Abstract

With a wide array of communications needs associated with the many facets or components of the smart grid, it’s time to examine the various communication bandwidth requirements as well as some of the “tools” that are available for use in getting the message(s) from here to there.

1. Introduction

Long gone are the days where the transmission line ran from the utility’s generator to a substation, to a local distribution point and on to a residence and all that was “sent” was power. The current situation is a hybrid of power delivery and communications signaling going from the appliance to the utility’s control center. There is a vast array of “points” (physical and/or logical) within the circa 2011 energy delivery system that are monitored and/or controlled. In order to realize the functionality that the Smart Grid is to provide – summarized in Table 1 - new levels of understanding about the status of the equipment, personnel, customers, and the environment are required. The communications infrastructure must support these new levels of understanding, interaction, analysis and reporting; all at levels of complexity and breadth unheard of in the past.

1. “Situation Understanding” – by whom?
   a. Homeowner
   b. Utility
   c. Regulators
   d. Vendors/other stakeholders

2. Real-time control and analysis
   a. Connect/disconnect
   b. Power factor correction
   c. Load shedding – Demand response
   d. Load following – new generation capabilities
   e. Operations support – what-if scenarios

3. Off-line analysis
   a. Capacity planning
   b. Disturbance analysis
   c. Diagnostics/Prognostics/Anticipation
   d. Training
   e. Algorithm development/verification
   f. Business planning

Table 1. Smart Grid functionality requires differing communication bandwidths.
The information required to fulfill the functions listed in Table 1 has varying levels of confidentiality and therefore requires the communication system to deliver such information in a secure manner. As the information flows through various communication paths and through various technologies, this situation leads to an intersection of the information technology (IT) sector’s communications systems and those of the industrial automation and control technology (IC) sector. From a system networking perspective, the transport network is a combination of technologies each with differing performance specifications, hence a network of networks – as in Figure 1. The situation is clarified by simply looking at the bandwidth requirements associated with the different applications within the smart grid.

2. Body

Public policy statements from various governments coupled with vendor advertisements would lead the casual observer to believe that the “Smart Grid” is a revolutionary new effort. While the Government efforts in the USA and elsewhere brought attention to the realization that the electrical grid needs updating, thankfully a great deal of thought, planning, technology development and integration has been underway throughout this decade. Such efforts have culminated in large and small demonstration projects being conducted around the world on various aspects of what is now collectively called as the “Smart Grid”.

The components of the Smart Grid (SG) may be viewed as fitting in the generic areas of Figure 2. Therefore your perspective of the Smart Grid could be that it is providing the customer with information about your electricity consumption and usage patterns via smart meters.

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1 The security aspects of data transmission, and how the IT and IC communities’ priorities to accomplish their security needs, are outside the bounds of this “bandwidth” paper. Such points are addressed in a companion document. Please contact the ORNL authors as questions arise.
The role of communications within the information exchange between each box of Figure 2 is fundamental to the efficient operation of the electricity delivery system. The change to the existing paradigms for power delivery and billing lie in devices in each area that are able to provide data to the customer/consumer as well as the electric utilities. Consider simply the meter itself: millions of electromechanical meters based on Thomson’s design where approximately 2W are used to rotate an aluminum disk where the total number of revolutions are proportional to the current that has passed through the device. Millions of such electromechanical meters are installed worldwide. Advancements in this design have concentrated on embedding techniques for monitoring other electrical parameters (power factor, reactive power, etc) coupled with methods of communicating in both directions from the meter.

The SG requirement for allowing the customer/consumer to have visibility – and potentially some level of control – into their electrical power consumption implies that the installation process and information relay/visualization be easy. This enables a graceful shift of demand towards optimal operating point of the whole grid. When distilled, this leads to numerous organizations touting their methods of displaying the information to the home user. The typical method involves some application running within a device that is installed on the customer premise, then the customer accessing the application (web service) for the presentation of the usage information. The need for ease of use and installation necessitates a high level of integration of the components and communication protocols – most notably IP.

Another view of the elements to provide the underpinnings of the end-to-end communications of Figure 2 shows the various technical elements that are involved. Such a view of multiple components that make up the Smart Grid is presented by Figure 3.
It is obvious from Figure 3 that there are numerous protocols to be used at different “sectors” of the SG communication world. Examination of the key protocols shows that each may be transported on a IP-based network. This situation is shown graphically in Figure 4.

![Figure 4. SG protocols have a common IP transport platform.](image)

Individuals with emphasis on certain areas within the Figure 3 components can see how addressing, security, and communications in general may be enhanced by relying on an IP-based communications system for the data transport method.

A further refinement of the smart grid areas of Figure 3 can be made along different types of networks. Consider the situation where the “consumer network” - also referred to as a home area network (HAN) - connects into the utility’s neighborhood area network (NAN) which then connects to some flavor of wide area network (WAN). The data flow from the home then reaches the enterprise network for activities such as centralized billing. The communication path doesn’t end there for the utility corresponds with power generators (etc) in the External network. There are a wide range of users and organizations that rely on this data communication path – with some manner of reliably of this data transport network dictated by a maze of regulations. The U.S. National Institute for Science and Technology (NIST) has coordinated a “crosswalk” through the numerous standards and regulations that are applicable for the various Smart Grid sectors. The situation is shown in Figure 5.

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2 This communications “cloud” was sometimes referred to as the Field Local Area Network (LAN).
With such areas identified, it becomes easier to delve into the groups that are depicted in Figure 3. An attempt to illustrate the standards and possible technologies is shown in Figure 6.

Stakeholder organizations such as the ISA Power Industries (POWID) group have stipulated that in order to meet the demand response aspects of the SG, the communication system must have a latency that is less than 100 ms. Other applications require different levels of communication latency. This operational requirement provides a method of sorting through the
various technologies that could be used. The understanding that IT-"friendly" technologies must be deployed has led to detailed examination of using TCP and/or UDP for transport protocols. This type of detailed analysis looks at complex application interaction with real-world utility systems such as that of the Long Island (NY) Power Authority’s which is shown in Figure 7.

Figure 7. A bewildering array of applications intersect and interact within a utility’s integrated system such as this provided by the Long Island (NY) Power Authority.

Taking a structured approach to the applications that are to be served by the Smart Grid leads to a look at the various standards and specifications currently being used in SG activities. A table of the most relevant standards is presented as Figure 8.
3. Bandwidth Requirements for Smart Grid Applications

For most in-home applications, communications needs are modest. The amount of data being transferred at any one moment will likely consist only of the instantaneous electricity use of each device, measured in watts, and thus industry experts state that the bandwidth needs to accomplish this will likely fall between 10 and 100 kbps per node/device. UTC and Verizon assert that the ideal latency for in-home applications should be between 2 and 15 seconds.

1 - Customer Premise to Aggregation Point: The next step in the network is to carry this information away from the customer premises to an aggregation point, which will often be a substation, a utility pole-mounted device, or a communications tower. Bandwidth requirements will be similar to those for in-home networking, in the 10-100 kbps range per device in the home or office, although this will scale up quickly if appliance-level data points as opposed to whole-home data are transmitted to the aggregation point.

2 – Real-Time AMI: While power line carrier (PLC) is low cost and can reach all utility customers in a territory, it has very low bandwidth (often below 20 kbps) and requires hopping of the PLC signal around transformers by using a bridge, for instance via a wireless connection, that bypasses this grid element that would normally scramble the PLC signal. The bandwidth provided by PLC may not be adequate to meet the requirements of real-time AMI at the per-device level (up to 100 kbps per device).

3 – Real-Time Pricing: To enable more advanced applications such as real-time pricing, which would bill for electricity at the current rate, a two-way communications system is required, and lower latency may be necessary as well. The backhaul of aggregated data from an aggregation point to a utility is likely to have bandwidth requirements in the 500 kbps range.

4 – Synchronphasor Communications: The communications requirements of synchrophasors vary depending on the nature of data being transmitted.106 In terms of data requirements,
Florida Power & Light notes that phasor measurement data will be continuous, rather than variable. UTC and Avista estimate that synchrophasors will require between 600 kbps and 1500 kbps. GRE characterizes synchrophasors as requiring “high speed, high throughput communications,” pointing specifically to the IEC standard 61850, which is applicable for these types of communications.

5 – Distributed Energy Resources: According to UTC and Avista, the bandwidth required for distributed energy resources (DER) will be along the same lines as that required for AMI, i.e. 9.6 kbps to 56 kbps, with this bandwidth requirement allocated per individual distributed source.

6 – Electric Vehicle Communications: The requirements for EV communications will not be all that different from other home applications, however, and many of the same communications technologies will likely be used. It is estimated that the bandwidth required for both load balancing and billing purposes will be between 9.6 kbps and 56 kbps, although for effective demand response system integration, the 100 kbps bandwidth noted previously for DR applications may be a good target.

7 – Distribution Automation: Distribution automation (DA) bandwidth requirements will be in the range of 9.6 kbps – 100 kbps, and the required level of reliability will be 99 percent to 99.999 percent. It has been discussed in numerous forums that this particular communication “path” will probably be coresident on a shared medium – meaning that the communication system will not be dedicated just for DA communications. Of particular note is if DA is to involve control systems functions while the “other” shared communications channel applications may involve all of the other applications discussed in this section.

8 – Video Applications (including surveillance): The many possible uses of video in the smart grid – such as traditional video surveillance to using video cameras to relay images of analog dial “readings” to a control room - present the communications infrastructure with slightly different requirements than for the aforementioned applications. Video transmission is bandwidth intensive with the bandwidth required varying widely based on resolution and frame rate requirements. Consider the results provided by a video bandwidth calculator. Notice that for an SXVGA (high definition) transmitting 30 frames per second with minimal compression, the bandwidth requirement is ~47Mbps per camera.

As with all such calculators, the results are approximations. Standard IP-network best practices suggest a 20-30% residual bandwidth for the network (e.g., if the IP network bandwidth is 10 Mbps, design a 13 Mbps transport network). Combining the HD, 30fps, low compression bandwidth calculations of Figure 9 (~47 Mbps/camera) with the 30% “margin”, leads to a single network transport bandwidth in the 60 Mbps/camera range.

Combining the target bandwidth requirements of various applications envisioned for the Smart Grid provides the basis for Figure 10.
Examination of Figure 10 shows that with the exception of video the required data rates lie in the 10kbps ~ 2 Mbps.

Most utilities have in place some level of existing communications infrastructure for (classic) SCADA transmission from, for example, substation to generation facility (which may be 100s of kilometers). Appropriately configured iber optic communications systems provide ample bandwidth for the transmission of the data rate requirements shown in Figure 10.

4. Enter Wireless

Wireless communications technology plays an integral role in the cost-effective deployment and utilization of the elements of the Smart Grid. Just as there are over 30 differing protocols that are transmitted over wire/cable/fiber in support of various existing power industry needs, there are a number of differing wireless technologies that may be chosen to deliver the IP-based communications for the applications shown in Figure 10.

While cost certainly factors into the decision of “which wireless” to choose for a given SG application, the underlying technology of different wireless systems may be broken down along the lines of: bandwidth requirements, RF footprint requirements, battery/mains-powered operation requirement.

Figure 11 is extracted from Wikipedia and presents a fairly inclusive look at standards-based wireless technologies that are applicable for mobile application.

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3 “Mobile” implies that the devices/cameras/etc may also be geospatially fixed.
Figure 11. Comparison of wireless technologies for mobile applications.

Note that the network architecture, or topology, associated with the deployments of Figure 11’s wireless technology is typically a star (e.g., Wi-Fi’s “base station and associated clients”, cellular telephony’s “cell tower and mobile devices”). Depending on the sophistication of the individual base stations, the base stations may be interconnected to form a wide variety of networking topologies including a mesh network.

The star topology for Figure 11’s wireless technologies has an associated RF footprint meaning that the client must be within the footprint to be able to communicate with the base station (e.g., cell tower). It is worthwhile noting that the client device’s received signal strength (RSS) will decrease as the base station – client separation distance increases. In most cases, the communication channel’s error rate will be fixed meaning that as the RSS decreases – for fixed error rate – the throughput will decrease.4

While Figure 11 presents some information on uplink and downlink speeds – data throughputs – knowing that certain SG applications require a certain minimum amount of bandwidth (Figure 10) necessitates a slightly more detailed look into the data throughputs of the various wireless technologies shown in Figure 11; leading to Figure 12.

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4 Individuals interested in further understanding these concepts – and performance tradeoffs – are urged to contact the authors who can provide additional technical papers on these topics.
Of particular note are the “range” or RF footprint values shown in Figure 12. Wireless technologies are frequently segregated into “classes” based on this range value resulting in the loosely defined regions of “wireless personal area network (WPAN)”, “wireless local area network (WLAN)” or “wireless wide area network (WWAN)”. A comparison of candidate technologies is presented in Figure 13.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Max Downlink (Mbit/s)</th>
<th>Max Uplink (Mbit/s)</th>
<th>Range</th>
<th>Typical Downlink (Mbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDMA RTT 1x</td>
<td>0.3072</td>
<td>0.1556</td>
<td>~16 mi</td>
<td>0.125</td>
</tr>
<tr>
<td>CDMA EV-DO Rev. 0</td>
<td>2.4500</td>
<td>1.5300</td>
<td>~16 mi</td>
<td>0.75</td>
</tr>
<tr>
<td>CDMA EV-DO Rev. A</td>
<td>3.1000</td>
<td>1.8000</td>
<td>~16 mi</td>
<td>0.014</td>
</tr>
<tr>
<td>CDMA EV-DO Rev. B</td>
<td>4.0000</td>
<td>1.8000</td>
<td>~16 mi</td>
<td>0.014</td>
</tr>
<tr>
<td>GSM GPRS Class 10</td>
<td>0.0856</td>
<td>0.0428</td>
<td>~16 mi</td>
<td>0.014</td>
</tr>
<tr>
<td>GSM EDGE type 2</td>
<td>0.4796</td>
<td>0.4796</td>
<td>~16 mi</td>
<td>0.014</td>
</tr>
<tr>
<td>GSM EDGE Evolution</td>
<td>1.6944</td>
<td>0.9472</td>
<td>~16 mi</td>
<td>0.014</td>
</tr>
<tr>
<td>UMTS W-CDMA R99</td>
<td>0.3840</td>
<td>0.3840</td>
<td>~16 mi</td>
<td>0.014</td>
</tr>
<tr>
<td>UMTS W-CDMA HSDPA</td>
<td>14.400</td>
<td>3.8400</td>
<td>up to 124 mi</td>
<td>4.1</td>
</tr>
<tr>
<td>UMTS W-CDMA HSUPA</td>
<td>14.400</td>
<td>5.7600</td>
<td>up to 124 mi</td>
<td>4.1</td>
</tr>
<tr>
<td>UMTS W-CDMA HSPA+</td>
<td>42.000</td>
<td>22.000</td>
<td>up to 124 mi</td>
<td>4.1</td>
</tr>
<tr>
<td>UMTS-TDD</td>
<td>16,000[^2]</td>
<td>16,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LTE</td>
<td>336.4</td>
<td>86.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Burst: 80ns)</td>
<td>24</td>
<td>8</td>
<td>~7.5 mi</td>
<td>&gt;20</td>
</tr>
<tr>
<td>Flash-OFDM: Flash-OFDM</td>
<td>5.3</td>
<td>1.8</td>
<td>~18 mi</td>
<td>avg 2.5</td>
</tr>
<tr>
<td>WMAX: 802.16e</td>
<td>70,000</td>
<td>70,000</td>
<td>~4 mi</td>
<td>&gt;10</td>
</tr>
<tr>
<td>WiFi: 802.11a</td>
<td>54,000</td>
<td>54,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WiFi: 802.11b</td>
<td>11,000</td>
<td>11,000</td>
<td>~30 meters</td>
<td>2</td>
</tr>
<tr>
<td>WiFi: 802.11g</td>
<td>54,000</td>
<td>54,000</td>
<td>~30 meters</td>
<td>10</td>
</tr>
<tr>
<td>WiFi: 802.11n</td>
<td>200.00</td>
<td>200.00</td>
<td>~50 meters</td>
<td>40</td>
</tr>
</tbody>
</table>

- **Downlink** is the throughput from the base station to the user handset or computer.
- **Uplink** is the throughput from the user handset or computer to the base station.
- **Range** is the maximum range possible to receive data at 25% of the typical rate.

Figure 12. Throughput and range of the wireless technologies presented in Figure 11. Note that the units change from miles (for cellular) to meters (for 802.11).

Figure 13. Types of wireless are frequently classified according to the RF footprint or range (range being the client-base station separation distance).

**Frequencies:** Bandwidth leads to a down selection of possible wireless technologies. Component costs and system robustness and deployment factors may lead to the selection of the core technology for the wireless technology to serve the Smart Grid application.
requirements. The Federal Communications Commission (FCC) establishes the frequency at which the wireless system operates – Figure 14.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Allocated Frequencies</th>
<th>Spectrum Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>UMTS over W-CDMA</td>
<td>850 MHz, 1.9, 1.9/2.1, and 1.7/2.1 GHz</td>
<td>Licensed (Cellular/PCS/3G/AWS)</td>
</tr>
<tr>
<td>UMTS-TDD</td>
<td>450, 850 MHz, 1.9, 2, 2.5, and 3.5 GHz[4]</td>
<td>Licensed (Cellular, 3G TDD, BRS/WMT-Ext, FWA)</td>
</tr>
<tr>
<td>CDMA2000 (inc. EV-DO, 1xRTT)</td>
<td>450, 850, 500 MHz 1.7, 1.8, 1.9, and 2.1 GHz</td>
<td>Unlicensed (see note)</td>
</tr>
<tr>
<td>EDGE/GPRS</td>
<td>850 MHz 900 MHz 1.8 GHz 1.9 GHz</td>
<td>Licensed (Cellular/PCS/PCN)</td>
</tr>
<tr>
<td>iBurst</td>
<td>1.8, 1.9 and 2.1 GHz</td>
<td>Licensed</td>
</tr>
<tr>
<td>Flash-OFDM</td>
<td>450 and 870 MHz</td>
<td>Licensed</td>
</tr>
<tr>
<td>802.16a</td>
<td>2.3, 2.5, 3.5, 3.7 and 5.8 GHz</td>
<td>Licensed</td>
</tr>
<tr>
<td>802.11a</td>
<td>5.25, 5.6 and 5.8 GHz</td>
<td>Unlicensed 802.11a and ISM</td>
</tr>
<tr>
<td>802.11b/gi/n</td>
<td>2.4 GHz</td>
<td>Unlicensed ISM</td>
</tr>
<tr>
<td>Bluetooth</td>
<td>2.4 GHz</td>
<td>Unlicensed ISM</td>
</tr>
<tr>
<td>WiBro</td>
<td>2.4 GHz</td>
<td>Unlicensed ISM</td>
</tr>
<tr>
<td>ZigBee</td>
<td>868 MHz, 915 MHz, 2.4 GHz</td>
<td>Unlicensed ISM</td>
</tr>
<tr>
<td>Wireless USB, UWB</td>
<td>3.1 to 10.6 GHz</td>
<td>Unlicensed Ultrawideband</td>
</tr>
</tbody>
</table>

Figure 14. The wireless technologies identified in Figure 11. Please note that there are many applications served by wireless devices operating in the ISM bands (such as remote controls, cordless telephones, etc).

A more graphical representation of the FCC frequencies for the SG wireless technologies is presented as Figure 15.

Figure 15. The license free, ISM and UNII frequency bands are shown.

5. Summary

As shown in Figure 16, there are a wide array of organizations and individuals who are impacted by Smart Grid communications. Any one group may have a focus that they feel is more important than what they perceive is associated with another group. Yet for the entire deployed system to be reliable and delivering the performance and functionality requirements associated with the Smart Grid, the communication needs of each piece of the puzzle must be presented on a flattened plane with equal priority associated.
Using a designed solution – versus haphazard deployment – the result is a communications infrastructure that may have a wide assortment of wireless technologies operating side-by-side throughout the grid providing the appropriate bandwidth for the data delivery requirements for that application/need. A designed solution will also minimize RF coexistence/interference issues while providing edge-to-core-to-edge transport through the integrated operational networks.

**Bibliography**

2. “Smart Grid Research Highlights”, Angela Chuang, EPRI, Presentation to ASERTTI, October 2009.