COMPARATIVE ANALYSIS OF COMMUNICATION ARCHITECTURES AND TECHNOLOGIES FOR SMART GRID DISTRIBUTION NETWORK

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Comparative Analysis of Communication Architectures and Technologies for Smart Grid Distribution Network

Thesis directed by Assistant Professor Fernando Mancilla-David

ABSTRACT

A critical piece of the Smart Grid infrastructure is the communications network for data gathering, control and supervision capabilities that extend to the customer demarcation point. Over several decades, the electric utilities built a robust communications networks connecting electric grid subsystems except for the “last mile” connecting to the end user premise. A primary goal of Smart Grid (SG) is to expand the communications network throughout the Distribution Network (DN) thus enabling a holistic management and control of electric grid from generation to consumption. In order for the Smart Grid goals to be realized, two-way communications network must extend to the Distribution Network allowing two-way data flow e.g., real-time energy pricing and real-time demand data back to the Utilities and Operators. This thesis presents five communications architectures and viable technologies for deployment within the Distribution Network of the Smart Grid. Then apply selected metrics to these architectures and technologies combinations and select top five scoring combinations.

This abstract accurately represents the content of the candidate's thesis. I recommend its publication.

Approved: Fernando Mancilla-David

DEDICATION

All thanks and praise is due to Allah for his blessing and guidance.
I dedicate this thesis to my loving parents, especially my father (the late Professor Abed El-Rahman Hammoudeh) who gave me the appreciation of education and taught me the value of perseverance and resolve. I also dedicate this thesis to my wife, Suhad, and my daughters (Mona, Hoda and Ayah) for their understanding and sacrifice while I was completing this thesis. I would like to thank all my family and friends who supported me to successfully finish this work.

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1. Introduction

Over several decades, the electric utilities built a robust communications networks connecting electric grid subsystems except for the Distribution Network (DN) feeding the end customer premise. A primary goal of Smart Grid is to expand the communications network to the consumption segment thus enabling a holistic management and control of electric grid from generation to consumption.

With the recent emphasis on deployments of Smart Grid within the United States of America and the passing of EISA (Energy Independent and Security Act of 2007) into law [1], the race is on to begin deployment of Smart Grid. Under Title XIII of EISA 2007, the U.S. Department of Energy (DoE) established a Federal Smart Grid Task Force. In its Grid 2030 vision, the objectives are to construct the 21st century electric system to provide abundant, affordable, clean efficient and reliable electric power anytime, anywhere [2]. A key enabler of Smart Grid deployment is the communications network that interconnects the numerous devices, users' smart meters and the electric grid subsystems. The first step of designing a robust communications network is establishing an architecture that outlines data flow among various parts of the system.

The North American power grids are made up of almost 3,500 utility organizations [3]. The basic principle of supplies and demand must be at equilibrium all times. Extensive communications networks that span hundreds of thousands of miles enable electricity grid operators to manage the demand and keep this supply demand equation balanced. However, the existing communications architecture is several decades old and has not benefited from recent technology advances. Additionally, the existing communications network primary function is to connect electrical substation with operators control centers leaving the distribution subsystem lacking adequate situational awareness [3]. To remedy the current limitations of the electrical grid, the U.S. Congress passed the EISA law in 2007 establishing goals for modernizing the electrical grid.

1.1 Scope of This Study

A critical piece of the Smart Grid infrastructure is the communications network that will extend the control and supervision capabilities to the end users. As described in [4], the Smart Grid communications network can be divided into four distinct segments:

- Core or metro segment – connects substations to the utilities' headquarters.
- Backhaul segment – connects data aggregators to substation/distribution automation at broadband speeds
- Neighborhood Area Network (NAN) or last-mile – connects the customer's smart meter or gateway to the data aggregators, and

- Home Area Network (HAN) – this is the customer’s home or building automation.

The generation subsystem enjoys full automation while transmission and substation have very high levels of automation, but the distribution network has poor automation level [5]. Additionally, the transmission-system level, area control centers and regional reliability coordination centers have been exchanging system status information. The communication links between these systems now cover the country with increasing exchange of information among electric utility companies [6].

The distribution segment of the electric grid is the least communicated with and least controlled segment of all the electric grid segments. The Distribution Automation (DA) is primarily led by substation automation with feeder equipment automation still lagging [6]. Because feeder automation lags other automation efforts widely, this area should be addressed directly in future work [6]. As discussed in [7], the Distribution Network remains outside the utility companies’ real-time control. Additionally, nearly 90% of all power outages and disturbances have their roots in the Distribution Network [7]. While 84% of utilities has substation automation and integration underway in 2005, the feeder penetration is still limited to about 20% [6]. So, it makes sense to begin Smart Grid at the bottom of the chain, in the Distribution Network [7].

The scope of this thesis is limited to the communications networks in the Distribution Network of the Smart Grid to address the aforementioned gaps. In other words, the focus is on the “last mile” communications segment. This thesis documents the results of a thorough survey of technical papers and governmental agencies’ reports then provides the author’s critical analysis of communications architectures and technologies for Smart Grid Distribution Network.

1.2 Organization of Thesis

This thesis is organized into chapters. Chapter 2 covers Smart Grid objectives, functions and benefits. Chapter 3 describes data collection in the Distribution Network for both end-users and service providers’ usage. Chapter 4 addresses the needs for communications networks in the Distribution Network. Chapter 5 discusses five communications architectures. Chapter 6 provides an overview of wireline and wireless technology options. Lastly, chapter 7 describes the analysis methodology and presents three dimension comparison matrix with a conclusion.

2. What is Smart Grid?

The United States of America and several other countries have made it a national strategic goal to modernize their electric grid [8] to make it more robust, secure, expand overall control and make it capable of supporting renewable energy resources and anticipated growth demand. Many definitions of Smart Grid (SG) exist all around the world [9]. Smart Grid is the modernization and automation of the electric power grid changing from a producer-controlled network to one that is less centralized and more consumer-interactive and is more than just “smart meters”. The use of two-way communications and advanced control capabilities will result in the realization of a host of benefits and new applications. One can think of SG as an Information and Communication Technologies (ICT) based power system [9]. The National Institute of Standards and Technology (NIST) defines the Smart Grid as:

> a modernization of the electricity delivery system so it monitors, protects and automatically optimizes the operation of its interconnected elements – from the central and distributed generator through the high-voltage network and distribution system, to industrial users and building automation systems, to energy storage installations and to end-use consumers and their thermostats, electric vehicles, appliances and other household devices [9].

In general, all definitions refer to an advanced power grid through the use of digital computing and communications technologies [8].

2.1 Recent American Laws Driving Smart Grid Deployment

Starting with the Energy Policy Act of 2005 (EPACT 2005) Section 103 titled "Energy Use Measurements and Accountability" that established a deadline of October 1, 2012 for all federal building to have some sort of advanced meters that provide data of the electricity consumption [10]. Additionally, EPACT 2005 Section 1252 titled "Smart Metering" obligates electric utilities to supply each of its customers upon request, a time-based rate schedule.

On December 19, 2007, the United States Congress passed the Energy Independent and Security Act (EISA) of 2007 into law that mandated the modernization of the electric grid with an end goal of Smart Grid [1]. Finally, the American Recovery and Reinvestment Act of 2009 (ARRA) included $10 billion in investments to encourage transformation to a smarter grid [8]. All these federal laws brought visibility and attention to the need for modernizing the electric grid. Additionally, several states and electric utilities initiated infrastructure deployments in preparation for Smart Grid. Common deployments include the installation of advanced meters by utilities companies and Smart Grid test beds as the case with Xcel's project in Boulder, Colorado known as "SmartGridCity".

2.2 Smart Grid Functions and Goals

In December 2007, the Energy Independence and Security Act (EISA) was signed into law. This law established clear national goals to implement Smart Grid. Some of the stated benefits include:

- Self-healing from power disturbances
- Enables active participation by consumers in "demand response"
- Operates resiliently against physical or cyber attack
- Provides power quality for 21st century needs
- Accommodates all generation and storage options
- Enables new products, services, and markets
- Optimizes assets and operational efficiency

A Smart Grid provides the flexibility to adapt to a changing mix of demand-side resources, including changeable load, dispatchable distributed generation and storage, as well as output local generation such as wind and solar [6]. Smart-grid-enabled distributed controls within the electric delivery system will aide in dynamically balancing electrical supply and demand, thus resulting in a more adaptable system to imbalances and limit their propagation when they occur [6]. A Smart Grid is needed at the distribution system to manage voltage level, reactive power, potential reverse power flows and power conditioning, which are critical to running grid-connected Distributed Generation (DG) systems [6].

Table 2.1 provides a side by side comparison of key attributes of the existing electric grid and the Smart Grid, which is also referred to as “Intelligent Grid”. There is clear need for Smart Grid at the distribution level to manage: voltage levers, reactive power, potential reverse power flows and power conditioning [6].

Table 2.1: The Existing Grid vs. The Smart Grid [7]

Existing Grid	**Smart Grid**
Electromechanical	Digital
One-Way Communication	Two-Way Communication
Centralized Generation	Distributed Generation
Hierarchical	Network
Few Sensors	Sensors Throughout
Blind	Self-Monitoring
Manual Restoration	Self-Healing
Failures and Blackouts	Adaptive and Islanding
Manual Check/Test	Remote Check/Test
Limited Control	Pervasive Control
Few Customer Choices	Many Customer Choices

The expected functions of Smart Grid are detailed in [11] and summarized below:

- Operation Reliability and Blackout Prevention
- Condition Monitoring and Asset Management
- Protection and Station Automation
- Distribution Network Management

- Distribution Network Automation
- Smart Metering

2.3 Smart Grid Benefits

The benefits of Smart Grid show up in many areas including the infrastructure management and protection, the gained efficiency, economic benefits for the consumer and reducing business losses from blackouts. Data from wide-area measurement system could have eliminated the $4.5 billion in losses as a result of the 2003 blackout of the eastern U.S. and Canada [6]. Another study results show that Smart Grid technologies would reduce power disturbance costs to the U.S. economy by $49 billion per year [12]. Table 2.2 provides an average estimated cost of one-hour power interruption for selected enterprises businesses.

Table 2.2: Cost of One-hour Service Outage [12]

Industry	Average Cost of 1-Hour Interruption
Cellular communications	$41,000
Telephone ticket sales	$72,000
Airline reservation system	$90,000
Semiconductor manufacturer	$2,000,000
Credit card operation	$2,580,000
Brokerage operation	$6,480,000

Smart Grid can enable reduced overall energy consumption through consumer education and participation in energy efficiency and demand response/load management programs [13]. Additionally, shifting electricity use to less expensive off-peak hours can optimize use of existing power generation that could add $5 billion to $7 billion per year back into the U.S. economy [12]. Smart Grid would reduce the need for huge infrastructure investments between $46 billion and $117 billion over the next 20 years [12]. The Federal Energy Regulatory Commission (FERC) study reported that a moderate amount of demand response could save about $7.5 billion annually [14]. Finally and most recently, EPRI prepared a new set of cost of power interruption and power quality estimates ranging from $119 billion to $188 billion per year [15].

3. Data Collection in The Distribution Network

At the Distribution Network and end-user levels, there are opportunities for automation and advanced data collection [16]. There are two methods for gathering end-user data: Automated Meter Reading (AMR) and Automated Metering Infrastructure (AMI). AMR enables the electric utility to remotely read power meters. But it does not address the major issue utilities need to solve, which is demand-side management [7]. On the other hand, AMI is much more powerful since it is the basic building block for a two-way communications between the end users and utilities operators [16]. As described in [17], an AMI system consists of four main components:

- Smart digital meter, which functions as premise gateway
- Home portal that offers display of information from the gateway
- Neighborhood access point that aggregates end-users data before transmitting it to the substation
- Central office (usually a substation) where all customers' data is aggregated.

There is often a reference to an AMI meter, which is defined as a digital meter with two-way communications, automated meter data collection, outage management, dynamic rate structures and demand response for load control [17].

Managing Smart Grid metering data is difficult due to the sheer size and complexity of the number of data point [18]. Useful data in the Distribution Network can be classified as: consumer specific data or device and control data. Each of these data types is explained in the next two sections.

3.1 Consumer Energy Usage Data

Smart meter system involves large amount of data transfer between the utility company, smart meter and home appliances connected to the network [19]. The smart meter data will be used by the utilities operators for further analysis, control and real time pricing method [20]. The customer gateway will interact with all smart appliances and the Distribution Network and functions: integrated operation and control of supply and demand and demand response [21].

3.2 Device Status Data and Control

A major benefit of Smart Grid containing renewable Distributed Generation (DR) is the possibility of forming islands when separation from the main electric system occurs due to fault condition or system failure [22]. So, continuing to communicate with the islanded section of the grid is required. Table 3.1 provides a sample of the data requirements.

Table 3.1: Sample Data Requirements [22]

System Component	**Inputs**	**Outputs**	**Computed Values**
Breakers Switches Protective elements (Fuses)	Breaker Status Enable/Disable	Breaker Status Voltages Currents	
Generators: Wind Solar (PV)	Enable Dispatch	Voltages Currents Phase	Power Quality Availability Health index Power
Transformers	Tap Positions	Temperature Pressure Gas, Vibration Noise	Reliability
Lines	Enable/Disable	Voltages Currents	Real Power Reactive Power
Reactive Power Elements	Status Enable/Disable	Voltages Currents	Power Quality
Loads: Active Passive	Status Enable/Disable Rate (Tier Demand Management) Demand	Voltages Currents	Power Quality

As explained in [21], devices in the Distribution Network include the Distribution Automation System (DAS) and the Meter Data Management System (MDMS). The customer’s gateway interacts with the DAS for integrated operation and control of supply and demand of electricity. Where the MDMS collects and stores data from customers and provide them to the utilities operators for accounting and customer service [21]. The customers will be able to schedule appliances' operation and request loads using real time pricing data, thus reducing electricity usage during peak hours, which benefits both end users and utilities.

4. Communications for The Distribution Network

4.1 The Need for Communications

Without a robust communication system in the Distribution Network, only parts of the Smart Grid vision could be realized [5]. The Smart Grid is all about extending remote monitoring and control of devices in the Distribution Network and gathering real-time data. All of these functions require two-way communications [13]. The Distribution Network is facing increased frequency of unpredictable catastrophic events due to limited knowledge and management of these complex systems [23]. The current communications system deployed over the Distribution Network are oriented to support specific services, so that, the development of new services over the DN and the addition of new agents may result as very expensive [24]. The original design of Distribution Networks did not account for two-way power flows or active demand, hence, changes are needed in the way they are designed and operated to realize these functions through the use of advanced communications and information technologies [25]. Automation and communication infrastructures are needed to enable demand response and to make widespread end-user participation possible in support of Smart Grid and market operation [26].

4.2 Communications Requirements

A communication system is the key component of the Smart Grid infrastructure [20]. Smart Grid communication technologies must allow the utility's Control Center access to each connected meter several times a second [27]. As detailed in [28], communications network for the energy management must provide distinct qualities including: high reliability and availability, automatic redundancy, high coverage and distances, supports large number of nodes, has low delays, security and ease of deployment and maintenance.

The various functions of the Distribution Network have different requirements for a communications network. For example, meter reading can be scheduled for anytime and does not require permanent real-time communications. On the other hand, event or fault data must be communicated in real-time with maximum allowed delay of 300 milliseconds [21]. Additionally, depending on the communications architecture selected, communications among adjacent end-users' gateways could be required. Tables 4.1 and 4.2 summarize the communications requirements to and from customer's gateway.

Table 4.1: Communications From Customer's Gateway and Requirements [21]

	Data	**The other end**	**Frequency**	**Allowable Delay**	**No. of Entry**	**Applications**
From Customer Gateway	Request for reactive power	**Other customer Gateway**	On demand	1 second	1	Keeping output power of distributed power generation during voltage regulation
	Measured values for generation / consumption	SCADA system	Every 30 minutes	1 minute	121 *1	Optimal control of grid equipment Power flow leveling, Demand-supply balancing Meter reading, Customer service
	Forecasted values for generation / consumption		Twice per day	Several minutes	192 *2	Optimal control of grid equipment

*1: 4 items (active/reactive power of generation/distribution) ×30 (Value for 1 minute) + Time stamp
*2: 4 items mentioned above × 48 (data for 1 day)

Table 4.2: Communications To Customer's Gateway and Requirements [21]

	Data	**The other end**	**Frequency**	**Allowable Delay**	**No. of Entry**	**Applications**
To Customer Gateway	Request for reactive power	**Other customer Gateway**	On demand	1 second	1	Keeping output power of distributed power generation during voltage regulation
	Event information (e.g. earth fault)	SCADA system	At event	50 ~ 300 milliseconds	1	Power system protection
	Threshold of reverse power flow, Generation forecast		Every 30 minutes	1 minute		Power flow leveling, Demand-supply balancing
	Tomorrow tariff	Tariff server	Every day	Several minutes	48 *3	Optimal control of grid equipment
	Current tariff		Every 30 minutes	1 minute	1	Demand response
	DR event	DR server	Every 1 minute	10 seconds	1	Demand response

*3: Tariff per 30 minutes × 48 (for 1 day)

4.3 Are Smart Grid Standards Required?

Standards are the first and required step to ensuring interoperability between equipment from various vendors and enabling interconnection among different users and operators, which are necessary functions in the vast electric grid that is owned and operated by hundreds of stakeholders. Standards is an important issue that must be resolved before Smart Grid becomes a reality [29]. The evidence from other industries indicate that interoperability generates tangible and intangible benefits around 0.3% - 0.4% in cost savings and avoided infrastructure construction, which could net a $12.6 billion per year in Smart Grid benefits [12].

Under Section 1305 of EISA, the National Institute of Standards and Technology (NIST) has the primary responsibility of coordinating the development of framework including protocols and standards for information management to achieve interoperability [1]. NIST recognized the urgent need for Smart Grid standards by developing a three phase plan to identify existing standards as well as the need for new ones [8].

4.4 Emerging Smart Grid Standards

For the Smart Grid to be fully integrated, universal standards must be applied [30]. Several well known standards' bodies including the International

Electrical and Electronics Engineers (IEEE), International Standards Organization (ISO), International Electrotechnical Commission (IEC) and Internet Engineering Task Force (IETF) are actively developing new standards that are required for the proper and secure deployment of Smart Grid. NIST identified 16 specifications and 15 standards that are important for Smart Grid [8]. Additional standards are under review. There is a consensus on a set of standards regarded as core information technology standards for the future Distribution Network of a Smart Grid [31]. These standards are listed below [31]:

- IEC 61970/61968: Common Information Model (CIM)
- IEC 61850: Substation Automation Systems (SAS) and DER (Distributed Energy Resources)
- IEC 62351: Security for the Smart Grid
- IEC 62357: TC 57 Seamless Integration Architecture
- IEC 60870: Communication and Transport Protocols
- IEC 61400-25: Communication and Monitoring for Wind Power Plants
- IEC 61334: DLMS (Device Language Message Specification (originally Distribution Line Message Specification)
- IEC 62056: COSEM (Companion Specification for Energy Metering)
- IEC 62325: Market Communications using CIM

5. Communications Architectures

Architecture describes how systems and components interact and embodies high-level principles and requirements for Smart Grid applications and systems [8]. Like the Internet, the Smart Grid is a network of different networks that must interact together on regular basis. So, the Smart Grid architecture will be a composite of many system and subsystem architectures [8] rather than a single architecture. The communication architecture of the future Smart Grid is yet to be defined [32]. The rest of this chapter addresses architecture options for the Distribution Network.

Designing a communication system architecture that meets the Grid's complex requirements is essential to the successful implementation of Smart Grid [22]. In general, coordination and information exchange between devices can be implemented via different communication architectures. Four possible communications architectures are illustrated in [33].

This thesis report describes five communication architectures for possible deployment in the Distribution Network. The Distribution Network is similar to the "last mile" problem in the telecommunications network design. In the utility's communications network, the "last mile" connects the customer's smart meter to the backhaul network as depicted in figure 5.1. Each architecture is covered in the remainder of this chapter.

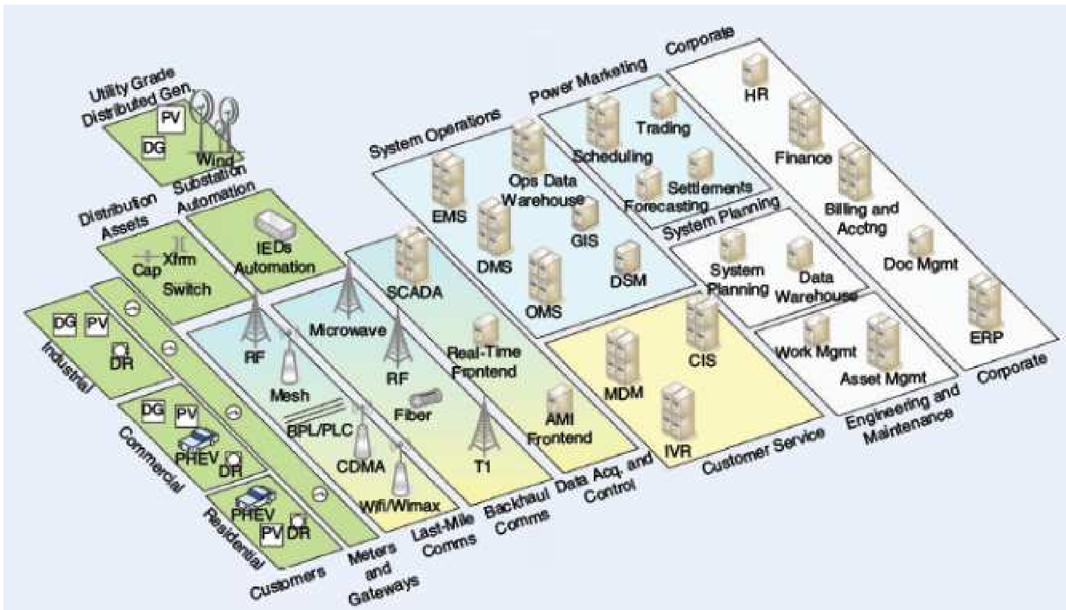

Figure 5.1: A view of the Utility Information Systems [34]

5.1 Direct Connect Architecture

This is most basic architecture where each smart meter has a dedicated linear connection to the data hub inside a substation. This setup is often referred to as "hub and spoke" network. In this scenario, there are no other devices, like aggregators, between the smart meter and the data hub inside the substation. In other aspects, this architecture is a star topology with the data hub inside the substation has hundreds to thousands of dedicated communication links out to the customers' smart meters. Each communication link can be of any medium type: wireline or wireless. Due to the large number of smart meters in urban areas, this architecture is not attractive. However, it could be a viable option for low population density areas. In this case, a single communication link from each home to a substation is low cost and does not require an elaborate communications infrastructure build or aggregators. Depending on the selected communication media type, this architecture has limitation. Figure 5.2 depicts the main components of this architecture.

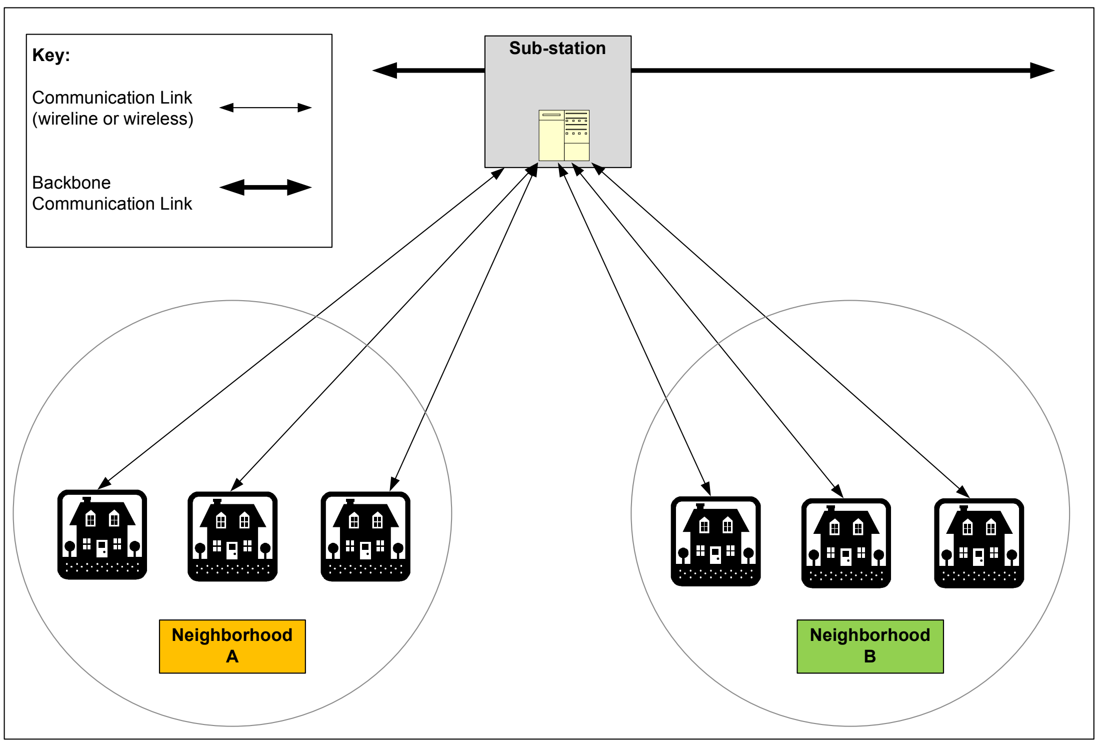

Figure 5.2: Direct Connect Architecture

5.2 Local Access Aggregators Architecture

The essence of the Local Access Aggregators architecture is aggregating smart meters data at a neighborhood level before transmitting it to a data hub inside the substation. The aggregator device sits between the smart meters and the data hub inside the substation. This model builds on the Neighborhood Access Network (NAN) where NAN ensures communications between the smart meter and the data aggregators [35]. The concept of NAN is recent and as such no standard NAN definition yet exists [17]. In general, the NAN aggregator connects with the customer home network on one end and with the Wide Area Network (WAN) on the substation end as illustrated in figure 5.3.

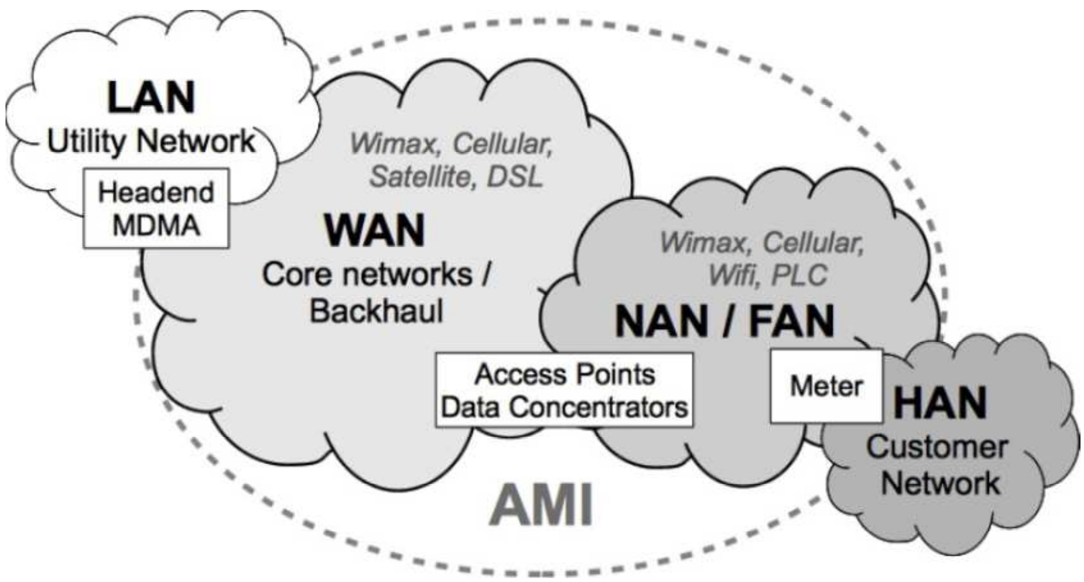

Figure 5.3: Overview of AMI Network with NAN

This architecture has advantages over the direct connect architecture because it reduces the number of dedicated communication links to the substation and benefits from data aggregation at the neighborhood level thus optimizing the communications links into the substation by using trunks. Additionally, the ability to collect and process data locally will not only reduce communication bandwidth requirements, but also reduce vulnerability to hacker attacks and reduce cyber security concerns [16].

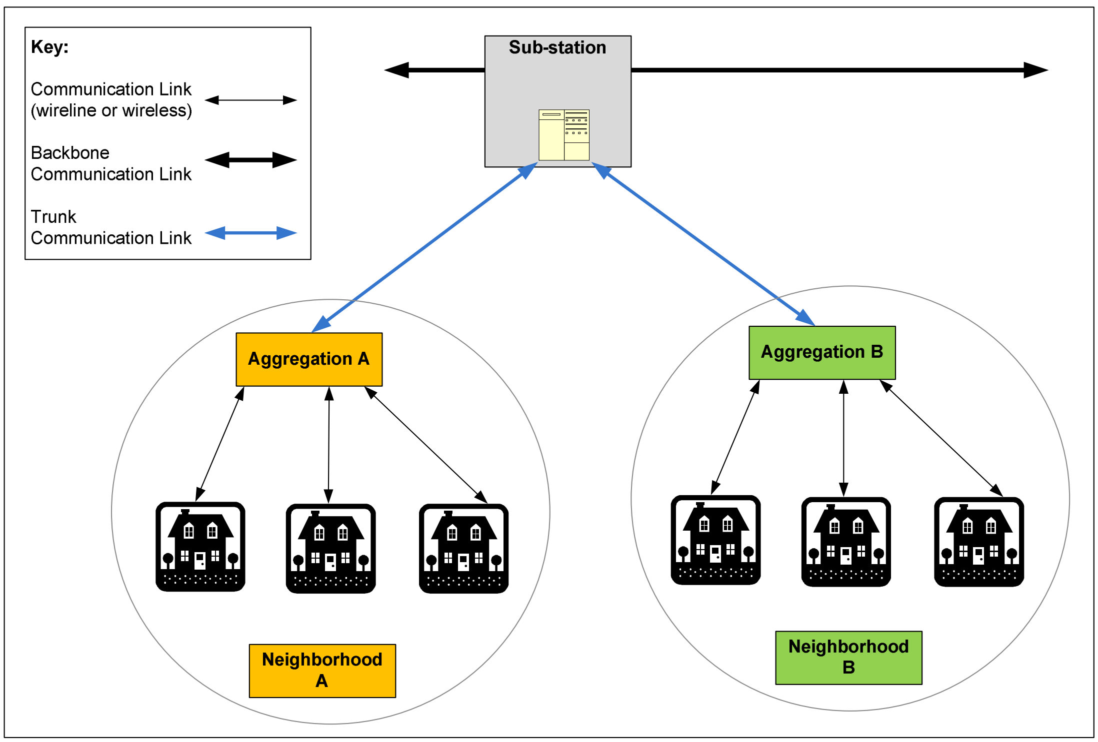

Figure 5.4: Local Access Aggregator Architecture

Figure 5.4 shows main segments of this architecture including: smart meter at the premise, aggregator in the neighborhood installed on a structure that is owned by the utilities e.g., pole or cabinet and data hub inside the substation.

5.3 Interconnected Local Access Aggregators Architecture

This architecture is similar to the previous architecture with one exception, which is adjacent NAN networks have interconnected trunks as shown in figure 5.5. These additional communication trunks provide redundancy for the aggregators thus allowing more routes to communicate with the substation's data hub and enable local communications among NANs should communication trunk with the substation is lost. This last feature is important for effective sharing of Distributed Generation (DG) resources available in adjacent neighborhoods during an islanding situation.

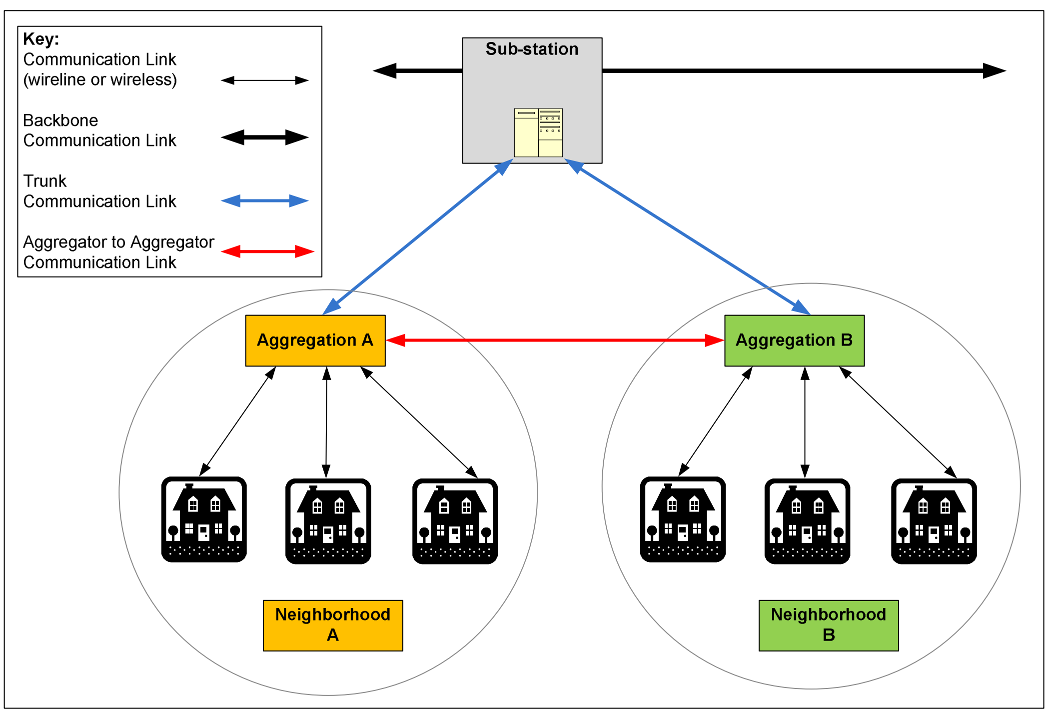

Figure 5.5: Interconnected Local Access Aggregators Architecture

5.4 Mesh Architecture

This architecture builds on the previous one with additional degree of connectivity at the smart meters' level in addition to the aggregators' level as shown in figure 5.6. Because of the additional required communication links among smart meters that are do not have wireline connections, wireless Radio Frequency (RF) technology is well suited for interconnecting smart meters in a particular area.

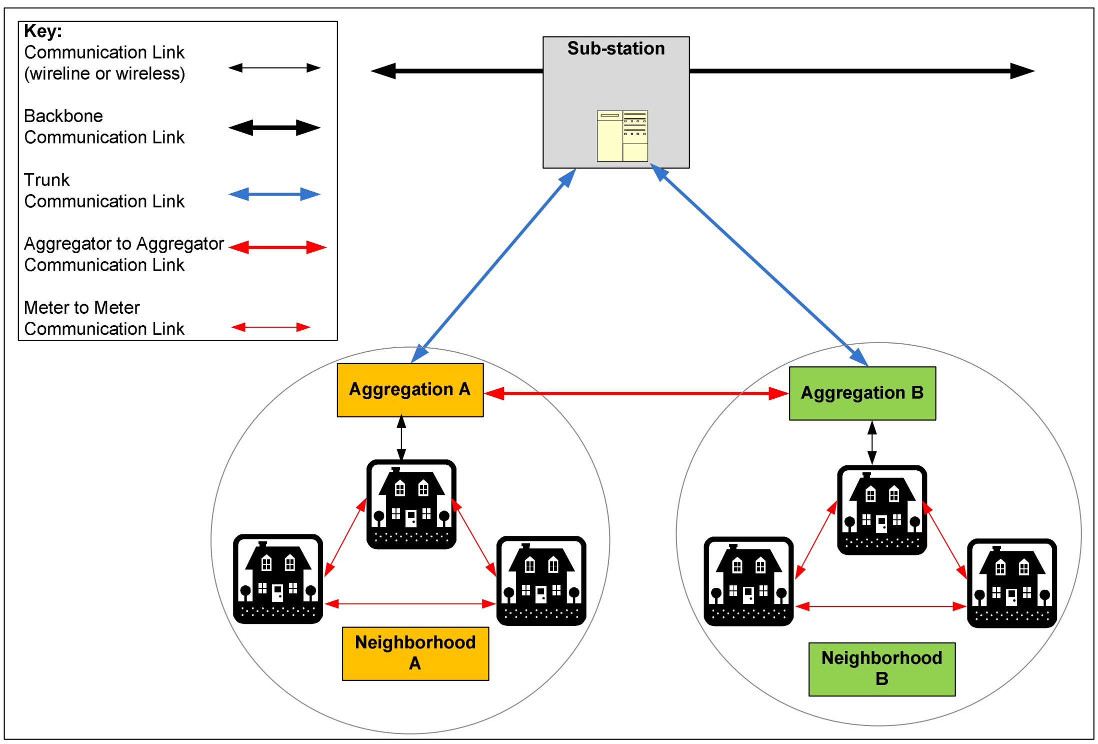

Figure 5.6: Mesh Architecture

Additionally, RF has the ability to dynamically establish ad hoc communications links between adjacent networks [36]. Another advantage is that communications range can be increased by establishing multiple hops until reaching the final destination. RF mesh operates in the unlicensed Industrial Scientific and Medical (ISM) frequency band ranging from IEEE 802.11 Wireless Local Area Networks (WLAN), Wi-Fi, Bluetooth and Microwave [20]. This fact makes RF less attractive for use in Smart Grid application due to high possibility of interference with commonly deployed private networks. Another disadvantage that is common to wireless communications is security concerns. However, strong data encryption is an effective way to remedy such security issues.

The wireless-wired architecture is the most popular approach and has been adopted in some pilot projects where smart meters in the neighborhood communicate with an aggregator through a wireless mesh network and the aggregator communicates with the central management facility through wired communication [37].

5.5 The Internet Cloud Architecture

The premise of this architecture is leveraging the customer's existing Internet service as a communication link between the end user and the utilities operator. The majority of houses subscribe to Internet service where service is available. Rural areas are the exception since Internet service is not always available. Under this architecture, the smart meter uses the existing Internet connection inside the house as a communication link via Ethernet port or Wi-Fi to transmit information to a utilities' server that most likely is hosted in a data center. The biggest advantage of this architecture is low cost since no additional monthly charges for communications are required. Another big advantage is for the utility companies since customers' data can be easily stored on servers without having expensive aggregators in the neighborhoods or inside the substation. Of course, the assumption is customers already have Internet service or can get it.

This architecture has many benefits including low cost for the customer by leveraging an existing Internet service and quick deployment due to minimal infrastructure build. It also allows for both peer to peer communications as well as centralized decision capability. This architecture facilitates the use of "cloud" services to gather, store, and analyze huge volumes of data and make it available for those with appropriate level of access.

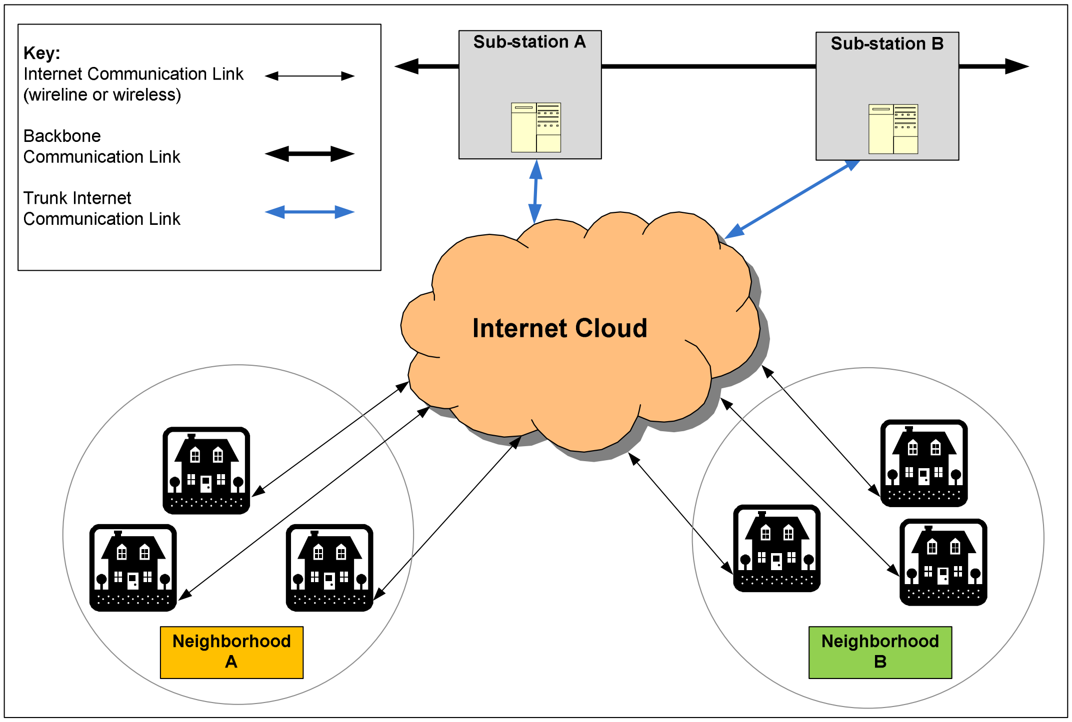

Figure 5.7: The Internet Cloud Architecture

6. Technology Options

Both wireline and wireless communication technologies are possible deployment options for Smart Grid. Some of the popular communication technologies are Power Line Communications (PLC), cellular, licensed and unlicensed radio, existing internet connection, Wi-Fi and WiMAX [19]. In certain situations, wireless technology have advantages over wired technologies, such as low cost and ease of connection but suffers from interference and signal attenuation [20]. On the other hand, wireline communication technologies are more reliable, less prone to interference, but very expensive to deploy especially if new infrastructure is required. Wired communication network can be established for smart meters, but it will be complicated and expensive solution, while wireless communication network can be implemented even on ad-hoc basis [38]. The Smart Grid, as a complex system, requires a heterogeneous communication technologies to meet its diverse needs [32].

6.1 Wireline Technology Options

Wireline communication media include: twisted pair copper cables, coaxial cables, power line and fiber optic cables. Each of these media types has unique characteristics that will be discussed in the remainder of this section.

Twisted Pair (TP) copper cables are the traditional telephone wiring, which are present in almost every home and connect back to a telecommunications carrier Central Office (CO). These copper wires have varying specifications and quality that is determined by their age. Unshielded Twisted Pair (UTP) is older cable that is prone to cross talk and interference. However, Shielded Twisted Pair (STP) is newer cable type that is less prone to cross talk and interference. Additionally, these wires are usually configured in a star topology where hundreds of homes and buildings have dedicated connections back to the carrier's CO. Hence, the existing cables would not support mesh architecture based on their physical routes. Hence, mesh requires placing additional cables, which is very expensive and takes a long time to deploy.

Coaxial cable is another wireline media type. These cable plants are used by cable companies to provide video services and in recent years voice and data. The cable plant is shared resource in a single neighborhood and as such shares bandwidth. This architecture has two fundamental issues: lower data rates during peak usage hours in densely populated areas especially for those customers located at the end of the cable route in a neighborhood and presents security concerns for customer's confidential data since the main cable is a shared medium in the last mile segment. With the introduction of DOCSIS 3.0, cable companies are offering Internet services using coaxial cable with high bandwidth rates, but it is still a shared bandwidth. Additionally, coaxial cables presence is limited to metropolitan areas and rarely found in rural areas.

Fiber Optics is the most advanced wireline media type with many superior characteristics like extremely high data rates, long distance reach and immunity from electromagnetic interference. There are two types of optical fiber cables: Single Mode (SM) and Multi Mode (MM) fiber. SM is used for long distances, while MM is used for short distances less than two kilometers. The trend is to use SM fiber for most applications. However, fiber optic cables are the most expensive wireline media type to install and the least widespread in homes and buildings. Most new buildings and homes are wired with fiber optic cables. New deployments include Fiber-To-The-Home (FTTH) or Fiber-To-The-Premise (FTTP), which typically use Gigabit Passive Optical Network (GPON). GPON is a network architecture that uses a point-to-multipoint scheme to serve multiple buildings. Encryption is used in this shared environment to ensure data security.

Power lines represent the densest network in this country, where every building has a power line connection and power line termination [39]. As such, Power Line Communication (PLC) system appears to be well suited to implement the Smart Grid network [40], [41]. These power lines can be used to transmit Smart Grid data from the home back to the substation directly. This is the most direct wireline media connecting the end-user with the substation. PLC, under normal operations, has an advantage that all smart meters can be reached as opposed to a wireless solution where 100 percent service coverage is not always possible [42]. However, using power lines for communications has its drawbacks. First, the interference issues around high voltage power lines and the need to bypass transformers where a bridge device is used to bypass the transformer. Using power lines is preferred by utility companies since they will have total control of the communication link from the substation to the end customer and do not need to rely on third party providers for this communication network. The biggest issue with using power lines for Smart Grid communication is losing this vital communication network during electric power lines being down, yet this is the time when communication is needed the most. Power line cuts will stop communications with the isolated areas and as such make it impossible to gather data, isolate problems and attempt to solve the problem quickly. Simply put, under this condition, Smart Grid objective for the Distribution Network won't be achieved.

Table 6.1: Qualitative Characteristics of Wireline Communication Media Types

Wireline Media	**Data Rate**	**Distance Reach**	**Existing Geographic Coverage**
Twisted Pair (TP)	high	long distance	high
Coax cable	high	medium distance	low
Power lines (PLC)	high	high distance	high
Fiber Optic Cable	very high	very long distance	limited

6.2 Wireless Technologies

Wireless technology is very attractive for Smart Grid deployment. In general, it is much faster to deploy than wireline medium due to minimal construction areas when compared with digging streets to deploy new conduit system and pull cables through it. Using wireless communications has many benefits [43]. Several wireless technology options, either licensed or unlicensed frequencies are available. Most popular technologies include: Satellite, microwave, WiMAX, cellular, Wi-Fi and Zigbee.

Satellite is the most expensive wireless technology and supports relatively low data rates. It is not suitable for general deployment in the distribution network, but may have role in the transmission segment. The signal receiver on the ground must be within the satellite coverage footprint. There is limited number of satellite operators or service providers due to high deployment cost of these systems. Additionally, latency is a big issue due to large distances a signal must travel from ground to the satellite and back to earth.

Microwave is based on licensed frequencies that are controlled by the Federal Communication Commission (FCC). These frequencies are limited and require line-of-sight between transmitter and receiver to operate. As such, depending on the terrain, they usually require tall tower structure to meet line-of-sight requirement. Microwave is not suitable for wide deployment in the Distribution Network. However, it may have limited and targeted application in rural areas where no other communications medium is available.

WiMAX stands for Worldwide Interoperability for Microwave Access that focuses on fixed wireless applications and is based on IEEE 802.16 standard. It supports data rates up to 72 Mb/s and a range up to 6 miles. Earlier version of the WiMAX standard requires line-of-sight, but not later version [11]. Additionally, WiMAX has limited deployment in the United States and it will be expensive to deploy an extensive WiMAX network to meet Smart Grid requirements in the Distribution Network.

Wi-Fi stands for Wireless Fidelity, which is a trademark of the Wi-Fi Alliance [44]. It is based on IEEE 802.11 standard and operates in the unlicensed 2.4 GHz Industrial Scientific and Medicine (ISM) band and has reach from 20 feet indoors to about 300 feet outdoors with the potential for even longer reach. It is widely used in home networks and several deployments by local municipalities to cover a citywide. Because Wi-Fi networks are common for use in-home applications and use unlicensed spectrum, interference is a big concern. Additionally, reach is limited and is not suitable for communications in the Distribution Network.

Zigbee is a low-power wireless protocol that operates in the unlicensed Industrial Scientific and Medicine band of 2.4 GHz. It is based on IEEE 802.15.4 standard. Zigbee, WirelessHART and ISA 100.11a are three protocols that use the 802.15.4 PHY standard but define their own Media Access Control (MAC) and network [11]. Zigbee and Zigbee Smart Energy Profile (SEP) have been realized as the most suitable communication standards for Smart Grid residential network domain by NIST [20]. However, they are not suitable for deployment in the Distribution Network due to short reach and serious security issues.

Cellular is a radio network distributed over a geographic area called cells. Cellular networks has several advantages including increased capacity, reduced power use, large coverage area and reduced interference from other signals through spectrum reuse. Initial roll out of cellular service is called first generation (1G), which is an analog signal followed by second generation (2G), which is a digital service followed by third generation (3G) and most recently fourth generation (4G). There is 2.5G, which is based on either General Packet Radio Service (GPRS) or Enhance Data Rates for GSM Evolution (EDGE). GSM is the abbreviation for Global System for Mobile Communications. While EDGE is still available in fringe areas not upgraded to 3G, GPRS have been mostly replaced by 3G networks [11]. The 3G and 4G technologies support higher data rates and faster service. Currently, select wireless communications providers deployed 4G networks. Cellular service is very attractive for use in the Distribution Network due to its widespread coverage. The broadband wireless communications technology has many inherent advantages when used in Smart Grid [45]. The qualitative summary in Table 6.2 is the result of combining wireless technology specifications presented in [20] and qualitative analysis presented in [11] except for satellite and microwave technologies.

Table 6.2: Qualitative Characteristics of Wireless Communication Technologies

Technology	Data Rate	Distance Reach	Existing Geographic Coverage
Satellite	high	high	high
Microwave	high	high	low
Cellular (2.5G)	low	high	good
Cellular (3G)	medium	high	good
Cellular (4G)	high	high	good
WiMAX	high	high	low
Wi-Fi	high	low	low
Zigbee	low	low	low

7. Analysis Methodology and Approach

7.1 Metrics

The success and failure of the Smart Grid rests on a communication system that is intelligent, secure, reliable and cost effective [16]. The communication network for the Smart Grid requires data transfer in a timely manner with adequate bandwidth and reliability [3] via two-way communication with low latency. Communication technologies for Smart Grid must be cost efficient, provide good transmittable range, excellent security features and adequate bandwidth [19]. Additionally, the selection of a communication technology should be based on several criteria including: bandwidth requirement, topology of network, reliability, security, feasibility of solution [33].

Based on the aforementioned discussion and general communication network design guidelines, the following criteria are selected for comparing the communication architectures described in chapter 5 and the wireline and wireless communication technologies presented in chapter 6.

a) **Bandwidth or Data rate**: bandwidth often refers to a data rate measured in bits per second. For digital signals, bandwidth is the data speed or rate, measured in bits per second (bps). Various parts of the Smart Grid have different bandwidth requirement [46]. A communications throughput of (2 – 5) Mb/s was estimated as a guideline for Smart Grid link to allow for transmitting voltage and current measurements for three phases, phase amplitude, phase angle as well as additional information like meter identification and overhead packets [22].

b) **Latency**: latency is a measure of time delay experienced in a communications network. It can be measured as one-way, the time it takes a sender to transmit data to the destination receiving it, or round trip, which is the time it takes for data to travel from the sender to the receiver and back to the sender. Information concerning faults on the Smart Grid must be transferred from the DAS to a customer gateway with the shortest possible latency and must be completed within 50 ms and communication involving a request for reactive power has the second strictest latency requirement [21]. Both rural islanding and urban meshed distribution scenarios have tolerance for a maximum of six cycles or 100 ms [22]. This requirement imposes even stricter requirement on the communications network. Latency in a WiMax link is 10 ms from the smart meter to the base station, so, the communication network must be carefully designed to ensure the latency end-to-end is less than 50 ms [22]. Also, Long Term Evolution (LTE), which is 4G wireless technology enjoys similar latency characteristics as WiMax, with latency of (5 – 10) ms [22].

c) **Security**: network security is extremely important to ensure all customers data remain private and no unauthorized access to the network. Several techniques including user authentication, access control authorization and data encryption are usually implemented to ensure network security. Because a wireless network uses broadcast medium, it must be resistant to tampering of messages, preserving confidentiality of information and prevents unauthorized access [11]. In general, wireline medium is more secure than wireless media, but Smart Grid requires a higher level of security. The legacy cyber security techniques for enterprise networks can hardly fit well for Smart Grid requirements to operate securely in the public data communication networks like the internet [47].

d) **Scalability**: is the ability of a system or network to handle expansion without the need for replacing major segments of the network. In the case of Distribution Network, the network must be flexible to accommodate high volumes of smart meters connecting new houses and businesses.

e) **Resilience**: is the ability of a network to function properly during interference either random or intentional. In order for a network to be resilient, it must be capable of continued operation even in the presence of localized faults [48]. In this respect, mesh architecture provides the maximum resiliency due to multiple paths to get between nodes.

f) **Reliability**: is the ability of a network to perform within its normal operating parameters to provide a specific level of service. Reliability can be measured as a minimum performance rating over a specified interval of time. In general, availability for communication networks ranges from 99.9% (3 nines reliability).to 99.999% (5 nines reliability).

g) Interoperability: means devices and services from multiple vendors are compatible with each other and can be integrated into a generic network. Interoperability is very important consideration in network deployment. Ensuring devices and subsystems are interoperable is of high importance to ensure Smart Grid goals are achieved. Standards are key enabler to achieve interoperability. For communications in the Smart Grid to be truly effective, they must exist in a fully integrated system and to be fully integrated, universal standards must be applied [30]. Hence, the urgency for developing and updating many standards to encourage Smart Grid deployment.

h) Distance Reach: each wireline and wireless communication technology has its unique signal reach distances. Signal reach ranges from few meters to tens of kilometers depending on the technology. Terrain characteristics affect wireless signal reach and as such must be considered during technology evaluation stage.

i) Existing Geographic Coverage: the electric Distribution Network covers vast geographic areas with varying terrain characteristics. Selecting technologies that already cover the areas where Smart Grid will be deployed can reduce the deployment cost. However, a single technology may not provide all coverage in all area.

j) **Cost of Ownership**: capital expenditure (CAPEX) and operation expenditure (OPEX) are practical considerations when designing any network. Given the high numbers of smart meters requiring communications infrastructure, low CAPEX and OPEX will be key for early adopters of Smart Grid.

7.2 Analysis Methodology

The methodology used to compare the architectures, technologies and metrics for suitability in the Smart Grid Distribution Network is:

A) identify key communications architectures

B) select viable communications technologies

C) choose applicable metrics

D) assign weighting factors using the following scale from highest to lowest: good fit = 3, moderate fit = 2, poor fit = 1 and not suitable = 0. Additionally, the following metrics guidelines were adopted from [11].

Table 7.1: Metrics Guidelines [11]

	Ave. Data Rate	**Ave. Latency**	**Distance Reach**	**Scalability**
Good	> 1.5 Mb/s	< 250 ms	> 1000 meters	> 1000 nodes/ data hub
Moderate	500 Kb/s - 1.5 Mb/s	250 ms - 1 sec	(100 - 1000) meters	(100 - 1000) nodes/ data hub
Poor	< 500 Kb/s	> 1 sec	< 100 meters	< 100 nodes/ data hub

E) summarize the results in a multi dimension matrix

7.3 Summary of Results

Each technology option is analyzed against the five architectures using the selected ten metrics. The result is a three dimension matrix. Then normalize the total score for each architecture and technology combination and select the top five scores representing the best overall solutions. The next series of tables present the detailed scores for each architecture, all wireline and wireless technologies against the ten criteria.

Table 7.2 provides summary of architecture 1 scenarios. Most wireless technologies and one wireline technology i.e., power line communication are suitable for this architecture since power lines already exist between the end user facility and the utilities substation. However, copper twisted pairs, coax and fiber optic cables do not exist and as such require significant installation and are very expensive, which excludes them to be practical options for architecture 1. Satellite service is very expensive to deploy and maintain in addition to high monthly charges. Microwave communication network requires valuable and scarce spectrum and significant capital investment to build such infrastructure. It requires line-of-sight (LOS) between transmitter and receiver. Hence, microwave is not suited for architecture 1 especially in residential areas. WiMAX also requires large capital investment to build a network that covers all residents in the U.S.A. Wi-Fi lacks the required distance reach and geographic coverage.

Some cities across the country partnered with private providers to build a citywide Wi-Fi network. However, these examples are rare and a countrywide Wi-Fi coverage won't be cheap to build nor practical. Zigbee is an in-home network that will communicate with smart devices within a household. Hence, it has very short distance reach, which makes it not suitable for Smart Grid communication in the Distribution Network. For architecture 1, the best overall options are those using cellular technology with 4G being the best since it supports the higher data rates.

Table 7.2: Summary of Architecture 1 Metrics

Criteria	Architecture #1 (Direct Connect)											
	Wireless								Wireline			
	Satellite	Microwave	Cellular (2.5G)	Cellular (3G)	Cellular (4G)	WiMAX	Zigbee	Wi-Fi	Twisted Pair (TP)	Coaxial Cable	PLC	Fiber Optic Cable
Bandwidth / Data Rate	3	3	1	2	3	3	1	3	3	3	2	3
Latency	1	2	2	2	1	3	1	3	3	3	3	3
Security	3	3	2	2	3	3	2	2	3	2	2	3
Scalability	1	1	2	3	3	3	1	1	1	1	3	1
Reliability	2	2	2	2	2	2	1	2	3	3	2	3
Interoperability	2	2	2	2	2	1	1	3	3	3	2	2
Resilience	2	2	3	3	3	3	2	1	3	3	3	3
Distance Reach	3	3	3	3	3	3	0	1	2	2	2	3
Existing Geographic Coverage	2	0	2	2	2	0	0	0	0	0	1	0
Cost of Ownership	1	1	3	3	3	1	1	1	1	1	2	1
Sum of points:	**20**	**19**	**22**	**24**	**25**	**22**	**10**	**17**	**22**	**21**	**22**	**22**
Max. No. of Points	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**
Normalized Score:	**67%**	**63%**	**73%**	**80%**	**83%**	**73%**	**33%**	**57%**	**73%**	**70%**	**73%**	**73%**

Table 7.3 presents summary of architecture 2 scenarios. The discussion for architecture 1 listed above applies here as well. Hence, the best overall technology options are those using cellular technology with 4G being the best option since it supports the higher data rates. However, 4G is not available in all areas and some areas may be limited to 3G or 2.5G only. Moreover, some remote areas may not have any cellular service, so in these cases, PLC can be a viable wireline option.

Table 7.3: Summary of Architecture 2 Metrics

Criteria	Architecture #2 (Aggregator)											
	Wireless								Wireline			
	Satellite	Microwave	Cellular (2.5G)	Cellular (3G)	Cellular (4G)	WiMAX	Zigbee	Wi-Fi	Twisted Pair (TP)	Coaxial Cable	PLC	Fiber Optic Cable
Bandwidth / Data Rate	3	3	1	2	3	3	1	3	3	3	2	3
Latency	1	2	2	2	1	3	1	3	3	3	3	3
Security	3	3	2	2	3	3	2	2	3	2	2	3
Scalability	1	1	2	3	3	3	1	1	1	1	3	1
Reliability	2	2	2	2	2	2	1	2	3	3	2	3
Interoperability	2	2	2	2	2	1	1	3	3	3	2	2
Resilience	2	2	3	3	3	3	2	1	3	3	3	3
Distance Reach	3	3	3	3	3	3	0	1	2	2	2	3
Existing Geographic Coverage	2	0	2	2	2	0	0	0	0	0	1	0
Cost of Ownership	2	1	3	3	3	1	1	1	1	1	2	1
Sum of points:	**21**	**19**	**22**	**24**	**25**	**22**	**10**	**17**	**22**	**21**	**22**	**22**
Max. No. of Points	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**
Normalized Score:	**70%**	**63%**	**73%**	**80%**	**83%**	**73%**	**33%**	**57%**	**73%**	**70%**	**73%**	**73%**

Table 7.4 depicts scenarios for architecture 3. Once again, the same analysis for architectures 1 and 2 applies here with one exception. Power line communication is not as favorable for architectures 3. Under architecture 3, additional power lines are required to interconnect the Aggregators since the power lines are radial by design. This fact will increase the cost of ownership for PLC technology under this architecture.

Table 7.4: Summary of Architecture 3 Metrics

Criteria	Architecture #3 (Interconnected Aggregators)											
	Wireless								Wireline			
	Satellite	Microwave	Cellular (2.5G)	Cellular (3G)	Cellular (4G)	WiMAX	Zigbee	Wi-Fi	Twisted Pair (TP)	Coaxial Cable	PLC	Fiber Optic Cable
Bandwidth / Data Rate	3	3	1	2	3	3	1	3	3	3	2	3
Latency	1	2	2	2	1	3	1	3	3	3	3	3
Security	3	3	2	2	3	3	2	2	3	2	2	3
Scalability	1	1	2	3	3	3	1	1	1	1	3	1
Reliability	2	2	2	2	2	2	1	2	3	3	2	3
Interoperability	2	2	2	2	2	1	1	3	3	3	2	2
Resilience	2	2	3	3	3	3	2	1	3	3	3	3
Distance Reach	3	3	3	3	3	3	0	1	2	2	2	3
Existing Geographic Coverage	2	0	2	2	2	0	0	0	0	0	1	0
Cost of Ownership	2	1	3	3	3	1	1	1	1	1	2	1
Sum of points:	**21**	**19**	**22**	**24**	**25**	**22**	**10**	**17**	**22**	**21**	**22**	**22**
Max. No. of Points	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**
Normalized Score:	**70%**	**63%**	**73%**	**80%**	**83%**	**73%**	**33%**	**57%**	**73%**	**70%**	**73%**	**73%**

Table 7.5 summarizes the results for architecture 4. Under the mesh architecture, wireless communications has a major advantage over wireline options due mainly to the high capital expenditure to implement a wireline technology in a mesh configuration. However, satellite and microwave technologies are expensive while Wi-Fi and WiMAX do not currently have the geographic coverage. Zigbee is eliminated due to its short distance reach. The result is cellular technology is the best option. Cellular networks cover the majority of United States residents with few exceptions in the rural areas or areas with challenging terrain.

Table 7.5: Summary of Architecture 4 Metrics

Criteria	Architecture #4 (Mesh)											
	Wireless								Wireline			
	Satellite	Microwave	Cellular (2.5G)	Cellular (3G)	Cellular (4G)	WiMAX	Zigbee	Wi-Fi	Twisted Pair (TP)	Coaxial Cable	PLC	Fiber Optic Cable
Bandwidth / Data Rate	3	3	1	2	3	3	1	3	3	3	2	3
Latency	1	2	2	2	1	3	1	3	3	3	3	3
Security	3	3	2	2	3	3	2	2	3	2	2	3
Scalability	1	1	2	3	3	3	1	1	1	1	2	1
Reliability	2	2	2	2	2	2	1	2	3	3	2	3
Interoperability	2	2	2	2	2	1	1	3	3	3	2	2
Resilience	2	2	3	3	3	3	2	1	3	3	3	3
Distance Reach	3	3	3	3	3	3	0	1	2	2	2	3
Existing Geographic Coverage	2	0	2	2	2	0	0	0	0	0	1	0
Cost of Ownership	2	1	3	3	2	1	1	1	1	1	2	1
Sum of points:	**21**	**19**	**22**	**24**	**24**	**22**	**10**	**17**	**22**	**21**	**21**	**22**
Max. No. of Points	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**
Normalized Score:	**70%**	**63%**	**73%**	**80%**	**80%**	**73%**	**33%**	**57%**	**73%**	**70%**	**70%**	**73%**

Table 7.6 summarizes the results for architecture 5, which is based on using existing Internet connections to the cloud. This architecture is unique because it leverages existing Internet service the majority of end users have, which makes it least expensive architecture to deploy. Hence, using the Internet for Smart Grid communications is almost free for those who already have an Internet service. Based on the overall criteria, Internet service over TWP, which is called Digital Subscriber Line (DSL), is the best option due to its widespread geographic coverage.

Table 7.6: Summary of Architecture 5 Metrics

Criteria	Architecture #5 (Internet Cloud)											
	Wireless								Wireline			
	Satellite	Microwave	Cellular (2.5G)	Cellular (3G)	Cellular (4G)	WiMAX	Zigbee	Wi-Fi	Twisted Pair (TP)	Coaxial Cable	PLC	Fiber Optic Cable
Bandwidth / Data Rate	3	3	1	2	3	3	1	3	3	3	2	3
Latency	1	2	2	2	1	3	1	3	3	3	3	3
Security	3	3	2	2	3	3	2	2	3	2	2	3
Scalability	1	1	2	3	3	3	1	1	3	2	2	1
Reliability	2	2	2	2	2	2	1	2	3	3	2	3
Interoperability	2	2	2	2	2	1	1	3	3	3	2	3
Resilience	2	2	3	3	3	3	2	1	3	3	3	3
Distance Reach	3	3	3	3	3	3	0	1	2	2	2	3
Existing Geographic Coverage	2	0	1	2	2	0	0	0	2	1	1	0
Cost of Ownership	1	1	2	2	1	1	1	1	3	3	2	1
Sum of points:	**20**	**19**	**20**	**23**	**23**	**22**	**10**	**17**	**28**	**25**	**21**	**23**
Max. No. of Points	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**	**30**
Normalized Score:	**67%**	**63%**	**67%**	**77%**	**77%**	**73%**	**33%**	**57%**	**93%**	**83%**	**70%**	**77%**

Since a specific technology and architecture combination may not be available nationwide, it is important to provide few choices that can work in different environments. Table 7.6 presents the top five scoring scenarios out of all possible combinations i.e., scenarios presented in tables 7.2 – 7.6. It is clear that architecture 5, Internet Cloud, has the highest score for the overall metrics. Additionally, Internet service over TWP and Coax cable are best media/technology options, due to existing widespread coverage and relatively low monthly costs.

Table 7.7: Top Five Architecture and Technology Combinations

Criteria	Architecture #1 (Direct Connect)	Architecture #2 (Aggregator)	Architecture #3 (Interconnected Aggregators)	Architecture #5 (Internet Cloud)	
	Wireless	Wireless	Wireless	Wireline	
	Cellular (4G)	Cellular (4G)	Cellular (4G)	Twisted Pair (TP)	Coaxial Cable
Bandwidth / Data Rate	3	3	3	3	3
Latency	1	1	1	3	3
Security	3	3	3	3	2
Scalability	3	3	3	3	2
Reliability	2	2	2	3	3
Interoperability	2	2	2	3	3
Resilience	3	3	3	3	3
Distance Reach	3	3	3	2	2
Existing Geographic Coverage	2	2	2	2	1
Cost of Ownership	3	3	3	3	3
Sum of points:	**25**	**25**	**25**	**28**	**25**
Max. No. of Points	**30**	**30**	**30**	**30**	**30**
Normalized Score:	**83%**	**83%**	**83%**	**93%**	**83%**

7.4 Conclusion

After analyzing the five architectures and applicable wireline and wireless technologies for deployment in the Distribution Network in support of Smart Grid objectives, it is evident that each architecture and technology combination has strengths and weaknesses. Additionally, a single architecture solution will not be suitable for every deployment and in any environment. Hence, the author provides the top five scoring architectures and technology combinations. Architecture 5 is the overall favorable choice. This architecture functions with both wireline and wireless technologies, provides most flexibility, least cost of ownership, has widespread coverage and scales to support large deployments. Two concerns about this architecture include security risks from using the Internet to transport sensitive data and the utilities' acceptance to use third party providers for the communication networks. The first concern is manageable with added security layers. Currently, the Internet is widely accepted for sensitive financial transactions including online shopping, banking and stocks transactions. As for the second concern, while most utilities prefer to have complete ownership and total control of the communication networks that support Smart Grid, deployment costs and implementation timelines will force utilities to revaluate their position and start partnering with communication providers to realize Smart Grid benefits sooner than later.

Future study opportunity is to evaluate a mixture of technologies to implement each of the five architectures. For example, use PLC and cellular to build mesh architecture. Such approach will leverage vast power lines for primary link and use cellular links to complete the mesh network.

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