A Survey on Technologies for Implementing Sensor Networks for Power Delivery Systems

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Abstract--The task of monitoring asset status and optimizing asset utilization for the T&D industry, given millions of assets and hundreds of thousands of miles of power lines distributed geographically over millions of square miles, seems particularly challenging if not impossible. Given the traditionally high cost of sensing and communications, the grid has minimal 'smarts' with much of the intelligence located at major substations. Dramatic reductions in sensor, computing and communications costs, coupled with significant performance enhancements has raised the possibility of realizing widely and massively distributed sensor networks (SNs) to monitor utility asset status. Under NEETRAC funding, a survey was conducted to review existing sensor technologies and products, and to estimate the possibility of extending these to realize distributed SNs. Possible applications for such SNs were also explored, as was the issue of cost point at which such networks would become commercially viable. This paper provides an overview of the highlights from the detailed survey that was conducted, and identifies 'gaps' in currently available sensor technologies, both from a performance and cost point.

***Index Terms*—Power delivery systems, Sensor networks, distributed monitoring, sensing, monitoring, communications.**

I. Introduction

The US power grid represents perhaps the most complex edifice built by man. While, over the last two decades, electricity consumption and generation have continually grown, investment in the T&D infrastructure has been minimal, and it has become increasingly difficult and expensive to permit and build new power lines. The aging power grid is congested and under stress, resulting in compromised reliability and higher energy costs. As the utility industry transitions to an unregulated or semi-regulated model, the ability to use its assets efficiently will provide a significant competitive edge.

Geographically spanning the entire continent, most of the power grid is in excess of 50-60 years old. Significant work has been done on the sensing of utility assets, and substantial data is available within a substation. The utility typically has less information on system and/or component status and operating margins outside the substation. For a typical utility with 25,000 km of high voltage (>69 kV) power lines and thousands of transformers, capacitors and breakers, this could require the monitoring of over 100,000 distinct and distributed sensors or sources of data spread over a 20-80,000 sq km area. Implementation of a grid-wide monitoring system using conventional sensors and communications technology would be prohibitively expensive.

The concept of Sensor Networks (SNs) was introduced more than two decades ago driven by the need for wide area surveillance with the collaboration of cheap, smart and unattended sensors networked through communication links and deployed in large numbers. Recent advances in sensing, computing and communication have allowed the deployment of cost effective ad hoc sensor networks for various applications, such as military sensing, physical security, traffic surveillance, industrial and manufacturing automation, environment monitoring, and building and structures monitoring. Because of inherently large geographically spread characteristics of the national power grid, distributed sensing for power delivery systems becomes another potential application of SNs.

A survey project "Potential Applications for Sensor Networks in Power Delivery" funded by NEETRAC, was conducted to explore the potential need for such SNs from an end-use perspective. Working with utility advisors through a survey, a project final report extracts the needs and issues with existing sensing technology and identifies the most significant gaps between what is needed and what is available. The report also explores available technologies, products and the ability to scale them to the 'pervasive sensing' level. Finally, the report also identifies key technologies and solutions that could allow implementation of the communications backbone that would be a critical part of such a distributed sensor network.

This paper provides an overview of the highlights from the detailed survey that was conducted and identifies 'gaps' in currently available sensor technologies, both from performance and cost point perspective. The paper is organized as follows. First, general SNs are introduced and the state of the art is discussed. It is followed by an extensive review of existing sensing products and technologies in the market, as well as a review of published literature discussing new approaches that could be used for implementing a sensor network. Then, a survey is presented on communications technologies that are either in use at this time or are imminent in terms of commercial release. Finally, 'gaps' in currently

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available sensor information are identified both from a technology and cost perspective and a suggestion is provided on how to move forward.

II. Introduction of Sensor Networks and the State of the Art

The development of SNs is motivated by the need to coordinate a large numbers of sensors on a higher-level sensing task (e.g., reporting with greater accuracy than possible with a single senor, environment monitoring, motion monitoring).

Research on SNs was originally driven by military applications [2]. However, the availability of low-cost sensors and communication networks has resulted in the development of many other potential applications, such as infrastructure security [3], environment and habitat monitoring [4] and industrial sensing. Because of potentially harsh, uncertain, and dynamic environments, along with energy and bandwidth constraints, SNs pose many technical challenges [1]. SNs are different for various applications; still, they share several common features and requirements, as summarized in Table I.

TABLE I
Sensor Networks General Features and Requirements

Features	Requirements
Sensor Nodes	
Sensor nodes are in large numbers and densely deployed	Cost-effective; small size.
Power source is limited and generally irreplaceable. (Less power constraint with energy scavenging.)	Low power consumption
Performance is limited in power, computational capacities, and memory	Simple network protocols and algorithms
Networking	
Position of sensor nodes need not to be engineered or pre-determined.	Self-organizing capability
Topology of a SN may change frequently, due to system upgrade, or geographic expansion requirements.	
Sensors nodes are prone to failure due to hostile environments.	Self-healing capability
Short distance communication between sensor nodes requires multi-hop communication.	Optimized network routing
Information processing	
Sensor nodes may not have global identification (ID) because of a large number of sensors.	Localized computation.
The cooperative effort of sensor nodes is needed.	Data aggregation and collaborative signal processing.
Information concentration and extraction are needed to prevent data overload.	

Many researchers are currently engaged in developing schemes that fulfill these requirements. The technologies are generally from three different research areas: sensor node hardware; networking and communications; networked information processing.

A. Sensor Nodes

A sensor node is made up of four basic components: a sensing unit, a processing unit, a transceiver unit and a power unit [2]. Thanks to advances in modern technologies, sensors, processors and communication devices are all getting smaller and cheaper. All subunits can fit into a matchbox-sized module with a relatively low product cost.

Table II summarizes some hardware constraints and technical solutions for a network of small and embedded sensor nodes.

TABLE II
Sensor Nodes Development

Constraints	Technical solutions
Sensing Unit: - Low power - Low product cost - Fault tolerant	Many commercially available sensors are suitable for SNs applications: SUNX Sensors, Schaevitz, Keyence, Turck, UE Systems (ultrasonic), Leake (IR), CSI (vibration), etc. MEMS sensors are developed and are available for many sensing applications, such as 'Smart Dust sensors' from Dust Inc [5].
Processing Unit: Limited power, computation, and memory capacity	Memory storage: - Larger flash memory on a separate chip, up to several megabytes - Tiny multi-threading distributed operating systems requiring less OS code space: Tiny-OS, μ-OS operating system [1]
Transceiver Unit: - Worldwide accepted - Low power - Low cost	Optical devices: Smart dust motes; Radio frequency devices: Most of the ongoing sensor node products are using 915 MHz and 2.4 GHz ISM bands.
Power source [6] [8]: Long operating lifetime	Batteries: Days to weeks Energy scavenging: - Solar cells: 10 milliwatts.cm^{-2} - Mechanical sources: 100 microwatts.cm^{-2} - Temperature variations: 40 microwatts.cm^{-2}

Fig. 1 shows some commercial products currently on the market.

Crossbow   MicroStrain   Dust, Inc [5]

Fig. 1. Commercial sensor nodes

B. Networking and Communications

A SN is generally organized by a star topology. Some other types of topology also exist, such as a cluster tree, mesh, or ring, depending on the application. Among them, a cluster tree topology is more suited to networks that cover larger physical areas, where no single device is able to directly link with every other device, as shown in Fig. 2.

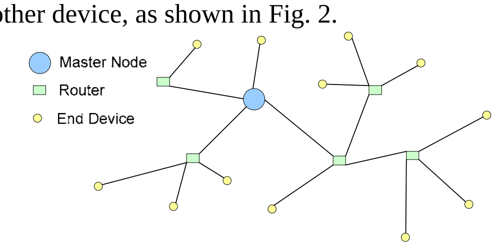


Fig. 2. Cluster-tree topology

The large cluster tree network self-organizes into smaller subnets, each of which has a master node. Data flows from an end device to its master node, through a router node to a higher subnet, and continues upward until reaching a central collection device [7].

Many protocols and algorithms are proposed thus far for SNs to fulfill their special networking requirements, such as network discovery, network self-organization, and network control and routing [2]. Table III summarizes the research efforts in terms of the layers of a protocol stack.

TABLE III
SENSOR NETWORKS COMMUNICATION ARCHITECTURE [1]

	Research Issues	Solutions
Physical Layer	- Low power, simple but robust modulation, transmission and receiving schemes are required; - Signal propagation effects need to be overcome.	- Binary modulation - M-ary modulation - DSSS - UWB
MAC Layer	- Self-creation/organization of the network infrastructure is required; - Communication resources must be shared fairly and efficiently between sensor nodes, and collision with neighbor's broadcast needs to be minimized; - Power conservation is of big concern.	- SMACS and the EAR algorithm - Hybrid TDMA/ FDMA - CSMA based
Network Layer	- Special multihop routing protocols between sensor nodes and the master node are needed, which could be based on power efficiency, data centric and/or data aggregation. - Internetworking with external networks is needed.	- SMECN - Flooding - Gossiping - LEACH - Directed diffusion.

C. Networked Information Processing

Collaborative signal and information processing over a SN is a new area of research and is related to distributed information fusion. Important technical issues include two aspects as follows [2],

- Processing data from more sensors generally results in better performance but also requires more communication resources.
- The less information is lost (e.g. when raw data is transmitted), the more bandwidth is required.

Therefore, one needs to consider the multiple tradeoffs between performance and resource utilization. Examples of recent research results can be found in [9], where localized algorithms and directed diffusion are developed.

As a large geographically distributed system, the national power grid, with its many sensors, can be viewed as one large sensor network. Some monitoring systems were developed with specialized computers and communication capabilities several decades ago, even before the term "sensor networks" came into vogue. However, the state of the art at that time in sensors, computers, and communication networks made the concept of distributed SNs for power grid monitoring more of a vision than a technology ready to be exploited. Fortunately, technological advances in the past decades have completely changed the situation. The sensor network becomes an exciting and promising solution for large area monitoring of the power grid and could drastically enhance our understanding of its condition, if cost effective and reliable SNs are developed.

NEETRAC supported a project "Potential Applications for SNs in Power Delivery" from July 2005 to May 2006 to evaluate the potential applications for sensor networks and the main obstacles and concerns.

III. POTENTIAL APPLICATIONS FOR SENSOR NETWORKS IN POWER DELIVERY

A targeted survey was conducted to gather comprehensive input from Project Advisors and other interested experts in the T&D community. The survey provides a better understanding of the full scope of potential applications, concerns, constraints and issues for the wide scale deployment that are perceived.

While the survey was necessarily limited in scope, some general observations stood out.

1. While asset monitoring, for either the broader T&D system or substations, in general is far from satisfactory, monitoring outside the substation is more needed. The recommendation was to focus on asset monitoring outside the substation.

2. Several areas of primary concern in terms of a gap between the need and current capability of SNs were identified for power delivery monitoring applications, as listed in Table IV.

TABLE IV
POTENTIAL APPLICATIONS OF SNS FOR POWER DELIVERY

Overhead conductor temperature, sag and dynamic capacity
Overhead structure integrity, reclosers, capacitors, and sectionalizers
Underground cable and neutral conductors, temperature and capacity
Overhead and underground faulted circuit indicators
Padmount and underground network transformers
Wildlife and vegetation contact warning
Underground network transformers, switches, vaults, manholes, switches

In this project, literature and products reviews were conducted with the above survey results as a guideline and are aimed to explore available technologies, products and the ability to scale them for a sensor network.

IV. SENSING TECHNOLOGIES FOR POWER DELIVERY SYSTEMS

This section summarizes the state-of-the-art for sensing technologies and products available in the market.

A. Overhead (OH) Conductor Sag Measurement

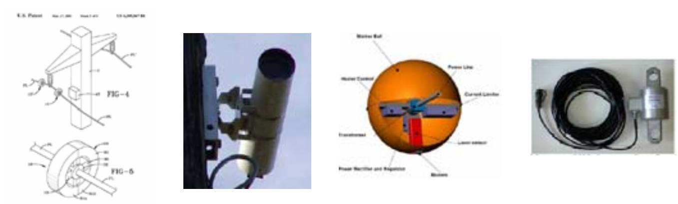
OH conductor sag clearance is critical to determine power line thermal capacity. For dynamic thermal rating, it is important to accurately assess conductor sag in real-time.

Several direct sag measurement methods are proposed as shown in Table V. At the same time, two active methods to reduce sag clearance are also reviewed in this section.

Fig. 3 shows some sag measurement devices mentioned in Table V. Fig. 4 shows two active devices able to reduce the conductor sag. The SLiM [16] device can reduce sag by 112 cm on a 152 m span of ACSR conductor when heated. Several high temperature low sag conductors are available on the market, such as Aluminum Conductor Composite Core (ACCC) from CTC [19] and Aluminum Conductor Composite Reinforced (ACCR) from 3M [20].

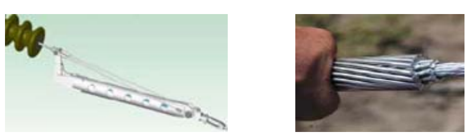
TABLE V
OH CONDUCTOR SAG MEASUREMENT

GPS [10]	Direct sag measurement by using Differential GPS technology	Around 20cm accuracy
Inclinometer [11]	The phase conductor angle (with respect to horizontal) is measured to indicate the sag	Precise angle measurement is required.
Resistive wires [12]	Conductor sag is evaluated by the E-field near a HV power line, which is measured by the current induced on a high resistance grounded wire by the E-field near the HV conductor.	Sensitive to external disturbance; Induced and actual currents are difficult to be distinguished.
Tension measurement [13]	Sag clearance is indirectly measured by the tension of the conductor within the ruling span sections.	Average conductor temperature can be monitored
Sagometer [14]	Sagometer unit is typically mounted on one of the supporting structures, and provides video-based sag measurement.	Around ±2 inches accuracy
Laser Distance Measuremen t [15]	As an associated project to Sagometer evaluation, a laser distance sensor is used to monitor line sag clearance.	Around ±2 inches accuracy



Inclinometer | Sagometer | LDM Sensor | Tension Sensor [18]

Fig. 3. Sag measurement devices



Sagging Line Mitigator | ACCR

Fig. 4. Sag reduction devices

B. Conductor Temperature Profile Measurement and Dynamic Thermal Capacity

With the importance of knowing conductor operating temperatures, there is a need for the industry to have direct measurements. There are several ways this can be done: temperature measuring devices mounted on the conductors; fiber optic distributed sensors (FODTS); infrared (IR) measurements. The survey is summarized in Table VI.

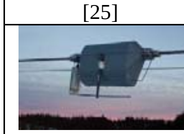
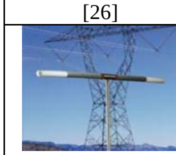
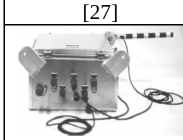
C. Dynamic Thermal Rating Systems

Real time monitoring of conductors/cables thermal conditions, such as sag, tension, and temperature, will lead to more realistic ratings being assigned to power lines and will increase the utilization of their power-carrying capabilities. Several dynamic thermal rating systems (DTRS) are developed recently for OH power lines. Table VII presents a review of these different systems.

TABLE VI
CONDUCTOR TEMPERATURE PROFILE MEASUREMENT

Conventional Thermal Sensors	Thermocouples, Thermistors and RTDs One spot measurement
FODTS [21][22][23]	Real-time distributed temperature measurement using optical time-domain reflectometry (OTDR) Electromagnetic interference (EMI) immunity Inbuilt communication solution
IR-based [12]	Non-contact temperature measurement on energized conductors

TABLE VII
DYNAMIC THERMAL RATING SYSTEMS

	Features
 Power Donuts [25]	On-line temperature monitoring system: - Conductor temperature is directly measured; - Conductor sag and tension measurement is based on conductor inclination; - The device is self-powered.
 Power Line Sensor [26]	On-line temperature monitoring system: - Several measurement devices are included in the sensor for sag clearance, conductor and temperatures, wind, etc. - The sensor is self-powered
 Conductor replica [27]	Weather dependent system: - Conductor replicas located near the line are used to evaluate the weather conditions of the line. - Accuracy is retained at low electric load and low wind conditions - Physical modifications of lines are avoided
 Tension Monitor [18]	On-line tension monitoring system: - Average conductor temperature is calculated by on-line tension measurement; - A net radiation sensor is used to provide combined effects from ambient temperature, solar and wind.

D. Mechanical Strength of Towers and Poles

Failures of poles, towers, and structures may lead to power outages, high repair costs and are potentially very dangerous. Therefore, inspecting and maintaining them in a timely manner is essential to system integrity and maximizing service life of equipment.

Several measurement techniques are proposed such as drilling or chipping, stress wave, sonic or ultrasonic, electrical resistivity, infrared, radar, and tomography. These techniques are normally destructive, and/or only test a local area of the structure rather than evaluating the state of the entire structure. In [28], a nondestructive, noncontact method is proposed, utilizing a helicopter-based laser vibrometer to measure vibrations induced in a cross-arm by the helicopter's rotors and engine.

E. Conductor Galloping

Conductor galloping and vibration in overhead lines can cause the breakdown of the air dielectric between conductors on different phases or mechanical failure of the conductor or structure. How to effectively detect conductor galloping and vibration is an important issue.

However, little work has been reported on detection of conductor galloping. The effort seems to have been focused on avoiding conductor galloping by using certain antivibration or damping schemes [29][30].

F. Conductor Contact with Vegetation and Animals

Utility distribution systems in the U.S. are likely to experience contact with tree branches or animals. Detection of these phenomena could provide vital predictive maintenance information.

Some work has been done for this pre-fault detection. The effect of spruce trees on the nearby electric field is evaluated in [31]. In [32], a method is presented to identify tree/animal caused faults using historical fault record data and intelligent techniques.

G. Underground Cable Systems

While UG power lines experience fewer interruptions than OH lines, there are a variety of failures that do affect UG cables especially in joints and terminations. However, service interruptions in underground systems can last much longer, when the fault is located and service is restored. Therefore, in-service monitoring and diagnosis of UG cables is receiving significant attention from electric utilities. Some related technologies are reviewed and are summarized in Table VIII.

TABLE VIII
UG NETWORK CONSTRUCTION MONITORING

	Technologies
Partial Discharge (PD) detection: Cables, Joints and Splices	Capacitive sensors: - Coaxial cable sensors [33]
	Inductive sensors [34][35][36]: - High frequency current transformer - Radio frequency current transducer - Loop Antenna
	Acoustic emission techniques [37]
Cable thermal conditions	Bolometer equipped with a television camera and mounted on a track or aircraft.
	Infrared imaging advanced as a diagnostic tool for coronas and heat detection
	Fiber optic distributed sensor

H. OH and UG Faulted Circuit Indicators (FCIs)

FCIs have been used for over fifty years on distribution circuits to identify the location of faulted equipment. The ability to quickly pinpoint from a central location where a fault is located, and to verify that the FCI trip is not due to a false reading, can significantly shorten the time to restore power after a fault.

Significant effort has gone into understanding what system variables can affect fault indicator operation [38], such as inrush current, cable discharge, proximity effect, back-feed voltages/currents and so on.

Some of the available FCI products feature short-range point-to-point communication between the device and a handheld receiver for remote indication, such as

- Remote fiber optic cable [38];
- Radio frequency communication [39][40];

I. Distributed Sensor Operating Power Supply

Sensor nodes placed in a high voltage area require an energy source. A typical power supply for a stand-alone sensor could be cell-powered, vibration-powered, or thermal-powered, which has been introduced in Section II. In this section, two methods utilized under HV conditions are presented, as shown in Table VIIII.

TABLE VIIII
SENSOR OPERATING POWER SUPPLY

Optical source [41]	Low efficiency of electronic converters Complex structure and expensive
CT source [42]	Current transformers clamped onto power lines Simple structure and easy to implement Subject to fault inrush current affects

V. NETWORKING AND COMMUNICATIONS TECHNOLOGIES REVIEW

A. Smart Sensors

Sensor interface and time synchronization protocol standardization efforts are underway to unify the market and hopefully lead to a large number of low-cost and interoperable devices.

IEEE 1451 Standard (Smart Transducer Interface for Sensors and Actuators) is a serial of standards to provide a single generic interface between a transducer and external network, independent of the network protocol in use [43].

IEEE 1588 Standard (Precision Clock Synchronization Protocol for Networked Measurement and Control Systems) defines a protocol enabling precise synchronization of clocks in measurement and control systems implemented with technologies such as network communication, local computing and distributed objects [44].

B. Wireless Communications

Wireless communications offer the most flexible and easiest interconnection between devices without relying on any physical connection. Over the last few years, great progress has been made in new types of wireless systems. Fig. 6 compares cost, complexity and data rates of many wireless technologies.

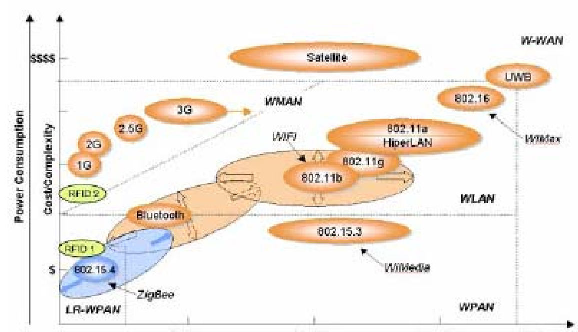


Fig. 6. Overview cost/complexity versus data rates of many wireless technologies [45]

- The IEEE 802.15 Working Group focuses on WPANs, which support instant connectivity between devices involving little or no infrastructure [47][48].

- IEEE 802.15.4 supports low-rate wireless "meshed networks", runs at 20/40/250 kpbs, and uses the 915 MHz / 2.4 GHz band, with a range up to 100 m.
- ZigBee builds upon the 802.15.4 standard to define application profiles that can be shared among different manufactures to provide system-to-system interoperability.

- IEEE 802.16 (WiMax) addresses the "first-mile/last-mile" connection in Broadband Wireless Access (BWA) [49]. The main focus is to enable a wireless alternative for cable, DSL, and T1 communication channels for consumer last-mile access to the Internet.
- Cellphone – Global System for Mobile communications, also termed GSM, allows cellphone users to 'roam' across many cellphone systems and between most countries world-wide. New generations of cellphone technologies, termed 2.5G, 3G, and 4G, are deployed in certain countries or are still under development [45].

Wireless data communications systems are becoming more popular, with increasingly mature technologies and standards, as well as decreasing costs. However, the use of wireless technologies in power system environments also presents a number of security and reliability concerns, such as eavesdropping on non-secured channels; wireless signal disruption due to electromagnetic interference (EMI); faded signals due to long distance transmission or obstacles in the line-of-sight; overloading of bandwidth; immaturity of wireless lower layer protocols, and the need for testing within the substation environment [45].

In order to help the industry address the potential of these technologies, the IEEE has begun work on a new standard to create functional, performance, security and on-site testing practices for wireless technologies in power system operations.

The standard, IEEE P1777(TM), "Using Wireless Data Communications in Power System Operations", will focus on newer technologies, such as WiFi, Bluetooth, Zigbee, WiMax and cellular phones. In addition to the practical aspects of wireless use, it also will address the dissemination of information on the uses, benefits and concerns of wireless technologies in the industry [50].

C. Power Line Communications (PLC)

It would be highly desirable if the electric power lines could be used to deliver both electric power and communications signals. Therefore, PLC becomes a promising alternative for sensor network implementation.

Using the power lines for communications is not a new concept. Since the 1950s, electric utilities have been using low frequencies to send control messages to equipment on the power grid. By the 1980s, bi-directional communications in the 5 ~500 kHz band were being used for low data-rate PLC applications (IEEE 643) [51]. Today, broadband over power lines has been developed and commercial products for LAN applications and Internet access are becoming more widely deployed (IEEE P1675 expected) [52] [53].

In general, there are three main areas of PLC applications [54], as summarized in Table VIII.

TABLE VIII
PLC APPLICATIONS AND COMMERCIAL PRODUCTS

	Applications	**Characteristics**	**Commercial Availability**
Utility PLC	Transmission of speech, protection signals, control signals, monitoring states, etc., for HV power line protection	HV power lines; Narrowband; Low data rate up to 64 kbps	ABB RFL
Access PLC	Delivery of broadband services, e.g. Internet, to every household and office, instead of DSL or cable.	MV or LV power lines; Broadband; Data rate up to 200 Mbps.	Ambient Ilevo
In-house PLC	LANs in buildings (broadband); Home automation (narrowband)	LV power lines; Broad/narrow-band; Data rate up to 200 Mbps	Intellon Echelon

There are several industry standards specified for home automation networking, or home LAN applications, such as CEBus [56], LonWork [55], HomePlug [56], etc. Among them, the HomePlug protocol is expected to support data rates up to 200 Mbps.

PLC technologies have tremendous potential for growth in providing a networking infrastructure to support the concept of SNs for power delivery. However, use of PLC technologies, particularly over HV or MV power lines, presents several concerns as follows [54] [57],

- It is a challenge to design a cost-effective PLC coupler over HV power lines.
- Signals must pass through or around transformers, or other T & D equipment.
- Line connections and branches cause signal reflection and attenuation.
- At high frequencies power lines act as antennas both for emitting and receiving electromagnetic radiation, which makes reliable data communication via this medium extremely difficult. Encryption must used to prevent the interception of sensitive data by unauthorized personnel.

VI. TECHNOLOGIES FOR SYSTEM INTEGRATION

A. SCADA/EMS Interface

When SNs are applied to power grid monitoring, the information integration to the existing Supervisory Control and Data Acquisition (SCADA) systems must be considered.

There are several industry protocol and communications standards commonly in use today. Traditional challenges presented by incompatible communication protocols have recently been addressed with widely accepted LAN-based standards such as,

- IEC 61850 (US) [59];

- DNP-IP (US) [58];
- IEC 60870-5-104 (Europe) [59].

While some competition among these standards is expected, the fact that the number of contenders has been reduced to three is very encouraging. Furthermore, all three standards can peacefully coexist on the same Ethernet network, thus enabling gradual transition to the LAN-based environment.

B. Satellites

The use of satellites by electric utilities has been investigated for a number of years [60] with some cost effective applications being implemented. By using satellite technology, accurate positioning, precise time synchronization for distributed measurement, and remote monitoring can be obtained. A primary review of several satellite technologies is given as follows.

- GPS [61]: A GPS receiver can triangulate its position on the Earth's surface within 30 meters or less with signals from three of the satellites. GPS can also provide a time stamp with accuracy on the order of 1 to 10 milliseconds based on atomic clock oscillators.
- VSAT (Very Small Aperture Terminal) [62] provides up and down links ranging from 64kbits to 1 Mbps and provides "world wide" coverage making it ideal for remote communications. However, VSAT terminals and hubs are quite expensive with high operating costs.
- LEOS (Low Earth Orbiting Satellite) that navigate the earth at much lower altitudes and operate at lower frequencies are starting to appear. Due to these factors, low cost terminal devices are being developed specifically for SCADA applications. LEOS provides the user with moderate data rates (1200 to 4800bps).

However, the main disadvantages of satellite technologies are operating costs and terminal devices costs. Based on these factors, they are not widely used for SCADA applications unless they employ exception reporting or no other cost-effective medium is available.

VII. Gaps between the Existing Technologies and Potential Applications

The benefits of SNs have been widely recognized in various applications, and there is consensus that distributed asset monitoring data and integrated communications could result in value added services and improve power system reliability. However, the implementation of SNs for distributed power delivery monitoring poses several technical challenges and issues including:

- Sensor Nodes:
    - Reliability, low maintenance, and low O&M cost;
    - Standardization of sensors between various sensor venders providing interoperable solutions that would interface with existing systems and data formats;
- Networking and Communications:
    - Low O&M cost;
    - Highly secure wireless communication seems to be the most attractive technology;
    - Standard open protocols are important to decrease costs and resources required to maintain a network of sensors;
- System integration:
    - The issue of large streams of data from thousands of sensors overloading system operators is a concern. The data will be compacted without causing data overload.
    - Data extraction would be required to create information from disparate data sources.
    - Integration to the existing SCADA system is another big concern;

- Finally, the price point is estimated for such SNs that would be desirable. Acceptable price per sensor node ranged from $1,390-3,000 per node for initial cost, with an annual O&M cost ranging from $38-60 per node.

VIII. Conclusions

This paper has examined the idea that low-cost communications enabled SNs that provide grid-wide monitoring of utility assets could provide value in terms of enhancing system reliability and asset utilization. A survey of utility experts was used to identify the gaps between available sensors and what was considered to be important and potentially useful. A prioritization and estimate of cost points provided further benchmarking for examining potential solutions.

An extensive survey of literature in terms of sensing technologies was followed by a listing of available products that provided some of the desired sensing functions. Wireless and power line communications protocols available and under development were also explored. System integration technologies were presented.

IX. Acknowledgment

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