particularly interesting physical layer. A list of candidate wireless technologies is presented in Figure 4.

- ✓ When selecting physical media, consider message *data rate* (throughput), message *latency* (delay), message *reliability* (probability of messages being lost), and message *redundancy* (data repetition or forward error correction) as required by the specific application(s) to be served. These all need to be measured against cost and the value of the information being transported for the particular application.

Presently, emerging smart grid networks are deployed using a variety of communication technologies, including wired (fiber, microwave, and power line) and public and private wireless networks, using licensed and unlicensed spectrum. In general, unlicensed wireless technologies such as 802.11 offer low-cost solutions as compared with licensed wireless and certainly wired networks, with the one exception of PLC solutions. Both wireless and power line solutions, however, face significant impediments in terms of having to find acceptable mechanisms for coexisting with increasing, diverse time- and spatially varying interferences.

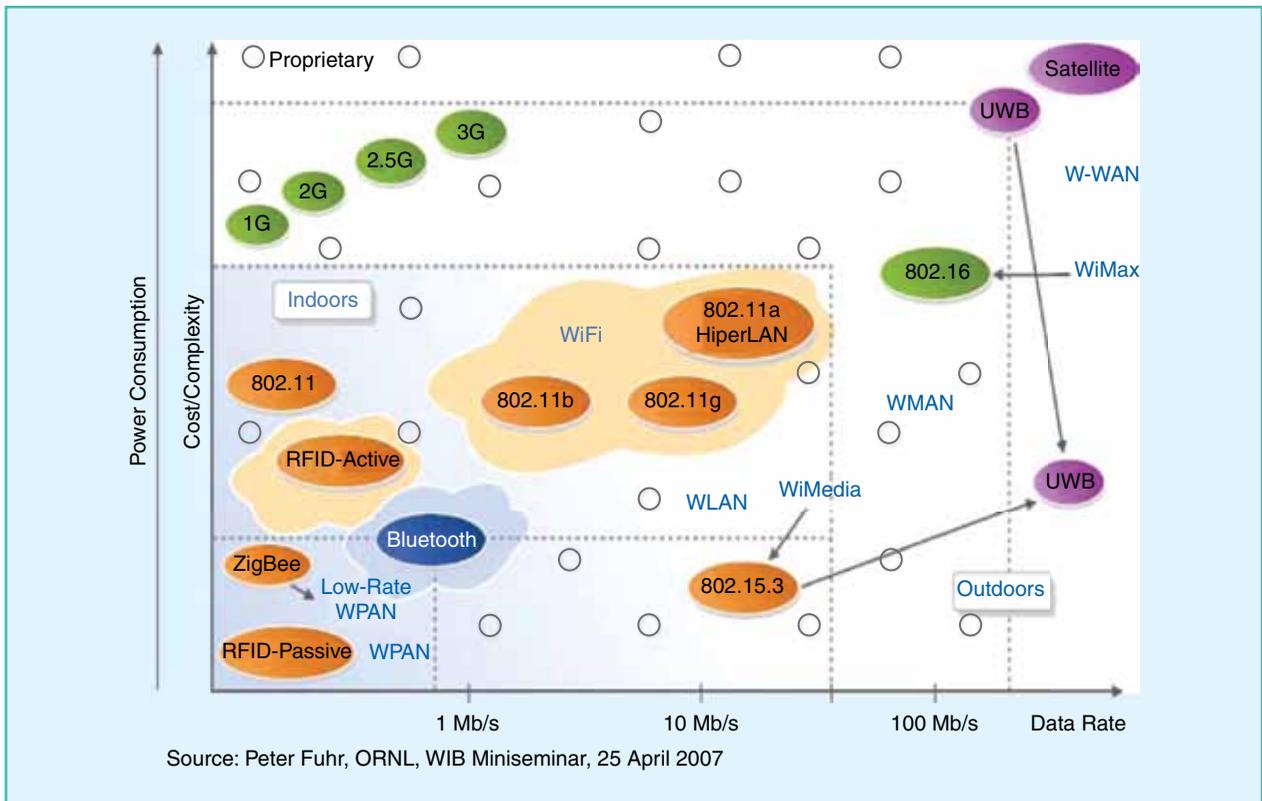
Historically, narrow-band PLC communication was developed for high-voltage transmission power lines extending over long distances, using low frequencies (typically in the kHz range), and achieving very modest data rates (only a

few kilobits per second). The technique has been extended to the medium-voltage distribution segment as well as in-home networks using higher-frequency bands (around 1–30 MHz) through the use of more sophisticated modulation techniques like quadrature amplitude modulation (QAM) and orthogonal frequency division multiplexing (OFDM, which uses multiple bits per symbol) and consequently achieving much higher signaling rates.

Utilities have also successfully used unlicensed spectrum wireless for automatic meter reading <AU: OK?> (AMR) and will naturally look to expand on these in distribution primary and secondary networks, as backhaul. Currently, new licensed spectrum wireless allocation for smart grid applications does not appear to be available, leaving utilities to either use unlicensed (such as 802.11) or licensed cellular (e.g., WiMAX within 4G) technologies for the distribution primary and secondary scales Figure 4 shows the various wireless physical layer options <AU: reference inserted–OK?>. Given the well-recognized underutilization of some licensed spectrum, an interesting recent proposition centers around the potential for opportunistic usage of “TV white space” for this purpose.

### Architectural Considerations for an Integrated Smart Distribution Grid

A wide variety of communication technologies will be used in smart grid networks at the various scales, determined largely by a combination of factors: the network requirements on rate, reliability, and criticality and the always relevant considerations of coverage and cost. Broadly speaking, for high-rate, high-reliability communications—particularly those at the network core, such as connecting distribution substations to SCADA—customized fiber-optic cables and microwave links will be preferred. For moderate performance in the



**figure 4.** Wireless physical layer options. *<AU: Do you have permission from the source to use this image? We cannot publish it without permission>*

intermediate scale, that is, between the substation and distribution transformer, both licensed and unlicensed wireless and wired alternatives could be used. (Wired systems such as fiber optics are expensive, however). For short ranges in the home area, unlicensed wireless technologies and PLC solutions are the obvious choices. In particular, the provisioning of low-latency applications is facilitated by reliable physical delivery media; hence, wired and optical networks may be preferred to wireless. In summary, the overall SDG network will almost certainly use a combination of technologies at different network scales, with specific choices based on the appropriate matching of application needs and communication network capabilities and costs.

While the above discussion has focused on the desired bandwidth and latency goals for various applications, considerations of coverage, network availability, and cost are equally important pieces in the final trade-off analysis. The fact that utilities cover large service areas, including segments that are remote or difficult to access, has significant implications for outlay cost. Grid equipment located in remote regions is not usually able to take advantage of public wireless networks and may require customized private networks. Reliability is also of paramount concern for critical monitoring and control applications: the communication networks must be available during emergency conditions, when they are needed most.

In consideration of the many factors listed above, some utilities are planning to use custom fiber-optic installations to connect elements within the core, i.e., at the distribution primary. New distribution substations required for load growth are also likely to be equipped with fiber-optic communication in preparation for future smart grid services. Microwave or other long-haul wireless communication may however be installed in rural areas to connect substations that are much further apart, where cable construction may be limited due to permit or cost issues. In summary, “suitable” technologies that meet utility requirements with respect to coverage and application QoS such as bandwidth and latency, security, and reliability while providing a pathway for reasonable return on investment within the marketplace and the regulatory environment will finally determine SDG implementations.

### SDG Components in Detail

We next describe in greater detail the components of the three SDG segments, categorized for convenience according to their power segment voltages: the home area network (HAN), the distribution secondary network (WAN for DA), and the distribution primary network (analogous to the field area network). We anticipate that variations in network topology and functionalities as well as choices of physical media will distinguish the various segments in this classification.

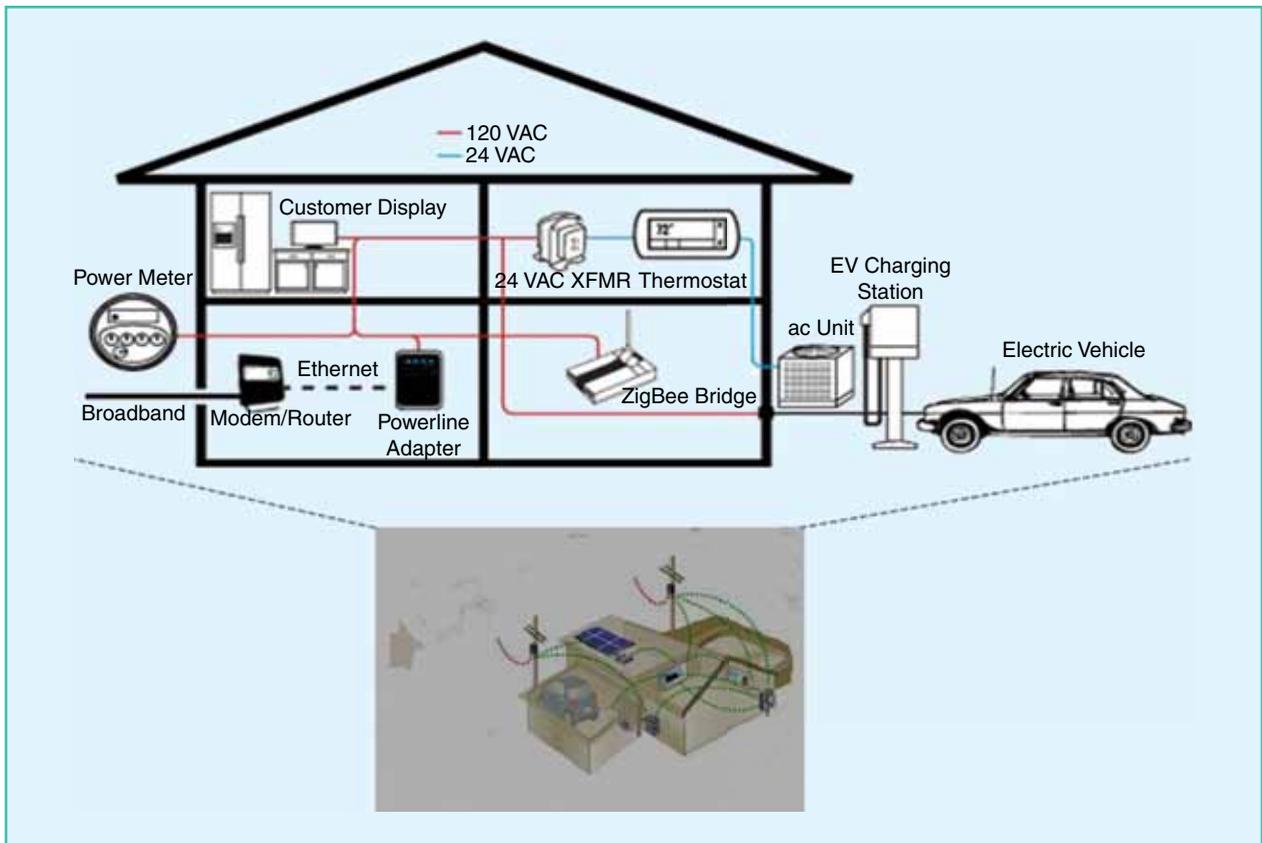


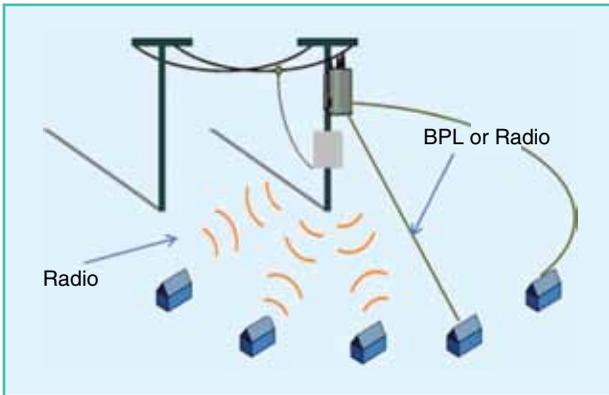
figure 5. The HAN.

### Segment 1: The HAN

A wide variety of in-premise devices—thermostats, lighting controls, energy displays, appliances, plug-in electric vehicles, distributed energy resources such as premise-based photovoltaic or wind resources, and premise-based energy storage units such as battery appliances—will be connected to the smart meter interface so that energy consumption and generation can be monitored and controlled. Initially, consumers may need a new gateway device (router) for the smart meter and any home energy management system (software provided by a third-party vendor residing on a PC within the home) for two-way communications. In due course, however, the functionality of the router may be integrated with that of the meter. Figure 5 shows the various elements of the HAN <AU: reference inserted-OK?>.

Technology choices for in-home networking include broadband-over-power-line (BPL) communication and IEEE 802.15.4/ZigBee wireless networks. The HomePlug Powerline Alliance initially developed BPL networks such as the HomePlug family of standards (HomePlug 1.0 and HomePlug AV). Presently, the IEEE P1901 Working Group is also finalizing its own BPL communication standard. Emerging communication technologies seek to achieve peak data rates of up to several hundred megabits per second in order to support audio and multimedia applications. They typically use advanced

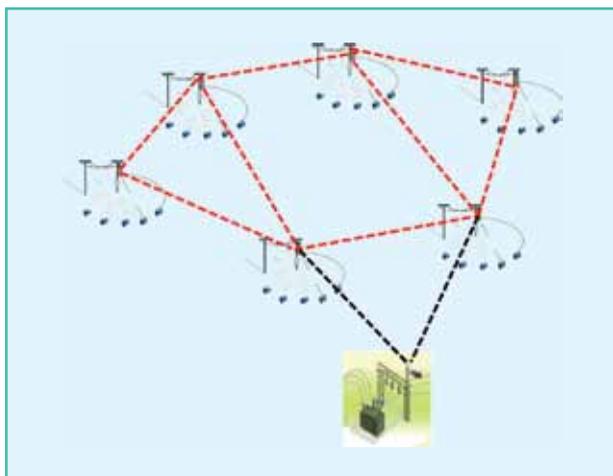
modulation techniques such as adaptive coded OFDM, which has been shown to be robust in noisy environments such as the power line while achieving scalability. BPL is an attractive option in that no new infrastructure is required—a major advantage vis-à-vis competing technologies, which all carry significant installation costs. As a competitive “third option” after DSL and cable for broadband Internet access, however, BPL has not had much success within established urban zones and has largely remained a niche choice for rural and underserved markets. Some of this is related to the rate-range performance characteristics of BPL within the home or enterprise environment, which limit achievable rates at longer distances from the source. For power lines, the achievable rates are primarily constrained by the very dynamic nature of line noise (due to frequent load switching) as well as the specifics of the line impedance due to varying topologies and the known difficulty of signaling outside the home through non-linear devices such as transformers. Due to these significant variations in power delivery characteristics as a function of time and location, it is much more difficult to provide QoS guarantees for BPL for high-end applications. As a result, the focus of BPL has recently shifted to supporting applications within the home or enterprise, based on its ability to control appliances already connected to the power line as part of demand response programs. This works well at lower data rates over shorter ranges, as contrasted with providing broad-



**figure 6.** The secondary distribution network.

band Internet access, and would appear to be much better suited to PLC technology capabilities.

The primary wireless candidate for in-home connectivity is the IEEE 802.15.4–based ZigBee standard for home automation applications, which uses the unlicensed industrial, scientific, and medical (ISM) 2.4-GHz band. It consists of transceiver link and data link layers (the physical layer, or PHY, and lower media access control, or MAC, protocols) that allow transmission at up to 250 kb/s; several experiments show its ability to coexist with cochannel interference from other 2.4-GHz signals such as Bluetooth and Wi-Fi. The MAC protocol supports mesh networking and implements an effective power-saving mechanism for longevity, key desirable attributes for SDG scenarios. The ZigBee Alliance (an industry consortium) has been proactive in positioning this technology for in-home networks, notably via the ongoing ZigBee Smart Energy 2.0 draft standard that provides an integration path for IP-based energy management systems as well as for interoperability with PLC technology.



**figure 7.** Primary distribution network: a multiple-hop mesh configuration.

### Segment 2: Distribution Secondary Networks

Low-voltage (110- and 220-V) lines carry power from the distribution transformers to consumer premises over tens of meters. Figure 6 shows such a network schematic, interconnecting a set of customers to a nearby distribution secondary node point such as a pole-mounted transformer enhanced with a processor and transceiver. Communication with the customer site may be via a short-range outdoor wireless network such as 802.11 (Wi-Fi), BPL over low-voltage power lines, or short-range radio such as ZigBee. The node at the transformer may act as a hub for aggregating data from individual smart meters (an uplink) and for sending control signals downstream for demand-side management. Alternatively, such a hub-and-spoke architecture may also serve the communication needs of microgrids in island mode, providing the required bandwidth and latency for energy trading.

The aggregate uplink AMR data (power consumption, QoS, and so on) from digital meters at customer premises should be supportable by an 802.11 network (offering up to 54 Mb/s shared between the users) over a distribution secondary area for clusters of several tens of homes. Furthermore, smart metering latency requirements for supporting applications like dynamic pricing (approximately once per hour <AU: OK?>) can also be readily met. The potential of BPL as an effective alternative to 802.11 and ZigBee in this segment has yet to be fully proven. In addition to cost considerations, BPL has been found to be the source of objectionable electromagnetic interference (EMI), caused by radiation from lines that are typically unshielded. Such EMI has a negative impact on in-band licensed services in the vicinity and constitutes a particular concern that may be a limiting factor. In terms of latency requirements for some applications in this network zone, teleprotection requires 10 ms or less and supervisory control operations better than 100 ms. Supporting latency-sensitive applications is not the strength of unlicensed technologies such as 802.11 that must contend with unpredictable (and generally increasing) levels of interference. The ability to guarantee end-to-end latencies of less than 100 ms in a mesh is unproven with the current 802.11 baseline distributed coordination function (DCF) MAC protocol. As a result, licensed wireless technologies such as 802.16d (WiMAX), which allow for prioritization and scheduling of data transmissions, other proprietary RF microwave backhaul, and wired alternatives such as BPL and optical fiber, are all potential options for such latency-sensitive applications <AU: OK?>.

### Segment 3: Distribution Primary Networks

This segment connects the distribution substations via radial and branch feeders to the distribution transformers using 4.16–34.5-kV (medium-voltage) buses. The architecture options for interconnection of network nodes to a distribution substation depend on the radio technologies employed. For example, in a hub-and-spoke architecture, the distribution substation could be equipped with longer-range radios

that connect directly to the distribution transformers. Alternatively, a mesh network, whereby distribution secondary transformers are interconnected, is shown in Figure 7. Here, the data from a node travel to the substation via multiple hops, potentially increasing end-to-end delay. Technology options include 802.11 configured for outdoor usage and wired BPL technologies.

## Conclusions

In this article, we have attempted to highlight the network architectural considerations and communication technology options within the context of their infusion into SDGs so as to achieve the desired system-level objectives outlined in the various published strategic plans and road maps. Some of these are listed below <AU: edits OK?>.

## For Further Reading

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Available: <http://www.gridwise.org/pdf/SmartGridMASTER.pdf> <AU: Please provide the author name(s), year, and article title.>

## Biographies

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### Callouts:

Energy distribution systems are at a crossroads due to significant imbalances of various kinds on present networks.

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