THE REPUBLIC OF TURKEY
BAHÇEŞEHİR UNIVERSITY

QUALITY OF SERVISE-BASED (QoS-BASED) ROUTING FOR SMART GRID APPLICATIONS

Master's Thesis

DİLAN ŞAHİN

İSTANBUL, 2012

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ABSTRACT

QUALITY OF SERVISE-BASED (QoS-BASED) ROUTING FOR SMART GRID APPLICATIONS

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Recently, the increasingly growing population and diminishing power resources have threatened the electric utilities in generating and distributing the necessary electricity and forced them finding new ways to generate the electricity with renewable energy resources. The imbalance between power demand and supply is one of the problems of the electric utilities, since generating electricity more than the actual necessity may result in huge electricity lost due to the non-existence of the advanced electricity storage options. In addition to the imbalance between power demand and supply, the equipment failures and the lack of comprehensive monitoring and control capabilities are other important signs to take incremental steps for switching to a smarter power grid with effective communication, automation and monitoring skills. This new concept is conceived as *smart grid*, which is a modern power grid system with advanced communication, monitoring, sensing and control capabilities.

In general, smart grid is a distributed system that many of its components are spread over a wide range of area. Thus, a reliable communication and coordination between distributed components of the smart grid is required for the safety and reliability of the power delivery system. To this end, effective management and reliable operation of smart grid can be achieved with the installation of wireless sensor nodes on the critical power grid equipment. In these systems, collected sensor data can be used to diagnose arising problems quickly, and hence, system breakdowns due to the cascading effect initiated by a single fault in the power grids can be prevented.

The main objective of this thesis is to analyze the behavior of a multi-path and multi-speed (MMSPEED) routing protocol in different line-of-sight (LOS) and non-line-of-sight (NLOS) smart power grid environments, e.g., 500kV outdoor substation, main power control room and underground network transformer vaults. MMSPEED routing protocol is a novel packet routing mechanism that guarantees QoS provisioning in two quality domains, e.g., reliability and timeliness domains. It provides several packet delivery options for timeliness domain and probabilistic multi-path forwarding for reliability domain. Furthermore, a comparison has been made for multi-path and single-path routing algorithms to see the performance for achieving service differentiation in different smart grid environment which has harsh environmental conditions that posse additional challenges for WSN technology to provide reliability and latency requirements. Hence, the wireless channel should be modelled by taking account multiple parameters that can affect the signal quality. Since log-normal shadowing model takes into account both fading and distance affects in the surrounding of transmitters and receivers, it is the preferred propagation model in this thesis. From the extensive simulations, the presented algorithm provides a clear service differentiation in smart grid environments.

Keywords: Smart Grid, Wireless Sensor Network, Multi-Path Routing Protocol

ÖZET

AKILLI ŞEBEKE UYGULAMALARI İÇİN SERVİS KALİTESİ TABANLI YÖNLENDİRME

Şahin, DİLAN

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Günümüzde, hızla artan nüfus ve tükenmekte olan enerji kaynakları, elektriğin yeteri oranda üretilmesini ve herkese ulaşabilmesi önündeki en büyük tehditlerden birisidir. Bu sebeple, yenilenebilir enerji kaynaklarının sisteme entegre edilebilmesi için çalışmalar hızla sürmektedir. Elektrik üretimi ve harcanmasındaki arz ve talep eşitsizliği, elektrik şirketlerinin en büyük sorunlarından birisidir. Gerçek zamanlı elektrik tüketiminin bilinmemesi, elektriğin fazladan üretilmesine, ve elektrik saklanamadığı için, kullanım fazlasının boşa gitme riski vardır. Elektrik sisteminin çok eski olması, sürekli arızalar çıkarması çok büyük tehdit unsurlarından bir kaçıdır. Bu nedenle, daha akıllı, yeni iletişim teknolojileri ile donatılmış akıllı şebekeye geçiş yapılmalıdır.

Akıllı şebeke sistemi yapı itibariyle dağıtıktır ve bir çok elemanı çok geniş bir coğrafik alana yayılmıştır. Bu nedenle, bu kadar geniş alana yayılmış sistem parçalarının gözlenmesi, aralarındaki alışverişin güvenilir bir şekilde yapılıp yapılmadığının anlaşılması için, kullanılacak iletişim teknolojisinin çok özenli bir şekilde seçilmesi gerekmektedir. Kablosuz algılayıcı ağlar (KAA) akıllı şebeke sistemi için gelecek vadeden bir teknolojidir. KAA'ların iletişim maliyetlerini düşürmesi nedeniyle dünya genelinde, akıllı şebeke sistemini hayata geçirmek için telekom şirketleri, elektrik dağıtım şirketleri ortaklaşa bir çok çalışma yürütmektedirler. Bu çalışmalarda telekom şirketlerinin iletişim altyapısını kullanan akıllı sayaçlar ve ev aletleri gibi bir çok akıllı cihaz elektrik şirketleri ile iletişime geçerek veri alışverişinde bulunmaktadır. Elektrik dağıtım şirketleri de toplanan bu verilerin analizini yaparak akıllı şebekenin sağladığı çift yönlü iletişim hattı ile bu cihazlara geri bildirimde bulunmaktadır. Bu geribildirimler günlük elektrik kullanımı, anlık kullanım ücreti gibi veriler içerebilmektedir. Hatta, akıllı sayaçlar üzerinden yapılan bu çift yönlü veri alışverişi sayesinde yasal olmayan kullanımlar tespit edilerek, anında müdahale ile elektrik sayaçlarının kapatılması ve elektrik kaçaklarının önlenebilmesi dahi

mümkün olabilmektedir. İletişim becerileri kısıtlı ve enerji açlığı çeken düğüm noktalarının bulunduğu KAA'larda bilginin doğru yönlendirilmesi çözülmesi gereken çok büyük bir problem olarak karşımıza çıkmaktadır. Bu yönlendirme problemini çözmek için geliştirilmiş pekçok yöntem de bu iddiamızı destekler niteliktedir. Düğüm noktalarının yerleşimi, KAA'nın enerji tüketimi, iletişim kanalındaki asimetri, hata toleransı, genişletilebilirlik ve servis kalitesi olarak özetlenebilecek pekçok etken yönlendirme algoritması tasarımı sırasında gözönünde bulundurulmalıdır.

Bu tezde, akıllı şebeke ortamında kullanılan ve servis farklılaştırılmasını başarılı bir şekilde sağlayan, çok-yollu ve tek-yollu yönlendirme algoritmasınının analizini yapıyoruz. Önerilen yönlendirme algoritması başarılı bir şekilde veri paketlerini güvenilir ve zamanında olmak üzere taşımayı başarabilmiştir. Yapılan birçok deneysel sonuçla ve çizilen grafiklerle bu başarı detaylı bir şekilde anlatılmıştır. MMSPEED adı verilen bu yönlendirme algoritması farklı paket iletim seçenekleri sunarken, aynı zamanda çok-yönlü iletim sağlayarak güvenilirliği arttırmaktadır. Ayrıca, çok-yönlü ve tek yönlü yönlendirme algoritmalarının akıllı şebeke ortamındaki performans değerlendirmesi de yapılmıştır. Log normal shadowing kanal modeli kullanılarak bütün performans sonuçları değerlendirilmiştir.

Anahtar Kelimeler: Akıllı Şebeke, Kablosuz Algılayıc Ağ, Çok-Yollu Yönlendirme Protokolü

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ABBREVIATIONS

ACK	:	Acknowledgement
AMI	:	Advanced Metering Infrastructure
AHAM	:	Association of Home Appliance Manufacturers
ADSL	:	Asymmetric Digital Subscriber Line
CTS	:	Clear to Send
CDMA	:	Code Division Multiple Access
DSL	:	Digital Subscriber Lines
EID	:	Embedded Intelligent Devices
EER	:	End-To-End Reachability
EC	:	European Community
FAN	:	Field Area Network
GPRS	:	General Packet Radio Service
GSM	:	Global System for Mobile Communications
HVAC	:	Heating Ventilating and Air Conditioning
HAN	:	Home Area Network
ICT	:	Information and communication technologies
IEC	:	International Electrotechnical Commission
LOS	:	Line-Of-Sight
LQE	:	Link Quality Estimation
LQER	:	Link Quality Estimation Based Routing Protocol
LTE	:	Long Term Evolution
LV	:	Low Voltage
MAC	:	Medium Access Control
MMSPEED	:	Multi-path Multi-SPEED Protocol
NIST	:	National Institute for Standards and Technology
NES	:	Networked Energy Services
NLOS	:	Non-Line-Of-Sight
PLC	:	Power Line Communication
QoS	:	Quality of Service
RTS	:	Request to Send
SG	:	Smart Grid
SIM	:	Subscriber Identity Module
SCADA	:	Supervisory Control and Data Acquisition
UMTS	:	Universal Mobile Telecommunications System
WAN	:	Wide Area Network
WCDMA	:	Wideband Code Division Multiple Access
WSN	:	Wireless Sensors Network

SYMBOLS

Shadowing Deviation	:	σ
Path Loss Exponent	:	η
Transmitted Power	:	P_t
Path loss at a reference distance d_0	:	$PL(d_0)$
Reference distance	:	d_0
Zero mean Gaussian random variable	:	X_σ
Noise power in dBm	:	P_n

1. INTRODUCTION

Today's electrical infrastructure has remained unchanged for about a hundred years. The components of the hierarchical grid are near to the end of their lives. While the electrical grid has been ageing, the demand for electricity has gradually increased. According to the U.S. Department of Energy report, the demand and consumption for electricity in the U.S. have increased by 2.5 % annually over the last twenty years (Gungor et al. 2010). Today's electric power distribution network is very complex and ill-suited to the needs of the twenty-first century. Among the deficiencies are a lack of automated analysis, poor visibility, mechanical switches causing slow response times, lack of situational awareness, etc. (Asuncion & Newman 2007). These have contributed to the blackouts happening over the past 40 years. Some additional inhibiting factors are the growing population and demand for energy, the global climate change, equipment failures, energy storage problems, the capacity limitations of electricity generation, one-way communication, decrease in fossil fuels and resilience problems (Erol-Kantarci & Mouftah 2011). Also, the greenhouse gas emissions on Earth have been a significant threat that is caused by the electricity and transportation industries (Saber & Venayagamoorthy 2011). Consequently, a new grid infrastructure is urgently needed to address these challenges.

To realize these capabilities, a new concept of next generation electric power system, the *smart grid*, has emerged. The smart grid is a modern electric power grid infrastructure for improved efficiency, reliability and safety, with smooth integration of renewable and alternative energy sources, through automated control and modern communications technologies (Gungor et al. 2010), (Cecati, Citro, Piccolo & Siano 2011*b*). Renewable energy generators seem as a promising technology to reduce fuel consumption and greenhouse gas emissions (Lu & Gungor 2009). Importantly, smart grid enabling new network management strategies provide their effective grid integration in Distributed Generation (DG) for Demand Side Management and energy storage for DG load balancing, etc. (Palensky & Dietrich 2011, Calderaro et al. 2011). Renewable energy sources (RES) are widely studied by many researchers (Cecati, Citro & Siano 2011) and the integration of RES, reducing system losses and increasing the reliability, efficiency and security of electricity supply to customers are some of the advances that smart grid system will increase (Vaccaro et al. 2011). The existing grid is lack of communication capabilities, while a smart power grid infrastructure is full of enhanced sensing and advanced communication and computing abilities as depicted in Figure 2.1. Different components of the system are linked together with communication paths and sensor nodes to provide interoperability between them ,e.g., distribution, transmission and other substations, such as residential, commercial and industrial sites.

In the smart grid, reliable and real-time information becomes the key factor for reliable delivery of power from the generating units to the end-users. The impact of equipment failures, capacity constraints, and natural accidents and catastrophes, which cause power disturbances and outages, can be largely avoided by online power system condition monitoring, diagnostics and protection (Gungor et al. 2010). To this end, the intelligent monitoring and control enabled by modern information and communication technologies have become essential to realize the envisioned smart grid (Gungor et al. 2010).

For overall, in Chapter 2 the smart grid system overview is briefly presented with its fundamental components, such as, communication architecture, proper communication technologies and communication requirements of each smart grid application, smart grid key players and the importance of wireless sensor network technology for smart grid. In Chapter 3, a literature survey on wireless sensor network based routing algorithms are introduced. In Chapter 4, the multi-path and single path routing algorithm is presented, and its performance evaluations in different line-of-sight (LOS) and non-line-of-sight (NLOS) smart power grid environments, e.g., 500kV outdoor substation, main power control room and underground network transformer vaults for reliability and timeliness domain are compared. Furthermore, the overhead analysis of the presented algorithm for data and control packets are also made. Finally, in Chapter 5 a future work and conclusion of this thesis have been presented.

2. SMART GRID SYSTEM OVERVIEW

Smart Grid is modernization of generation, transmission and distribution of power grid system with the integration of advanced ICT (Information and communication technologies) infrastructure. The electrical power grid is the most critical and complex infrastructure of today's world and it is vulnerable to tremendous security threats. SG with the decentralized nature enables the integration of the renewable energy resources and promises a two-way communication path between consumers and electric utilities, which will increase the efficiency of demand-response, customer participation, advanced smart metering and outage detection programs (Gungor et al. 2011).

USA, Canada, China, South Korea, Australia and European Community (EC) countries have started doing research and development on smart grid applications and technologies. For example, the U.S. Government has announced the largest power grid modernization investment in the U.S. history, i.e., USD 3.4 billion in grant awards, funding a broad range of smart grid technologies (Asuncion & Newman 2007). Local Distribution Companies (LDCs) are integrating advanced metering and two-way communication, automation technologies to their distribution systems (Paudyal et al. 2011). In addition to research and development projects, many electric utilities are also taking incremental steps to make the smart grid technology a reality. Most of them are signing agreements with telecom operators or smart meter vendors to carry out smart grid projects. All these agreements define the main requirements and features of the necessary communications infrastructure to provide online communication between smart meters and the utility's back-haul system, i.e., the so-called advanced metering infrastructure (AMI). In general, the AMI is a two-way communications network and is the integration of advanced sensors; smart meters, monitoring systems, computer hardware, software and data management systems that enable the collection and distribution of information between meters and utilities.

2.1 SMART GRID COMMUNICATION ARCHITECTURE

2.1.1 General overview

The smart grid concept is aiming to achieve a sophisticated system by integrating an information and communication technology infrastructure to the existing power system

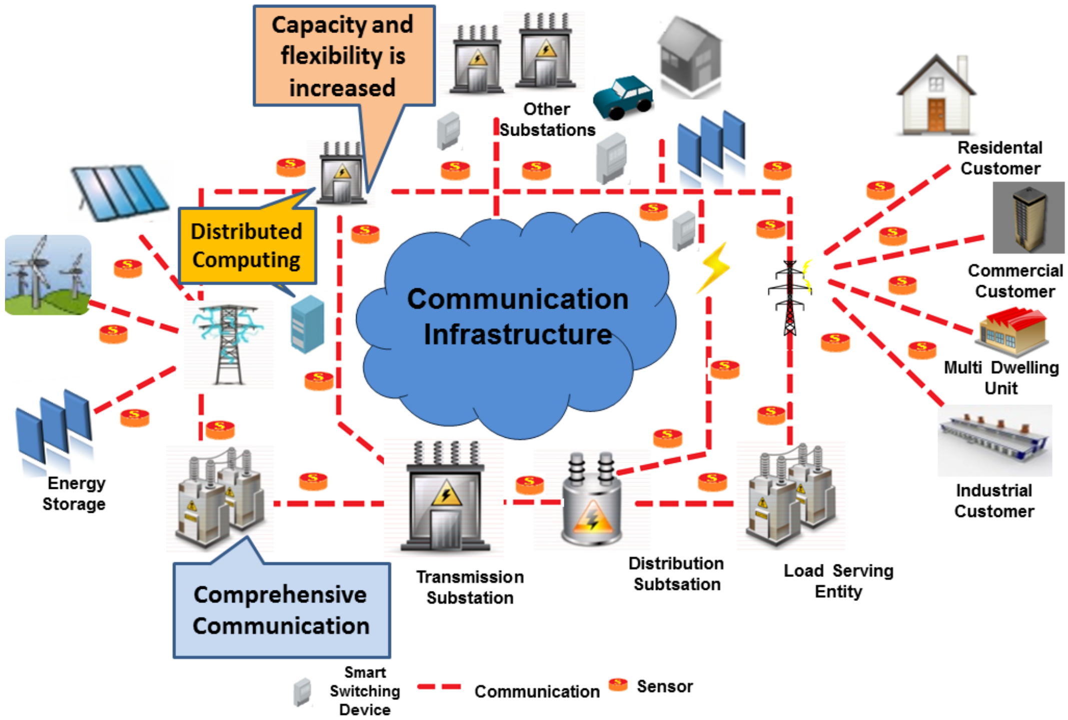


Figure 2.1: Smart grid architecture increases the capacity and flexibility of the network and provides advanced sensing and control through modern communications technologies, Gungor et al. (2011)

infrastructure and the new distributed generation system, in order to fully exploit the use of renewable energy systems and to maximize energy efficiency of the whole power system as depicted in Figure 2.2. From a slightly different perspective, a smart grid can be considered as a data communication network that achieves, with the support of specific power management hardware devices, flexible, seamless inter-operation abilities among different advanced components of the system for efficient utilization of the energy.

Smart grid end-to-end architectures basically comprise of three main layers: smart grid applications layer, the power layer and the communication layer:

Applications Layer:

It includes advanced applications providing inter-operability among them. Demand response management, outage management, advanced metering infrastructure, asset management, fraud detection, etc. are among the most considered.

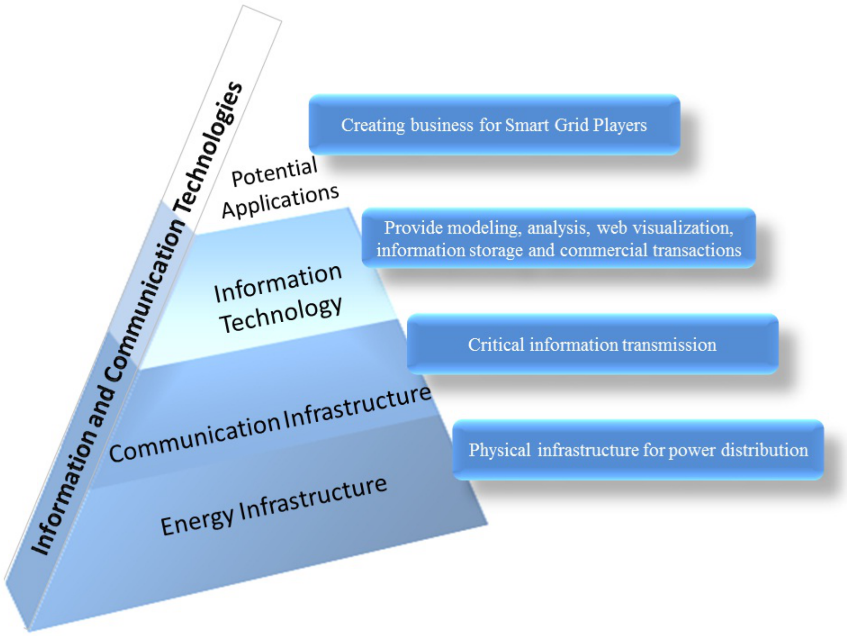


Figure 2.2: Smart grid framework integrating energy infrastructure with the communication, computing and information technologies, and business applications, Gungor et al. (2013)

Power Layer:

The fundamental novelty in smart grid comes with *i)* the integration of renewable energy sources that disrupt the balance of the prediction of energy sources and the replacement of the one-way communication system and *ii)* two-way communications between customer and the utility that will enable the possibility to balance between demand and supply of the energy. Therefore, the power generation, transmission and distribution system and customer premises are all included in the power layer part of the system. The changes applied to power layer will also affect the customer participation in an active way.

Communication Layer:

It represents the heart of the system by providing interconnections between all the systems and devices. The telecommunications technology is used at the communication layer to enable the data digitization, intelligent self-awareness and increased reliability. Nowadays, existing power grids are affected by severe drawbacks, such as *i)* fragmented architectures, *ii)* a lack of adequate bandwidth for achieving two-way communications, *iii)* a lack of inter-operability between system components and *iv)* the inability to handle the increasing amount of data from smart devices.

Importantly, the smart grid communication infrastructure could be either public or private. To this end, a public network like the Internet may offer an alternative communication path to remotely control and monitor the power grid due to its already existing, shared communication infrastructure. However, when a public network is utilized for smart grid applications, security and QoS concerns may arise. Therefore, the utilities should perform a detailed cost vs. benefit analysis to evaluate the performance of public vs. private networks for smart grid applications.

The communication layer consists of three transmission categories: *i)* a wide area network (WAN), *ii)* a field area network (FAN) and *iii)* a home area network (HAN). The three main tiers that are located between these three networks are the core backbone, back-haul distribution and the access point (Asuncion & Newman 2007).

The communication between back-haul aggregation points to the core backbone utility center is carried over different types of communication networks, such as star networks, fiber or wireless networks. In the following, a brief description of transmission categories is given:

Wide Area Network:

provides communication between the electric utility and substations. WAN should span all over the substations, distributed power generation and storage facilities, distribution assets, such as capacitor banks, transformers and reclosers, to be fully effective and scalable enough. It is a high bandwidth backbone communication network that handles long-distance data transmissions with advance monitoring and sensing applications. WAN provides a two-way communication network for communication, automation and monitoring purposes of smart grid applications. Each smart grid application running on WAN has unique communication and QoS requirements. Some applications like Wide-Area Situational Awareness Systems require real-time or near real-time responses; some of them like substation automation will require high bandwidth and fast response times; some applications like AMI will need considerable bandwidth and broadband data rates.

Wide Area Network Communications: Remote communication between utility and the smart meters is essential for exchanging relevant information, such as price signals or tariff information with the customer. Cellular networks, WiMAX and wired communications can be counted as the best candidate technologies for WAN. Importantly, the back-haul distribution system acts as an aggregation point between FAN and WAN, such as a substation, data concentrator, RF access point or a communication tower that collects the total metering information and transfers it to the backbone communication network. Moreover, aggregation points can serve as energy storing points for back-up power in the period of critical outages and other specific needs (Gungor et al. 2010). Fiber and microwave communication are preferred for high bandwidth requirements and reliable communication since this system is the aggregation point where large amounts of critical data are gathered for transmission to the back-office. Licensed and unlicensed wireless technologies and fixed wire line communication technologies can be used to transfer data from aggregation points to utilities' back-haul data centers. At the end, the communication technology will mostly depend on its cost-effectiveness and ability to provide suitable coverage.

Field Area Network:

can be described as the communication network for power distribution areas and includes distribution automation and control devices communicating over networks between individual service connections and backhaul points towards to the electric utilities. FAN acts as a bridge between customer premises and substations with collectors, access points and data concentrators. Intelligent nodes are deployed between customer premises and substations to collect and control the data from surrounding data points. These nodes are connected to a centralized gateway which is always supported by electric utilities to transmit the collected data. Low bandwidth FAN channels are highly robust for reliable data communications. FAN is ubiquitous and broadband wireless resource that meets the utility requirements for reliability and resilience. The coverage area includes urban-suburban and rural environments. FAN is highly supported by advanced metering infrastructure deployments and it is rapidly expanding the range of its application areas, e.g. advanced distribution automation and integration of distributed energy resources.

Field Area Network Communications: The choice of communication technology varies for FAN according to different smart grid applications. Some electric utilities prefer fiber optic cables to have low latency and superior communication performance, others prefer WiMAX where cellular and RF mesh technologies do not have coverage over the area. Moreover, current communication trends in substation automation and distribution automation systems of FAN are towards using IEC 61850' which provides interoperability between intelligent electronic devices and better device-to-device communication. IEC 61850 helps a wide of range applications to handle their needs. For example, the latency for mission critical data of FAN is between 3ms-10ms with the integration of the IEC 61850 protocol (Myoung et al. 2010).

Home Area Network:

Smart meters will have the ability to connect to the home area network (HAN) and this will enable consumers to be aware of electricity usage costs and manage their consumption behaviors and take control of smart appliances. Home area networks support low-bandwidth communication between home electrical appliances and smart meters. The primary task of in-home applications is to inform customers about the consumption behaviors via home displays or a web interface. Hence, the bandwidth needs are between 10 and 100 Kbps per/device and there is no urgent need for low-latency (Asuncion & Newman 2007). However, it is expected that new functions will quickly be integrated, thus implementing intelligent load management. Low-bandwidth, slow speed and cost-effective and flexible connections are preferred for HAN.

Home Area Network Communications:

The Association of Home Appliance Manufacturers (AHAM) has conducted research on the communication technologies that best meet the requirements of home-smart appliances. This research has shown that Zigbee, Wi-Fi, Homeplug, Z-wave and M-Bus are the candidates for the HAN category. ZigBee has the ability to operate in a mesh network topology, which offers some advantages, i.e. some devices in a ZigBee mesh can remain in sleep mode when they are not active in the network, which results in energy conversation. Wi-Fi is not preferred for mesh networking, since, it is more expensive and more energy hungry. On the other hand, Z-wave is an interference-free wireless standard that was specifically designed for remote control of the appliances and widely used for HAN. In architecture of HAN, the gateways are considered as the output points to the HAN and some communication technologies used as HAN protocols, such as Wi-Fi, ZigBee, HomePlug and Z-wave, are also shown as depicted in Figure 2.3. However, application layer information models have not been fully standardized by any of the technologies above. GEO Home Energy Hub is installed at customer premises to provide a display of customers' consumption behavior (Verschueren et al. 2010).

2.2 COMMUNICATION TECHNOLOGIES AVAILABLE FOR SMART GRIDS

A communications system is the key component of the smart grid infrastructure (Gungor et al. 2010), (Laverty et al. 2010). With the integration of advanced technologies and applications for achieving a smarter electricity grid infrastructure, a huge amount of data from different applications will be generated for further analysis, control and real-time pricing methods. Hence, it is very critical for electric utilities to define the communications requirements and find the best communications infrastructure to handle the output data and deliver a reliable, secure and cost effective service throughout the total system. Electric utilities attempt to get customer's attention to participate in the smart grid system, in order to improve services and efficiency. Demand side management and customer participation for efficient electricity usage are well understood, furthermore, the outages after disasters in existing power structure also focus the attention on the importance of the relationship between electric grids and communications systems (Gungor et al. 2010). Different communications technologies supported by two main communications media,

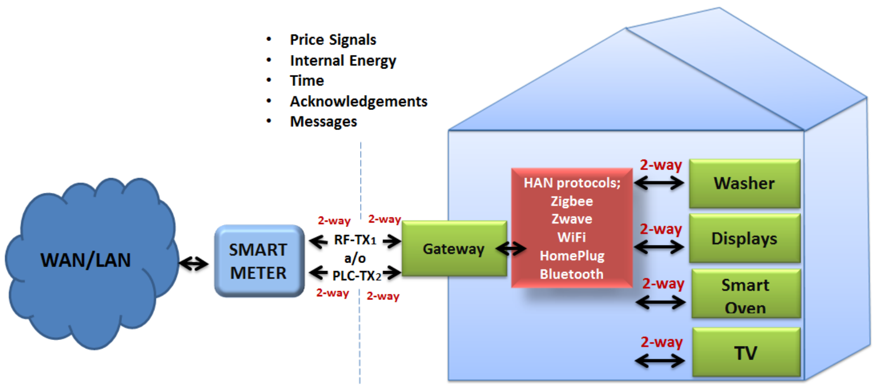


Figure 2.3: Smart grid home energy management with diverse wireless communications technology support, Gungor et al. (2013)

i.e., wired and wireless, can be used for data transmission between smart meters and electric utilities. In some instances, wireless communications have some advantages over wired technologies, such as low cost infrastructure and ease of connection to difficult or unreachable areas. However, the nature of the transmission path may cause the signal to attenuate. On the other hand, wired solutions have limited interference problems and their functions are not dependent on batteries, as wireless solutions do.

Basically, two types of information infrastructure are needed for information flow in a smart grid system. The first flow is from sensor and electrical appliances to smart meters, the second is between smart meters and the utility's data centers. As suggested in (Luan et al. 2010), the first data flow can be accomplished through power line communication or wireless communications, such as ZigBee, 6LowPAN, Z-wave and others. For the second information flow, cellular technologies or the Internet can be used. Nevertheless, there are key limiting factors that should be taken into account in the smart metering deployment process, such as time of deployment, operational costs, the availability of the technology and rural/urban or indoor/outdoor environment, etc. The technology choice that fits one environment may not be suitable for the other. In the following, some of the smart grid communications technologies along with their advantages and disadvantages are briefly explained.

2.2.1 ZigBee

ZigBee is a wireless communications technology that is relatively low in power usage, data rate, complexity and cost of deployment. It is an ideal technology for smart lightning, energy monitoring, home automation, and automatic meter reading, etc. ZigBee and ZigBee Smart Energy Profile (SEP) have been realized as the most suitable communication standards for smart grid residential network domain by the U.S National Institute for Standards and Technology (NIST) (Yi et al. 2011). The communication between smart meters, as well as among intelligent home appliances and in home displays, is very important. Many AMI vendors, such as Itron, Elster, and Landis Gyr, prefer smart meters, that the ZigBee protocol can be integrated into (Gungor et al. 2011). ZigBee integrated smart meters can communicate with the ZigBee integrated devices and control them. ZigBee SEP provides utilities to send messages to the home owners, and home owners can reach the information of their real-time energy consumption.

Advantages:

ZigBee has 16 channels in the 2.4 GHz band, each with 5 MHz of bandwidth. 0 dBm (1 mW) is the maximum output power of the radios with a transmission range between

1 and 100 m with a 250 Kb/s data rate and OQPSK modulation (Yi et al. 2011). ZigBee is considered as a good option for metering and energy management and ideal for short range smart grid implementations along with its simplicity, mobility, robustness, low bandwidth requirements, low cost of deployment, its operation within an unlicensed spectrum, easy network implementation, being a standardized protocol based on the IEEE 802.15.4 standard (Lu & Gungor 2009). ZigBee SEP also has some advantages for gas, water and electricity utilities, such as load control and reduction, demand response, real-time pricing programs, real-time system monitoring and advanced metering support (Yi et al. 2011), (Gezer & Buratti 2011).

Disadvantages:

There are some constraints on ZigBee for practical implementations, such as low processing capabilities, small memory size, small delay requirements and being subject to interference with other appliances, which share the same transmission medium, license-free industrial, scientific and medical (ISM) frequency band ranging from IEEE 802.11 wireless local area networks (WLANs), WiFi, Bluetooth and Microwave (Yi et al. 2011). Hence, these concerns about the robustness of ZigBee under noise conditions increase the possibility of corrupting the entire communications channel due to the interference of 802.11/b/g in the vicinity of ZigBee (Lewis et al. 2009). Interference detection schemes, interference avoidance schemes and energy-efficient routing protocols, should be implemented to extend the network life time and provide a reliable and energy-efficient network performance.

2.2.2 Wireless Mesh Networks

A mesh network is a flexible network consisting of a group of nodes, where new nodes can join the group and each node can act as an independent router. The self-healing characteristic of the network enables the communication signals to find another route via the active nodes, if any node should drop out of the network. Especially, in North America, RF mesh based systems are very popular. In PG&E's SmartMeter system, every smart device is equipped with a radio module and each of them routes the metering data through nearby meters. Each meter acts as a signal repeater until the collected data reaches the electric network access point. Then, collected data is transferred to the utility via a communication network. A private company, SkyPilot Networks uses mesh networking for smart grid applications due to the redundancy and high availability features of mesh technology (Gungor et al. 2011).

Advantages:

Mesh networking is a cost effective solution with dynamic self-organization, self-healing, self-configuration, high scalability services, which provide many advantages, such as improving the network performance, balancing the load on the network, extending the network coverage range (Yarali 2008). Good coverage can be provided in urban and suburban areas with the ability of multi-hop routing. Also, the nature of a mesh network allows meters to act as signal repeaters and adding more repeaters to the network can extend the coverage and capacity of the network. Advanced metering infrastructures and home energy management are some of the applications that wireless mesh technology can be used for.

Disadvantages:

Network capacity, fading and interference can be counted as the major challenges of wireless mesh networking systems. In urban areas, mesh networks have been faced with a coverage challenge since the meter density cannot provide complete coverage of the communications network. Providing the balance between reliable and flexible routing, a sufficient number of smart nodes, taking into account node cost, are very critical for mesh networks. Furthermore, a third party company is required to manage the network, and since the metering information passes through every access point, some encryption techniques are applied to the data for security purposes. In addition, while data packets travel around many neighbors, there can be loop problems causing additional overheads in the communications channel that would result in a reduction of the available bandwidth (Lewis et al. 2009).

2.2.3 Cellular Network Communication

Existing cellular networks can be a good option for communicating between smart meters and the utility and between far nodes. The existing communications infrastructure avoids utilities from spending operational costs and additional time for building a dedicated communications infrastructure. Cellular network solutions also enable smart metering deployments spreading to a wide area environment. 2G, 2.5G, 3G, WiMAX and LTE are the cellular communication technologies available to utilities for smart metering deployments. When a data transfer interval between the meter and the utility of typically 15 minutes is used, a huge amount of data will be generated and a high data rate connection would be required to transfer the data to the utility. For example, T-Mobile's Global System for Mobile Communications (GSM) network is chosen for the deployment of Echelon's Networked Energy Services (NES) system. An embedded T-Mobile SIM within a cellular radio module will be integrated into Echelon's smart meters to enable the communication between the smart meters and the back-haul utility. Since T-Mobile's GSM network will handle all the communication requirements of the smart metering network, there is no need for an investment of a new dedicated communications network by utilities. Telenor, Telecom Italia, China Mobile, Vodafone have also agreed to put their GSM network into service for data flow of smart metering communications. Itron's SENITEL electricity meter is integrated with a GPRS module and communicates with a server running SmartSynch's Transaction Management System. CDMA, WCDMA and UMTS wireless technologies are also used in smart grid projects. A CDMA smart grid solution for the residential utility market has been introduced by Verizon, and Verizon's 3G CDMA network will be used as the backbone of the smart grid communications with the SmartSynch smart grid solutions; UMTS is IP-based and a packet oriented service that is suitable for metering applications; Telenor with Cinclus technology is offering UMTS technology for smart grid communications (Gungor et al. 2011).

An Australian energy delivery company, SP AusNet, is building a dedicated communications network for smart grid applications and chose WiMAX technology for the communications need of the smart meters. WiMAX chip sets are embedded into the smart meters and wireless communications is dedicated between smart meters and the central system in SP AusNet's system. A U.S. wireless carrier, Sprint Nextel, had signed a partnership with the smart grid software provider, Grid Net, on a project to provide communication between smart meters and smart routers over its 4G wireless network. General Electric (GE) is developing WiMAX based smart meters with CenterPoint Energy and had collaborated with Grid Net, Motorola and Intel to focus on WiMAX connectivity solutions. In GE's smart meter project with CenterPoint Energy, it will deploy WiMAX based MDS Mercury 3650 radios to connect the utility's back-haul system to collection points, which will collect data from smart meters that are installed by CenterPoint (Gungor et al.

2011). Furthermore, some major companies, such as Cisco, Silver Springs Network and Verizon, also implement WiMAX smart grid applications. The world's largest WiMAX vendor, Alvarion, has announced its partnership with a U.S. utility company, National Grid, for a WiMAX based smart grid project. Lower deployment and operating costs, proper security protocols, smooth communications, high data speeds (up to 75 Mbps), an appropriate amount of bandwidth and scalability are the advantages of today's WiMAX technology.

Advantages:

Cellular networks already exist. Therefore, utilities do not have to incur extra cost for building the communications infrastructure required for a smart grid. Wide-spread and cost-effective benefits make cellular communication one of the leading communications technologies in the market. Due to data gathering at smaller intervals, a huge amount of data will be generated and the cellular networks will provide sufficient bandwidth for such applications. When security comes into discussion, cellular networks are ready to secure the data transmissions with strong security controls. To manage healthy communications with smart meters in rural or urban areas, the wide area deployment capability of smart grid becomes a key component and since the cellular networks coverage has reached almost 100 percent. In addition, GSM technology performs up to 14.4Kbps, GPRS performs up to 170Kbps and they both support AMI, Demand Response, HAN applications. Anonymity, authentication, signaling protection and user data protection security services are the security strengths of GSM technology (Gungor et al. 2011). Lower cost, better coverage, lower maintenance costs and fast installation features highlight why cellular networks can be the best candidate as a smart grid communications technology for the applications, such as demand response management, advanced metering infrastructures, HAN, outage management, etc.

Disadvantages:

Some power grid mission-critical applications need continuous availability of communications. However, the services of cellular networks are shared by customer market and this may result in network congestion or decrease in network performance in emergency situations. Hence, these considerations can drive utilities to build their own private communications network. In abnormal situations, such as a wind storm, cellular network providers may not provide guarantee service. Compared to public networks, private networks may handle these kinds of situations better due to the usage of a variety of technologies and spectrum bands.

2.2.4 Power Line Communication

Power line communication (PLC) is a technique that uses the existing power lines to transmit high speed (2 - 3Mbps) data signals from one device to the other. PLC has been the first choice for communication with the electricity meter due to the direct connection with the meter (Lewis et al. 2009) and successful implementations of AMI in urban areas where other solutions struggle to meet the needs of utilities. PLC systems based on the LV distribution network have been one of the research topics for smart grid applications in China (Zhai 2011). In a typical PLC network, smart meters are connected to the data concentrator through power lines and data is transferred to the data center via cellular network technologies. For example, any electrical device, such as a power line smart transceiver-based meter, can be connected to the power line and used to transmit the metering data to a central location (Gungor et al. 2011). France has launched the "Linky meter project" that includes updating 35 million traditional meters to Linky smart meters. PLC technology is chosen for data communication between the smart meters and the data concentrator, while GPRS technology is used for transferring the data from the data concentrator to the utility's data center (Gungor et al. 2011). ENEL, the Italian electric utility, chose PLC technology to transfer smart meter data to the nearest data concentrator and GSM technology to send the data to data centers.

Advantages:

PLC can be considered as a promising technology for smart grid applications due to the fact that the existing infrastructure decreases the installation cost of the communications infrastructure. The standardization efforts on PLC networks, the cost-effective, ubiquitous nature and widely available infrastructure of PLC, can be the reasons for its strength and popularity (Paruchuri et al. 2008). Data transmissions are broadcast in nature for PLC, hence, the security aspects are critical. Confidentiality, authentication, integrity and user intervention are some of the critical issues in smart grid communications. HAN application is one of the biggest applications for PLC technology. Moreover, PLC technology can be well suited to urban areas for smart grid applications, such as smart metering, monitoring and control applications, since the PLC infrastructure is already covering the areas that are in the range of the service territory of utility companies.

Disadvantages:

There are some technical challenges due to the nature of the power line networks. The power line transmission medium is a harsh and noisy environment that makes the channel difficult to be modeled. The low-bandwidth characteristic (20kbps for neighborhood area networks) restricts the PLC technology for applications that need higher bandwidth, furthermore, the network topology, the number and type of the devices connected to the power lines, wiring distance between transmitter and receiver, all, adversely affect the quality of signal, that is transmitted over the power lines (Gungor et al. 2011). The sensitivity of PLC to disturbances and dependency on the quality of signal are the disadvantages that make PLC technology not suited for data transmission. However, there have been some hybrid solutions in which PLC technology is combined with other technologies, i.e., GPRS or GSM, to provide full-connectivity not possible by PLC technology.

2.2.5 Digital Subscriber Lines

Digital Subscriber Lines (DSL) is a high speed digital data transmission technology that uses the wires of the voice telephone network. It is common to see frequencies higher was than 1MHz through an ADSL enabled telephone line (Laverty et al. 2010). The already existing infrastructure of DSL lines reduces installation cost. Hence, many companies chose DSL technology for their smart grid projects. The Current Group, a Smart Grid Solution Company, has collaborated with Qwest to implement a Smart Grid project. Qwest's existing low latency, secure, high capacity DSL network will be used for data transmissions. Xcel Energy's SmartGridCity project has also proved the interoperability of the technology by utilizing the Current's intelligent sensors and OpenGrid platform and Qwest's DSL network. A smart metering project has been carried out for Stadtwerke Emden-Municipal Utilities in Germany by Deutsche Telekom. In the project, Deutsche Telekom is responsible to provide the data communications for electric and gas meters. A communication box will be installed at the customer premises and the consumption information will be transmitted over DSL to Stadtwerke Emden (Gungor et al. 2011). Deutsche Telekom offers many services in this project, such as reading consumption data, installation and operation, data transmission, etc. However, the throughput of the DSL connection depends on how far away the subscriber is from the serving telephone exchange and this makes it difficult to characterize the performance of DSL technology (Laverty et al. 2010).

Advantages:

The widespread availability, low cost and high bandwidth data transmissions are the most important reasons for making the DSL technology the first communications candidate for electricity suppliers in implementing the smart grid concept with smart metering and data transmission smart grid applications.

Disadvantages:

The reliability and potential down time of DSL technology may not be acceptable for mission critical applications. Distance dependence and lack of standardization may cause additional problems. The wired DSL-based communications systems require communications cables to be installed and regularly maintained, and thus, cannot be implemented in rural areas due to the high cost of installing fixed infrastructure for low-density areas.

To conclude, wired technologies, such as DSL, PLC, optical fiber, are costly for wide area deployments but they have the ability to increase the communications capacity, reliability and security. On the other hand, wireless technologies can reduce the installation costs, but provide constrained bandwidth and security options.

2.3 SMART GRID KEY PLAYERS

Smart houses and smart grid technologies are gaining momentum in energy power market lately. It is a new opportunity for different kinds of companies to develop new products and services. There are three dominant players that will receive the big piece of pie of smart grid/house sector, i.e., electric utilities, telecom operators and company developing intelligent devices for energy control: the first are the leading players, the others have

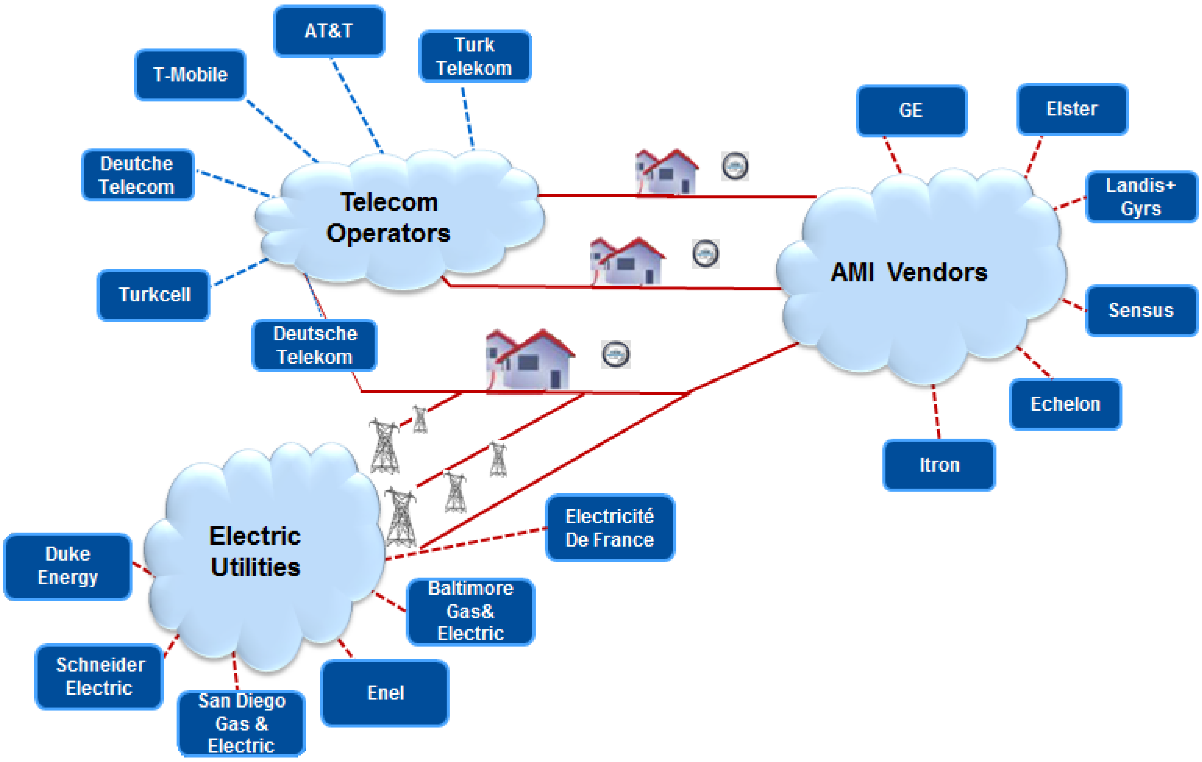


Figure 2.4: Smart Grid Key Drivers, Gungor et al. (2012)

a key role since they provide the backbone of the communication infrastructure and the end-user apparati as depicted in Figure 2.4. In the following part, this thesis will focus on those which can be considered the key players in the SG/SH arena, i.e. utility and communication companies Gungor et al. (2011).

2.3.1 Telecom Operators

Smart grid cannot be considered as smart without an advanced communication infrastructure. The major problems of existing grid have been the lack of communication techniques between devices and systems for better, reliable and secure power delivery and improved customer satisfaction. The achievement of inter-operability between smart grid components and management of data traffic produced by advanced appliances can be successfully carried out with the integration of robust, flexible communications network. Smart grid means a new area for business opportunities for telecom operators, hence they have to take a big responsibility to build and manage the communication infrastructure for advanced functions of smart grid systems. Many electric utilities have been struggling

Table 2.1: Telecom Operators and Smart Grid, Gungor et al. (2012)

Name / Country	Application	Techniques	Pilot Project	Participants
T-mobile USA	AMI	GSM	No pilot yet	Echelon
Telefonica Spain	AMI	GPRS,SMS,DSL, ZigBee, Satellite	No pilot yet	Endesa
British Telecom	AMI	Long range radio network	200,000 smart meters	Arqiva, Detica, Sensus
Telecom Italia	Home Energy Management	GSM, ZigBee	Trial phase of 32 million smart meters	Enel, Electrolux, Indesit
DoComo-Japan	Home Energy Management	3G	No pilot	NEC, Sekisui House, NAMCO BANDAI
China Mobile	AMI	GSM	No pilot yet	China Southern Power Grid,Huawei
Mobiltel-Bulgaria	AMI	RF	No pilot yet	Sensus
Vodafone Germany	Smart Metering	DSL, GPRS	12,000 smart meters	Alcatel Lucent, DIEHL Energy Solutions
Vodafone-UK	AMI	GPRS	Over one million trial installation of gas meters	British Gas, Landis Gyr, OSIsoft, SAP
Vodafone-New Zealand	Smart metering	GPRS	Deployment of smart metering	AMS
AT&T-USA	AMI	RF	800,000 smart meters	SmartSynch, Texas-New Mexico Power
Verizon-USA	AMI	RF,CDMA,Zigbee, WiMAX,802.11	No pilot yet	SmartSynch Texas-New Mexico Power
Orange-UK	AMI	GPRS	2.000 smart meters deployement	National Grid
Etisalat-UAE	Femtocell	Using femtocell as a small celluar base station	No pilot yet	Alcatel-Lucent
Qwest-US	AMI	DSL,PLC,BPL	Xcel Energy's SmartGridCity	CURRENT
Telenor-Norway	AMI	GPRS, GSM, SMS	In phase of deployment in Sweden, Denmark, Norway and Netherland	Siemens, HT, PowerAR, Landis Gyr
Deutsche Telekom Germany	AMI	DSL/Wireless	200 meters deployment	Stadtwerke Emden

with the complexity, reliability and maintenance costs of their own private networks, thus, many of them have signed agreements with telecom operators to hand over this big responsibility. Table 2.1 shows an analysis of the involvement of the telecom operators into smart grid sector Gungor et al. (2011).

2.3.2 Utility Companies

The reaction of utility companies to innovations for a smarter grid is the slowest among the others. The cost, long-term return on investment and reliability issues make them rethink before any investments for the new infrastructure of the power grid. However, the demand response applications of smart grid will make it easy to manage the power grid and to prevent massive peak demands for the utility company. The best way for utility companies to involve in the smart grid process is to understand the cost-benefits of the new system and investigate which communication technology best will serve for the need of smart grid infrastructure. They also need to make strategic partnerships to handle requirements of smart grid better. Table 2.2 briefly shows the investments and strategic partnerships of electric companies Gungor et al. (2011). They should involve in smart grid standardization efforts to make the smart grid a reality. Some electric utilities have taken incremental steps towards smart grid; Electricité De France (EDF) is in the pilot phase of its smart grid project with 300,000 meters, 7,000 concentrators deployment with the estimated cost of USD 6.4 billion; Southern California Edison's Edison SmartConnect project contains 5.3 million electric meters deployment between 2008 and 2012 with the cost of USD 1.63 billion; Pacific Gas & Electric's SmartMeter project contains 5.3 million electric meters and 4.5 million gas meters with the cost of USD 2.2 billion Gungor et al. (2011).

2.3.3 Customers

In the past, customer relationship with utilities was not an expected phenomenon. However, the smart grid puts customer adoption and satisfaction to the center of the system. Customer participation and feedback to the system will enable advanced applications to operate properly; the implementation of energy efficiency programs, demand respond and outage management applications will be effectively achieved through active customer participation to the system. Home energy management systems and demand response

Table 2.2: Electric Utilities and Smart Grid, Gungor et al. (2012)

Name / Country	**Project Objective**	**Technology**	**Participants**	**Pilot Project**
Southern California Edison-USA	AMI	RF Mesh, ZigBee	eMeter, Itron, IBM	Edison SmartConnect 5 million electric meters
Electricité De France(EDF)-France	AMI	Not mentioned yet	IBM Atos Origin Elster Actaris Landis Gyr EPRI	Pilot in Indre-et-Loire department
TEDAS-Turkey	AMI	Not-mentioned	Elektromed	1.500.000 smart meter deployment
KIBTEK-Turkey	AMI	Not-mentioned	European Union	132.000 smart meter deployment
Enel-Italy	AMI	Not mentioned	Alcatel, Current, Ericsson Espana	RWE AG Address Project
Schneider Electric-Germany	AMI	Not mentioned	ComEd, Pjm,Metropolitian Energy BOMA, Chicago	BOMA Chicago Project
Baltimore Gas & Electric-US	AMI	PLC	Accenture PLC Oracle Silver Spring Networks	1.840.000 smart meters
San Diego Gas & Electric-US	AMI	ZigBee	Itron(providing the meters),Oracle, Microsoft(SQL Server for Meter Data Management)	Smart Metering Project 572 million 2.300.000 meters
American Electric Power-US	AMI	RF Mesh network	Silver Spring S&C Electric and Cooper Power Systems, IBM	110.000 meters
PG&E Enersis-US	AMI	RF mesh, PLC	Silver Spring GE,Landis Gyr Aclara	SmartMeter program
Lake Land Electric-US	AMI	Wireless Technologies	Sensus, Science Applications International Corporation	125.000 smart meters
PPL Electric Utilities-USA	AMI	WiMAX	Alvarion, Alcatel-Lucent	1.3 million meters
Portland General Electric	AMI	Wireless network	Sensus	800,000 smart meters
PECO Energy Company	Smarter energy grid project	Wireless Communication	Sensus	600.000 smart meters,
Austin Energy	Smart Grid 1.0 deployment project	Combination of fiber and wireless	GE Energy,Elster Landis Gyr, Cellnet+Hunt's	500.000 devices installed
CenterPoint Energy	AMI	Not mentioned	Not mentioned	2.2 million smart meters
Consumers Energy	Smart Street program	Not mentioned	Michigan Public Service Commission, Honey well Utility Solutions, Silver Spring Networks,Cascade Renewable Energy	1.8 million electric meters
Oklahoma Gas and Electric Company (OG&E)	Smart grid project	Wireless communications network	EnergyICT (MDMS) Corix Utilities,Silver Spring, Comverge	42.000 smart meters

programs will improve energy efficiency and system reliability better with customer participation. However, smart grid concept is not known at the nation level and many of them do not have positive thoughts towards smart grid. The first step of the utilities should be education of customers about the advantages of smart grid system and the ways how they can contribute to the system for energy savings and respond to energy demand. Consumer Education Case Study programs helps customer to provide a better view of smart grid benefits. For instance, PG&E has carried out Consumer Education Case Study that is resulted in increased awareness of smart grid and its benefits. Energy Demand Research Project (EDRP) is a two year large-scale trial which tests the consumer response to the feedback of their energy usage with 26 trial groups and 6 different categories across the Britain Gungor et al. (2011). Providing two-way information flow to the customer and enabling them more decision making ability and control about energy usage patterns will shape their judgements towards smart grid positively.

2.3.4 Government

Smart grid concept can be a reality with the cooperation of electric utilities with IT companies. The role of government is to provide the creation of working groups and organizations while other various perspectives integrate their forces to build such a complex system. Providing financial support and R&D funding, encouraging agreements for smart grid projects should be actions taken by government. The government needs to accelerate the development process of standards as many protocols cannot communicate with each other. This situation lowers the implementation process of smart grid. On the other hand, in most countries, customer does not have the chance to purchase the electricity from the provider that he wants. Thus, government can arrange some regulations towards the flexibility and transparency of electricity market.

2.4 SMART GRID COMMUNICATIONS REQUIREMENTS

The communication infrastructure between energy generation, transmission, and distribution and consumption requires two-way communications, inter-operability between advanced applications and end-to-end reliable and secure communications with low-latencies and sufficient bandwidth (Sauter & Lobashov 2011); Moreover, the system security should be robust enough to prevent cyber-attacks and provide system stability and reliability with advanced controls. In the following, major smart grid communication requirements are presented.

2.4.1 Security

Secure information storage and transportation are extremely vital for power utilities, especially for billing purposes and grid control (Yang et al. 2011). To avoid cyber-attacks, efficient security mechanisms should be developed and standardization efforts regarding the security of the power grid should be made.

2.4.2 System Reliability, Robustness and Availability

Providing the system reliability has become one of the most prioritized requirements for power utilities. Aging power infrastructure and increasing energy consumption and peak demand are some of the reasons that create unreliability issues for the power grid (Moslehi & Kumar 2010). Harnessing the modern and secure communication protocols, the communication and information technologies, faster and more robust control devices, embedded intelligent devices (IEDs) for the entire grid from substation and feeder to customer resources, will significantly strengthen the system reliability and robustness (Moslehi & Kumar 2010). The availability of the communication structure is based on preferred communication technology. Wireless technologies with constrained bandwidth and security and reduced installation costs can be a good choice for large-scale smart grid deployments; on the other hand, wired technologies with increased capacity, reliability and security can be costly (Yang et al. 2011). To provide system reliability, robustness and availability at the same time with appropriate installation costs, a hybrid communication technology mixed with wired and wireless solutions can be used.

2.4.3 Scalability

A smart grid should be scalable enough to facilitate the operation of the power grid (Gungor & Hancke 2009). Many smart meters, smart sensor nodes, smart data collectors, and renewable energy resources are joining the communications network. Hence, smart grid should handle the scalability with the integration of advanced web services, reliable protocols with advanced functionalities, such as self-configuration, security aspects.

2.5 WIRELESS SENSOR NETWORK TECHNOLOGY AND SMART GRID

Smart power grid is such a distributed system that many of its components are spread over a wide range of area. The continuity of the reliable and secure power delivery between power generation, distribution, transmission units and consumer premises, should not be affected from the decentralized nature of the power grid system. A great coordination between distributed components of the power grid is needed for the safety, continuity and reliability of the electricity delivery system. Otherwise, any problems, e.g., equipment failures, power outage, slow response to the failures, may end up as a massive blackout and huge damage to the system and the daily lives of the citizens. This requirement arises the question what is the most appropriate technology that will keep this fragile and complicated system coordinated enough to be aware of the equipment failures beforehand to prevent unreliable, unsafe electricity delivery or power disturbances/power outages.

Wireless sensors networks (WSNs) are referred as the most proper solution for the realization of the smart grid due to the its special characteristics.

a. Expandable network range: Wireless communication and mesh network topology is established between sensor nodes. This capability enables the range of WSNs to be expandable enough to cover the geographically distributed power delivery systems.

b. Low-cost deployment: WSNs consist of low-cost sensor nodes. These nodes can be spatially distributed over the wide-range power delivery systems where the other communication technologies, e.g., cellular, satellite, wired, do not exist or difficult to be deployed. Hence, the entire power network can be monitored with reduction in deployment and maintenance costs which is the main reason that WSN technology is chosen over wired technologies.

c. Self Configuration Capability: The self configuration feature provides WSNs to be rapidly deployed over a wide geographical area and form a robust fault tolerant sensor network.

Consequently, the integration of WSN technology to smart grid system will provide efficient, low-cost, flexible, expandable communications network for advanced monitoring, analysis and data transmission purposes. However, some inadequacies of sensor nodes and specific smart grid environmental conditions may place some obstacles in the way of the successful, reliable and secure data transmissions between smart grid components. Sensor nodes are usually battery-powered which means that the energy limitation prevents a long life-span, and, advanced memory and processing capabilities of sensor nodes. Furthermore, harsh smart grid environmental conditions, e.g., noise, fading and interference from electric power equipment, make reliable communications impossible to achieve with wireless sensor nodes. The most important obstacle can be recognized as the existence of different QoS requirements of different smart grid applications. However, there have been conducted some researches for unexploited areas in WSNs applications. It is pointed that the appropriate link quality measurements, multiple wireless channel models, and successful QoS differentiation are the essential criteria to design reliable and energy efficient WSNs in smart grid environment (Felemban et al. 2006), (Gungor et al. 2010), (LaI et al. 2003).

2.6 RESEARCH CHALLENGES FOR WSNs-BASED SMART GRID APPLICATIONS

WSN has been one of most exciting and attractive topics in recent years due to the low-cost, scalable, mobile, withstanding characteristics of sensor nodes and the availability of a variety of applications in the area of monitoring, control and sensing. With the advances in miniaturization, WSN technology eases the integration of the electronic networks into everyday applications which have significant effect in increasing the quality of lives of human beings. Sensor nodes are battery-powered and thereby have limited resources which result in some limitations that affect the functionality and the life span of the sensor network. Hence, energy efficiency becomes one of the major concerns of WSN. Scalability, QoS, environmental conditions, unreliable wireless links etc. are some of the other challenges of WSN-based smart grid applications. Here below, we briefly explain major research challenges for WSNs-based smart grid applications Sahin & Gungor (2012).

a. **Interoperability:** Energy generation units, distribution networks, energy consumers all are important parts of the smart grid that need advanced communication techniques among each component to exchange information. To provide such a complex communication infrastructure will be very challenging if standard-based and interoperable communication protocols are not used.

b. **Memory Consumption:** Sensor nodes have limited memory capacity. Available memory capacity often limits the functionality of the system. The system software running on the sensor nodes, the communication protocol and complex computations should be chosen wisely to decrease memory consumption.

c. **Power Management:** Power management is a challenging task since the sensor nodes are battery powered. Minimizing the energy consumption is very important since performing computations, sensing the environment and communication with other sensor nodes are quite complex processes of sensor nodes, which mayincrease energy consumption. To this end, power-efficient communication protocols and advanced sleep schedules can be used to prolong the network lifetime (Osterlind et al. 2007).

d. **Dynamic Pricing and Configuration Updates:** Energy management systems pose another challenging task, that is the process of dynamically updating price information. In (Erol-Kantarci & Mouftah 2010), it is stated that better billing can be accomplished by using dynamic price rates according to energy demand, which could result in load oscillation.

e. **Security:** In the smart grid, sensitive and confidential data can be generated from smart meters and smart home appliances. This data should be safely transmitted to the power utility's data servers to prevent unauthorized access. Hence, secure end-to end communication protocols should be used to protect the confidential data against cyber and physical attacks. Security for wireless sensor networks is influenced by a number of factors, such as deployment strategy, system architecture, underlying communication infrastructure, the node platform and the application. It is likely that a new WSN deployment would not be able to use existing solutions without some degree of customization and further evaluation.

f. **Quality of Service Requirements (QoS):** WSN-based smart grid applications can have different quality-of-service (QoS) requirements and specifications in terms of reliability and communication delay. For example, in the case of alarm conditions and dynamic pricing notifications, it is important to receive the data in a timely manner. Data with long delay due to processing can be outdated and result in wrong decisions in the monitoring system. Hence, assigning appropriate QoS requirements for WSN-based smart grid applications is essentialfor providing a reliable monitoring system.

g. **Unreliability of Wireless Links:** The significant levels of unreliability and asymmetry of wireless links adversely affect the communication performance of WSNs. Signal attenuation by the distance, asymmetry in wireless links, non-uniform radio signal strength, fading and multipath effects are some of the causes of the unreliable nature of the wireless links (Shin, Ramachandran & Ammar 2007). Most of the proposed routing protocols work well for ideal conditions (Erol-Kantarci & Mouftah 2011). However, the harsh environmental conditions in the smart grid environment cause these mechanism to perform very poorly. Link quality estimation gains an important value to choose the best route for the data packets in WSN (Krogmann et al. 2009). The measurement, characterization and the utilization of the wireless link quality with less energy consumption of the sensor nodes (LaI et al. 2003) is a great motivation for researchers to find the link quality of the sensor networks. Real-time decision making processes require on-time packet delivery, hence, any latency related to this issue can lead to some serious problems in the power grid (Erol-Kantarci & Mouftah 2011). Routing and MAC protocols should be implemented wisely for mission critical WSN-based smart grid applications.

h. **Data Management:** A huge amount of data is generated from smart meters and smart home appliances. This confidential and sensitive data should be transmitted to the power utility centers securely. The communication network should be capable of performing the complex tasks related to transmission, collection, storage, and maintenance of this huge amount of data (Depuru et al. 2011).

i. **System Integration:** Compression and aggregation of data and thus preventing data overload, data extraction to create information from disparate data sources and integration with the existing SCADA system are critical requirements.

j. **Large Scale:** Covering wide geographical areas with large numbers of sensor nodes creates scalability challenges, which necessitate the use of intelligent and efficient aggregation and summarization techniques to manage the extensive data gathered from the sensor nodes (Pendarakis et al. 2007). The large scale sensor networks may lead to some delay-related problems for some mission-critical applications. Hence, the choice of the routing protocols should be done wisely.

k. **Heterogenous Communication Techniques:** WSN-based smart grid applications require a reliable, resilient, secure, flexible, cost-effective communication system (Ullo et al. 2010). The challenge is that there is no single communication technique that provides all these requirements simultaneously. Hence, a combination of communication techniques should be applied. However, the heterogeneity will create some additional problems, such as the interoperability between these techniques.

l. **Transmission Line Conductor Galloping:** A "galloping" condition is defined as a low frequency vibration of the conductor in the range of about 0.1 Hz to 1 Hz for a predetermined length of time (e.g. between 0.1 and 300 s, or several cycles or more). Effective detection of conductor galloping in overhead lines is important, as galloping can cause mechanical failure of the conductor or structure, or breakdown of the insulation between conductors on different phases. Research effort have focused on anti-vibration or damping schemes (Diana et al. 2005), (Wang et al. 2001), i.e., avoidance, but not detection of galloping.

m. **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 timeously and preferable continuously is essential to system integrity and maximizing service life of equipment (Yang et al. 2011). 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.

n. **Energy Harvesting for Powering Distributed Sensors:** Sensor nodes require an energy source. The typical power supply for a stand-alone sensor, i.e. batteries, is not a viable option. A solution being researched is energy harvesting from any available sources near to a sensor node such as solar, thermal, vibrations, magnetic or electric fields as discussed in (*Energy harvesting electronic solutions for wireless sensor networks and control systems* 2010). Other solutions are offered by methods utilized under HV conditions, using an optical source (Svelto et al. 2000) and a current transformer source (Gang et al. 2001).

2.7 Smart Grid Applications and Communication Requirements

2.7.1 Substation Automation

Substations are key elements of the power grid network and all their devices are monitored, controlled and protected by Substation Automation Systems (SASs). SAS collects the data and performs actions on it allowing robust routing of power from generators to loads through the complex network of transmission lines. The communication network

Table 2.3: Wireless sensor network applications in smart grid environments, Sahin & Gungor (2012)

Applications	Power Grid Sides
Wireless Automatic Meter Reading (WAMR)	Consumer Side
Residential Energy Management(REM)	Consumer Side
Automated Panels Management	Consumer Side
Building Automation	Consumer Side
Demand Side Load Management	Consumer Side
Process Control Monitoring	Consumer Side
Properties Control Monitoring	Consumer Side
Equipment Management and Control Monitoring	Consumer Side
Equipment Fault Diagnostics	T& D Side
Overhead Transmission Line Monitoring	T&D Side
Outage Detection	T&D Side
Underground Cable System Monitoring	T&D Side
Conductor Temperature and Dynamic Thermal Rating Systems	T&D Side
Animals and Vegetation Control	T&D Side
Real-time generation monitoring	Generation Side
Remote monitoring of wind farms	Generation Side
Remote monitoring of solar farms	Generation Side
Power Quality Monitoring	Generation Side
Distributed Generation	Generation Side

plays a critical role for SAS, to have full control and monitoring of the real time operating conditions and performances of substations. A highly reliable, scalable, secure and cost effective communication network is a prerequisite to prevent possible disruptions, e.g. power disturbances and outages. Wireless communication technologies, wireless mesh networks and WiMAX, are the communication technologies that can be used for SASs. Cellular technology can be used for remote monitoring of substation equipment; GPRS can be used for performing non-critical information exchange between distribution energy resources (DER). Wireless LAN (Local Area Network) can be used for monitoring, protection and control of distributed energy resources, especially for remotely located small substation and DERs, where data rate requirements and radio interferences are comparatively less. The National Institute of Standards and Technology (NIST) has recognized the IEC 61850 standard for substation automation and protection applications in the smart grid environment, which proposes Ethernet based communication networks to achieve interoperable SASs Higgins et al. (2011). IEC 61850 brings an object-oriented representation of the power system by separating the functions of power substation into monitoring, control and protection Higgins et al. (2011). Furthermore, IEC 61850 brings many advantages to substation automation systems such as, the complexity of utility automated solutions, and the operational and maintenance costs are reduced; the cost of copper wiring are provided with the proposition of an Ethernet-based communication network between process level switch-yard equipment Higgins et al. (2011).

Communication Requirements of SAS:

The communication requirements of substation automation are shaped by the hazardous electrical environments. The wired technologies need high protection from the problematic currents on the ground, hence wireless or fiber optic technologies are preferred mostly Asuncion & Newman (2007). On the other hand, the latency requirements must be low, e.g., less than 100 milliseconds, to prevent communication from timing out.

2.7.2 Overhead Transmission Line Monitoring

Overhead Transmission Line Monitoring is one of the most important T&D-side smart grid applications since transmission lines are vulnerable to icing, overheating and lighting strikes, which can adversely affect the lives of citizens. Hence, to monitor T&D systems, wireless senor nodes are deployed on some parts of the transmission lines, and communicate with the relay node to transmit the monitoring data. The relay node can be serviced by GSM/GPRS/UMTS as proposed in Hung et al. (2010), to send the collected data via cellular communication technologies to the control center.

Communication Requirements of Overhead Transmission Line Monitoring:

The communication requirements for overhead transmission line monitoring systems are depending on the network model, number of nodes, and the preferred communication technologies. Importantly, a large portion of energy is flowing through the transmission lines, hence, overhead transmission line monitoring systems should support reliable, secure, effective and real-time communication to respond to emergency situations quickly. According to the network model that is proposed in Hung et al. (2010), it takes 73s to send information from the relay node to the sink node in a 100 node network model with hybrid communication technologies, e.g., ZigBee, GPRS, etc.

2.7.3 Home Energy Management (HEM)

HEMs focus on the power management on consumer side, where home appliances can be monitored and controlled to balance and optimize the power supply and consumption. HEMs basically consist of smart meters, smart appliances, in-home displays and advanced control systems. The fundamental task of the HEM system is energy efficiency, data measurement and transmission. The real-time consumption data gathered from each appliance is measured and transferred to a data concentrator back to the utility. Hence, statistical analysis, intelligent advice generation, various kind of query support and the view of consumption data and electricity pricing can enable in-home displays to inform customers about their consumption behavior. Mesh topology can be used in HEM systems as it has many advantages due to the higher data reliability with multiple transmission paths.

Communication Requirements of HEM:

The communication needs of HEM systems on customer premises can be handled with low-power, short-distance technologies, such as ZigBee, Bluetooth and HomePlug. There is no need for a large amount of bandwidth or communication speed, since such applications are not counted as mission critical. Verizon declares that the reasonable latency time for in-home applications should be between 2 to 15 seconds Asuncion & Newman (2007). Since ZigBee is the predominant technology used in most installations and it offers flexible, low-power usage and low-cost deployment capabilities, it seems to be the best candidate for HEM systems.

2.7.4 Advanced Metering Infrastructure (AMI)

Advanced Metering Infrastructures create a two way communications network between smart meters and utility systems and the integration of advanced sensors, smart meters, monitoring systems, computer hardware, software and data management systems, thus enabling the collection and distribution of information between meters and utilities, allowing consumer participation in managing energy consumption Paudyal et al. (2011), Sauter & Lobashov (2011). AMI does not only mean the physical deployment of smart meters, but it also is a complicated communication network and IT infrastructure, including many systems, such as a Meter Data Management System that handles the huge amount of data and manages the raw data, to create meaningful information and messages for customers, assisting them in using energy intelligently. Hence, consumer awareness, interactive services for regulation of energy demand, avoidance of electricity-related frauds and more timely and precise billing services are the advantages of AMI system Benzi et al. (2011). Figure 2.5 summarizes the evolution from the early automatic meter reading (AMR), characterized by one-way communication, to the advanced metering infrastructure (AMI), incorporating two-way communications, and to the smart grid with intelligent applications and communication infrastructure. The choice of the communication technology for AMI

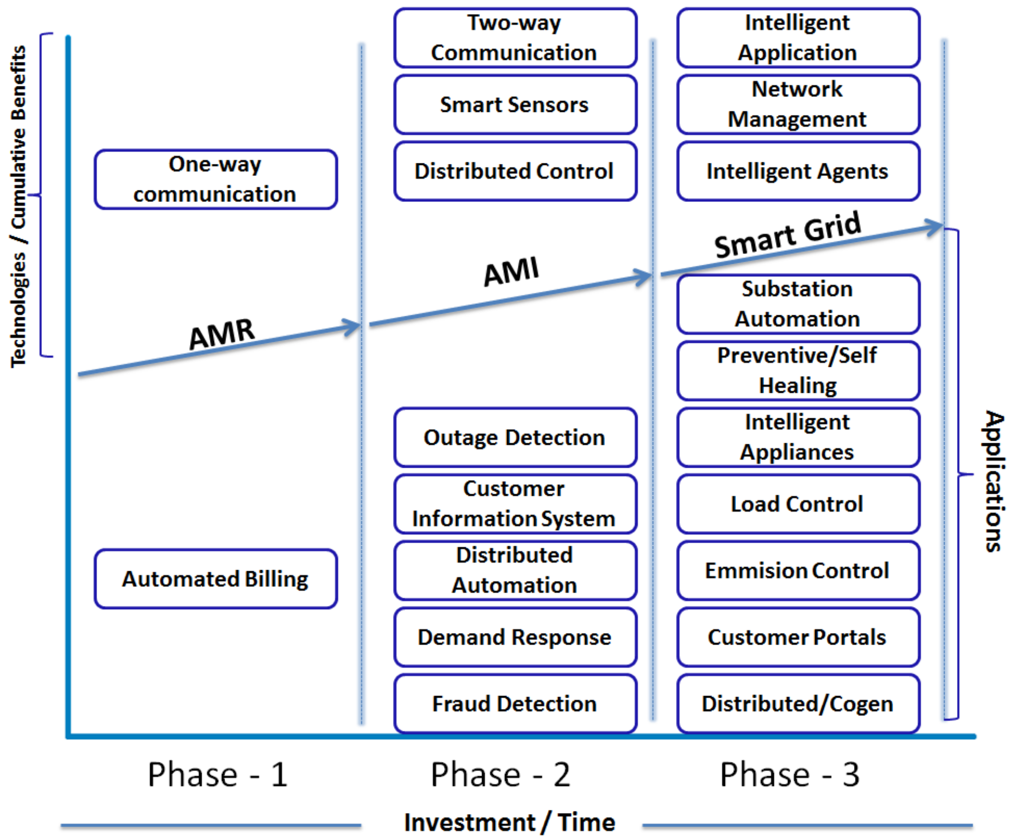


Figure 2.5: Smart Grid Evaluation Process, Gungor et al. (2013)

depends on the coverage and the number of customers per area, the availability of the Internet connection, the expected energy efficiency, scalability, the required data rate and the expected communication delay, etc. Figure 2.6 shows some possible communication from residences to data collector units and from data collector units to meter data management systems in the AMI.

Some benefits emanating from using AMI are:

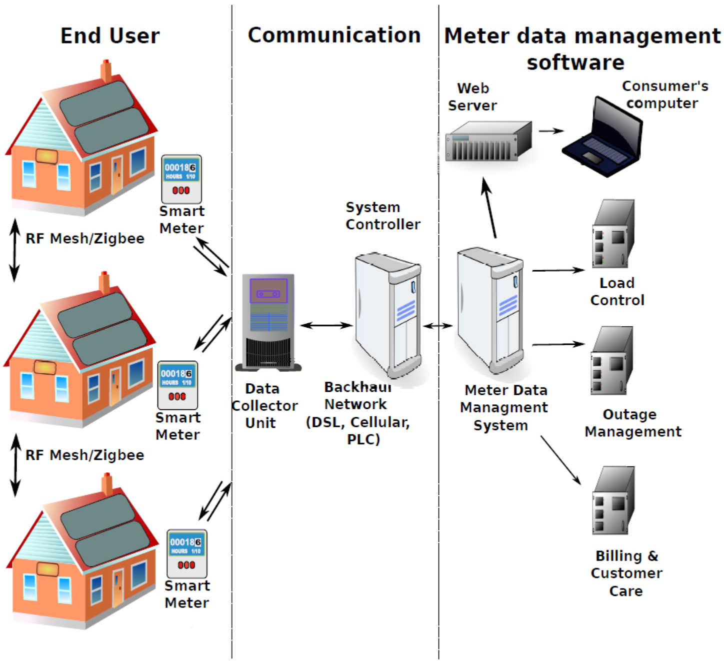


Figure 2.6: The detailed architecture of an Advanced Metering Infrastructure, Gungor et al. (2013)

a. *Reading cost*: Remote operations prevent incorrect manual readings and eliminate costly periodical readings.

b. *Real-time consumption information*: The customers can view the real-time consumption information and real-time pricing options via home displays/dashboards and shape their consumption behaviours according to these feedbacks. This will result in shifting loads from periods of high demand to those of lower demand, hence both customers and utility companies will benefit from the optimization of energy production, transmission and distribution.

c. *Multi-utility service*: Multiple services can be managed at the same time, such as electricity, heating, water and gas.

d. *Multi-vendor service*: Multiple vendors can share AMI, offering their services to customers, which can select the best market proposals, eventually changing them in real time.

Communication Requirements of AMI:

Communication requirements differ according to the communication technology chosen for AMI deployments. Low-latency and higher bandwidths are essential for some AMI applications. The latency should be around 12-20 ms for real-time metering Yan et al. (2012). Power Line Communication technology (PLC) is widely diffused, especially in urban areas, because of its use of the existing power lines. However, it may be insufficient for some real-time applications requiring bandwidths up to 100Kbps per device Asuncion & Newman (2007). RF mesh and GPRS technology for rural AMI deployments need some coverage requirements due to the insufficient meter density.

2.7.5 Wide-Area Situational Awareness Systems (WASA)

WASA can be defined as the integration of a set of technologies for effective power system monitoring and providing an overall, dynamic picture of the functioning of the grid Asuncion & Newman (2007). Wide area monitoring and situational awareness is one of the key functions of smart grids, since achieving reliability, security and inter-operability among so many interconnected systems and devices is a must for utilities. Furthermore, any abnormalities such as a disturbance in power supply can result in a widespread problem that threatens the overall system reliability and security. Synchrophasors are regarded as new wide area measurement technologies. The primary task of synchrophasors is to measure the different portions of the power system and put these measurements on the same time base, enabling a view of the whole power system at the same time and thus simplifies the comparison of different portions of the power system in real-time. Currently, Florida Power and Light and Alcatel-Lucent are supporting synchrophasor deployments.

Communication Requirements of WASA:

The latency prerequisite for real-time monitoring and control is strict. Synchrophasors is one of the wide area measurement technologies that facilitate the integration of intermittent and renewable resources and improve system modeling and planning. The communication requirements of synchrophasors depend on the nature of data being transmitted. For example, latency requirements are very low for real-time monitoring and control. Alcatel-Lucent cites a maximum latency of 20 milliseconds Asuncion & Newman (2007), while

UTC and Avista suggests that it should be below 200 milliseconds Asuncion & Newman (2007).

2.7.6 Demand Response Management

Demand response management (DRM) entails the control of the energy demand and loads during critical peak situations to achieve a balance between electrical energy supply and demand, thus obtaining a better utilization of the available energy and more reliable and cheaper operation of the whole power system. Customers can participate in the energy market competition by changing their energy consumption approach instead of being passively exposed to fixed prices, resulting in profits by both the companies and end-users Cecati, Citro, Piccolo & Siano (2011*a*). Improving system reliability and encouraging energy efficiency are the expectations from Demand Response (DR) programs. Different DR programs are examined in Cecati, Citro & Siano (2011), Siano et al. (2012), such as Incentive-Based Programs (IBP) and Priced Based Programs (PBP). Time of Use (TOU) rate, Critical Peak Pricing (CPP), Extreme Day Pricing (EDP), Extreme Day CPP (ED-CPP), and Real Time Pricing (RTP) are some of the mechanisms that present different electricity prices for different times and conditions. Figure 2.7 shows price-based and incentive-based demand response options, respectively. Time of use rate, real-time pricing and critical peak pricing are explained briefly. OpenADR is a modern automated demand response system, which is an open-source reference implementation of a distributed and client-server Demand Response infrastructure Palensky & Dietrich (2011). The integration of this system will provide effective deployment of dynamic pricing, demand response and grid reliability.

Communication Requirements of DRM:

The communication requirements of DRM applications depend on its purpose. If it is used as a load balancing tool, no special requirement for low latency for data transmission is needed. However, 14Kbps to 100Kbps bandwidth is required per node/device for typical DRM programs, providing system continuity and remote turn off of smart appliances for avoiding system overloads, or simply reducing peak demands Asuncion & Newman (2007). Low-speed communication can be tolerated with DRM smart devices.

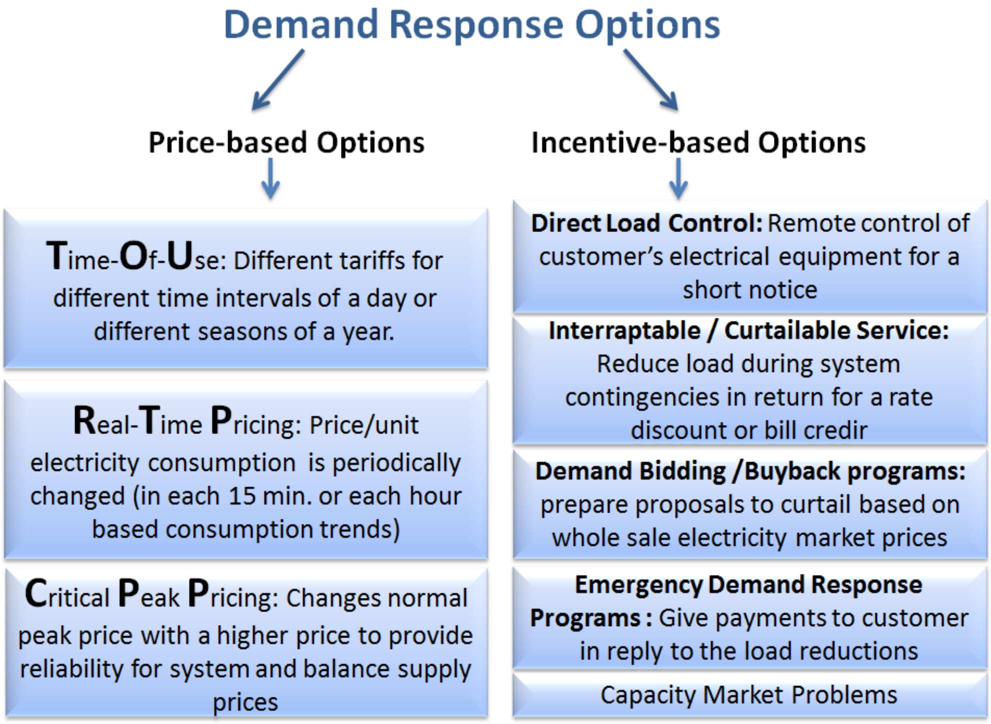


Figure 2.7: Demand Response Options with time-of-use rates, real-time pricing and critical peak pricing ,Gungor et al. (2013)

2.7.7 Outage Management

Power outage is basically defined as the loss in the electricity supply for a long or short-term period. Short circuits, failures at power stations and damage in transmission or distribution lines can be counted as reasons for power outages. Most electric utilities have been facing system outage crises. A blackout in the North-Western United States resulted in USD 6 billion losses. Hence, outage detection, management and restoration are very critical for the continuity of reliable electricity delivery, quality of service (QoS) and customer satisfaction. In restoration processes, outage management systems (OMS) are used for prediction of outage location, service restoration, additional customer services, outage analysis and prediction, crew management and reliability reporting, etc. These advanced functions can be accomplished through the integration of OMS interfaces into Supervisory Control and Data Acquisition (SCADA) systems, Automatic Meter Reading systems (AMR), Utility Call Centers, Customer Information Systems (CIS), and an Automated Mapping/Facility Management/Geographic Information (AM/FM/GIS) system. Recent discussions and activities are aimed at improving outage management processes by using smart grid technologies. AMI data integration into OMS can result in advanced customer services, improved outage management service reliability, outage notification and restoration notification. However, there have been negative business impacts on the integration of AMI and OMS in the past few years. There are many ways in which AMI can be integrated into the system and improve OMS, depending on the communications network. An outage management process is often initiated by an outage report from a customer call. However, a last-gasp or outage notification message from the AMI meter will be sent to the OMS sooner even if it is not reported by the customer, such as during the time when most customers are at work or sleep. The other advantage of the integration of AMI and OMS is the restoration notification functionality. Basically, it is used to improve the accuracy of reliability reports, or reduce the manpower needed to collect and analyze outages for the reports.

Communication Requirements of Outage Management:

Outage management systems need to be integrated with other systems and require good quality of data. The communication requirements will affect all three phases of outage management, being outage realization/detection, outage discovery and outage recovery. The main purpose of outage management is to enable utilities to respond to the power outage more quickly, hence 2000 ms latency and 56kbps bandwidth are the requirements of any outage management systems Asuncion & Newman (2007). Furthermore, integration of advanced and highly capable wired/wireless communication networks, high-powered computers and specialized software applications are essential for an advanced outage management system.

2.7.8 Distribution Automation (DA)

An electricity distribution system acts as a bridge between the transmission system and end-user premises. Electricity is delivered through distribution systems. DA is important for utilities to provide efficiency, reliability, and quality of electric services. DA is defined as the ability to automatically and remotely monitor, control, manipulate and coordinate distribution components in real time modes. According to US Smart Grid Market, DA has a vital role in the electricity distribution process. The emergence of DA provides much quicker fault corrections, reducing impacts and duration of outages. Area load control, load balancing and calculation of voltage sag are some of the advance application functions that a distribution automation system is capable of yielding. The SCADA software application system is generally used for remote manipulation, to allow dispatchers to see the system failures and make remote changes easier. With the advancements introduced by smart grid, DA can be elevated a further step, known as Advanced Distribution Automation (ADA). A more widespread communication interface and advanced integrated and coordinated protection using intelligent electronic devices, are some of the advantages of ADA.

Communication Requirements of DA:

DA is one of the mission critical smart grid applications that is not tolerant to latency. Less than 1 s of latency for alarms and alert communication and 100 milliseconds for messaging between points are preferred for some of the DA functions. The measured values for power system control signals should not exceed 15 ms Yan et al. (2012). In general, between 9.6Kbps and 100Kbps bandwidth for communications is needed for a reliable and flexible DA operation Asuncion & Newman (2007).

2.7.9 Distribution Management

Distribution networks have become too complex to be controlled and monitored manually. An advanced distribution management system (DMS) is required to provide an advanced overview of the distribution network and report abnormalities in the system. Distribution management can be defined as the ability to manage, operate and maintain the power distribution assets and provide reliable, secure and efficient power delivery. DMS has been one of the most important systems in the power industry, in other terms, it is mentioned as the actual brain of future distribution grids **?**. DMS is basically a complete ICT-based system to provide management of the overall real-time network operation. The data exchange, back-up and coordination in DMS are always achieved via the connection to a WAN. Today DMS systems are based on existing SCADA systems. The substations are remotely monitored by SCADA systems in distribution networks and the SCADA data is not available to other system, which therefore requires manual coordination. Hence, full integration of DMS is needed to achieve intelligent communication between different assets of the distribution network. Nearly 90 percent of all outages originate in the distribution network, emphasizing the importance of smart distribution technologies and prompting utilities to rebuild their SCADA systems or make investment in intelligent distribution management systems. To provide interoperability and seamless data exchange between different components of the smart grid, it is essential to adopt some standards across the communication network. There are some IEC standards (IEC 62357, IEC 61970 and IEC 61968) that describe different components and their inter-relationships with a hierarchical architecture Gungor et al. (2011). Moreover, the IEC 61850 standard aims to improve the interoperability between Intelligent Electronic Devices (IEDs) for substation automation systems.

Communication Requirements of DMS:

DMS is a comprehensive application system that is closely connected to real-time systems and provides complete management and maintenance functions for the distribution network. Thus, highly reliable and seamless communication with real time systems, a strong integration capability and advanced inter-operability between other components are the highest requirements for DMS. Furthermore, 9.6 to 100kbps bandwidth and 100 ms to 2 sec latency is needed for reliable data communications of DMS Asuncion & Newman (2007).

2.7.10 Asset Management

Electric utilities have been under pressure to assure a QoS at least cost for customers and regulators. Asset management is mainly developed as a response to this problem by offering management, automation, tracking, optimization of the work order process, field crews scheduling and field assets. Assets, replacement and maintenance costs, performance of the system, risk of failure and reliability impacts are the key drivers that can be balanced through asset management systems by the help of new technologies such as sensors, new communication infrastructures and new information and monitoring systems. Most utilities use some software programs and business models to monitor and control the plant and put asset management into practice. There are many assets that are managed through different software tools such as Asset/Work Management Systems, SCADA, and GIS. Furthermore, introducing smart grid technology adds new assets to the system to be managed for better service at appropriate cost levels.

Communication Requirements of Asset Management:

Transmission and distribution assets are needed to be managed to improve the system reliability. Equipment condition monitoring, coordinated asset management and dynamic adjustment of operating limits are the critical functions of an asset management system. Thus, advanced monitoring devices, seamless data traffic with other applications such as SCADA, GIS, meter data management systems and an appropriate bandwidth around 56Kbps Asuncion & Newman (2007) are required for better asset utilization.

2.7.11 Meter Data Management

Meter data management is a key requirement of the smart grid infrastructure, since the amount of metering data is growing dramatically due to the real time communication between smart meters and utilities' back office. The metering data needed to be stored, managed and further analyzed for dynamic pricing, better customer service, outage management, demand response and energy consumption management purposes. A meter data management system (MDMS) is responsible for storing and processing the metering data before making it available for other applications. Smart meters transfer the collected raw data to MDMS via a two-way communication network. MDMS acts as a database system for storing and analyzing metering data and furthermore has capabilities such as managing all kinds of meters (electric, gas, heat), transmitting data other than tariff and turn electricity on/off, etc.

Communication Requirements of MDMS:

The success of meter data management systems directly affects some critical applications such as demand response, outage management and dynamic pricing that need the information provided by MDMS. Hence, the communication requirements of MDMS are dependent on the other applications' requirements. For instance, demand response programs can be adversely affected by higher latencies in the required information. Thus, MDMS has to provide the analyzed information to DR as soon as possible. Basically, the bandwidth requirement is around 56Kbps and 2000 ms latency is appropriate for MDMS.

2.7.12 Renewable Distributed Energy Resources (DER) and Storage

DERs have an important role in the future power grid system and the environment, since it is the enabler technology for lower carbon imprints, lower fuel costs, and reduced power flows on transmission lines. The renewable resources, such as solar and wind, have a non-consistent nature; hence, they may not be available or meet the expected output levels all the time. In this regard, energy storage systems can provide the energy during periods of reduced production. The integration of energy storage system to DERs will increase the advantages of DERs and provide a consistent, controllable, fast acting power grid with increased reliability and power delivery capacity.

Communication Requirements of DERs:

The unpredictable nature of renewable energy resources requires fast-response, effective and advanced communication technologies for reaching instantaneous information on different electricity generation points and advanced weather forecasting. Based on studies in Asuncion & Newman (2007), the bandwidth requirement is around 9.6Kbps to 56Kbps, and latency requirement is between 300 milliseconds to 2 second, while reliability requirement is between 99 percent and 99.99 percent.

2.7.13 Vehicle to Grid (V2G)

In electric vehicles, the AC power (usually from 10 kW to 200 kW) needed for traction is supplied by a group of batteries or fuel cells. The same group, when fully charged and connected to the grid can reverse its power flow routing the stored energy from the car to the power grid, thus realizing the so called ”vehicle to grid” or V2G operation. Hence, EVs act as distributed resources in that the power previously absorbed from the grid or produced by the kinetic energy during motion can be sent back to the utility, which provide a smooth load curve and improve back-up capacity and reliability of the power system. One of the important roles of V2G is the ability to support renewable energy. Penetration and the intermittency of renewable energy can be problematic, if the fluctuating supply cannot be matched to the already fluctuating load with additional resources. In addition, V2G can provide back-up and storage for renewable energy generation.

Communication Requirements of V2G:

The communication needs of V2G should be considered for both fleet vehicles and dispersed vehicles. The communication needs of a fleet parked in one location are simple. A short-range, lower cost wireless communication techniques, such as ZigBee or Bluetooth, can be used for each parking space. Long distance communication are needed for dispersed vehicles for electronic identification of the electric utility meter that the vehicle is plugged into, billing systems and capacity identification. Hence, cellular communication technologies and land line communication can be the best for these purposes. In case of the creation of a significant new load from EVs, transmission enhancements are required to be analysed in the light of larger scale system planning or regional transmission planning. The communication needs are 5-10kbps and the data latency is a maximum of two seconds Asuncion & Newman (2007).

2.7.14 Electrical Vehicles (EVs) Charging

Electrical vehicles might be one of the key solutions to the rising energy costs, increase in oil prices and global warming issues. The energy storage seems the key technology for the realization of EVs technology Su et al. (2012). To make this technology practical and real, more and more charging stations should be built. One of the challenges is also the charging time of EVs. There are some studies towards this issue. For example, the SAE J2293, SAE J2836, SAE J2847 standards have been developed for energy transfer and communication purposes between EVs and the power grid. One of the proposed methods to reduce the charging time is increasing the charging voltage and current. However, this may cause an increase in chargers' capacity, safety, size, cost, which can limit the ultra-fast high-capacity charging. Local energy storage can be a solution for this issue, which will reduce the investments and increase the efficiency of the electrical system.

Communication Requirements of EVs:

The communication infrastructure should provide reliability, acceptable response times and appropriate throughput. In this regard, power line communications, GSM, GPRS and 3G wireless WAN technologies may provide alternative solutions for EV charging applications. The estimated latency requirement is between 2 seconds to five minutes and the bandwidth requirement for both load balancing and billing purposes will between 9.6Kbps-56Kbps Asuncion & Newman (2007).

2.8 WSNs-BASED SMART GRID APPLICATIONS

The existing and potential applications of WSNs in power grid span a wide range, including advanced metering, remote power system monitoring and control, electricity fraud detection, fault diagnostics, demand response and dynamic pricing, load control and energy management, and power automation, etc. However, the realization of these WSN-based smart grid applications directly depends on efficient communication capabilities among electric power system elements.

2.8.1 Consumer Side:

Residential Side:

a. **Wireless Automatic Metering:**The meter reading techniques, such as direct physical access to meter or visual meter reading, may not be cost-effective considering large scale of the metering infrastructure. Recent wireless sensor network platforms can offer several advantages, including decreased utility operational costs by eliminating the need for human readers, prevention of meter tampering. With the integration of wireless metering systems into the grid, real-time and dynamic pricing, which provides different charging techniques during the peak hours of a day, can be realized.

b. **Residential Energy Management:**WSN-based applications have been becoming indispensable parts of our daily lives since they have an extensive diversity from energy conservation domain, to health, safety and comfort domains. Since, the major concern of the power utilities is to take more control in reducing the peak demands and provide balance of the supply and demand match, many applications have been developed for industrial and residential customers to shift the demands to off-peak hours (Erol-Kantarci & Mouftah 2010). Energy-related applications provide real-time feedback about energy consumption behaviors to the customers which has a significant effect on reducing overall energy consumption during the peak hours or off-peak hours. Most of the big companies; Google, Microsoft, Alertme, Intel, Tendril, LG, try to get a big pie from this promising technology by developing smart energy dashboards, home energy monitors, smart plugs, smart energy meters with the integration of advanced communication technologies. The realization of WSNs in monitoring and managing power consumption is one of the most popular solution in residential energy management sector (Erol-Kantarci & Mouftah 2010).

c. **Automated Panels Management:** The generation of solar energy from solar panels will be more efficient with the integration sensor nodes to the system. According to the (*Smart Sensor Networks:Technologies and Applications for Green Growth* 2009), the sun rays can be captured in a more efficient way if sensor nodes are used to track the sun rays.

d. **Building Automation:** Building automation aims to control various of appliances's energy consumption process and enable a communication network to connect these appliances to act more efficiently and prevent redundant energy use. Lighting, heating, ventilation, air conditioning (HVAC) are some of the smart appliances that are actively participated in waste energy reduction process. WSNs reduce redundant cabling costs and complexity of the installation process of building automation systems. Recent studies have shown that it is possible to save up to 30 percent of energy consumption of buildings with efficient energy management (Guan et al. 2010).

e. **Demand Side Load Management :**Sustainable systems focus on providing a variety of energy services from low-risk energy sources. Since the demand side management is the key value of the sustainable energy systems, the optimization of the demand side management with the efficient use of the end-use energy should be performed to decrease the energy demand and the energy costs. The challenge in here is the demand-supply is not sustainable, however using advanced efficiency technologies, innovative management methodologies, integration of end-use energy efficiency and renewable energies may reduce the energy demand. WSNs can play a key role to realize such systems. For instance, Kantarci et. al proposes a load shifting mechanism by using wireless sensor network to reach the energy management units that schedules the appliances (Erol-Kantarci & Mouftah 2010).

Industrial Side:

a. **Process Control Monitoring:** With the continuous monitoring with wireless sensor nodes, real-time data transfer creates an efficient production process in industry by providing efficient energy usage, faults-minimized goods production, early-fault detection, reduced-deficient goods (Asuncion & Newman 2007), product consistency, and reduced-process time (*Smart Sensor Networks:Technologies and Applications for Green Growth* 2009).

b. **Properties Control Monitoring :**The control of the physical properties in production processes, the integration of WSN technology enables advanced monitoring with smart sensor nodes and the availability of different resources, measurement of different properties, energy savings during production and reduction of pollutants are just some of the consequences of WSN technology (Asuncion & Newman 2007).

c. **Equipment Management and Control Monitoring :** Temperature, pressure, humidity or vibration values of the industry machines that give signs about the health of the machine are measured by the sensor nodes and in case of critical data is gathered, the necessary signals are sent to make predictive maintenance possible (*Smart Sensor Networks:Technologies and Applications for Green Growth* 2009).

2.8.2 Transmission and Distribution Side

a. **Equipment Fault Diagnostics:** For generation and transmission side of the power grid, providing reliable and continued performance of power transformers is very important. Failures result in the discontinuity of power flow, unavailability of equipment and revenue loss. Equipment fault diagnostic systems with the integration of digital information technology and intelligence techniques is needed to increase in the performance of electric equipments and reduces the electrical system failures of power grid. The combination of equipment fault diagnostic systems with a cost-effective, scalable nature of WSNs will provide a reliable, efficient performance of the power grid.

b. **Overhead Transmission Line Monitoring :** Transmission line is the most critical section of the power grid. There exist many threats that will influence the safety, reliability and security features of transmission lines which have the direct effect on the economy of the country and safety and welfare of the citizens. Lighting strikes, icing, hurricane, landslide, bird damage and overheating of transmission lines are some possible threats that transmission lines may face. On the other hand, dispersed, longer, nature of the transmission lines also create difficulties in maintaining it easily. Hence, an intelligent monitoring system for overhead transmission line is required with the integration of advanced, low-cost, durable technologies. Wireless sensor network technology best fits for this kind of application as the scale of the grid expanding continuously, which will make other technologies rather than WSN technology impossible to be applicable due to the costly and inefficiency features. Hence, with WSNs technology, automatic energy transmission monitoring with fast response will be possible as smart grid offers more dynamic and distributed energy generation. Hung et. al. are pointing out the important issues in designing the network model to support overhead transmission line monitoring applications. Delay, reliability, energy efficiency are some of the factors that should be considered carefully while designing the network (Hung et al. 2010). In overhead transmission line monitoring applications, sensors deployed near the towers/poles collect the information and send it to the relay node which is deployed on the pole. Hung et. al. also presents a network model solution that is based on traffic characteristics and resource constraints in which sensor nodes transmit the data hop by hop manner to the relay node which is occupied with GSM/GPRS/UMTS device and turn it on when its needed. Hence, each relay node sends the collected data to the data collector via GSM towers.

c. **Outage Detection :** In the US, it is stated that the estimation of the annual cost of outages in 2002 is to be in the order of 79 billion dollars which is equivalent to the third of the total electricity retail revenue of 49 billion dollars (Moslehi & Kumar 2010). Hence, outages have both social and economic consequences. The lack of automated analysis, poor visibility are the basic reasons that outages in the electric system cannot be detected. Advanced sensors and monitoring systems are needed to reduce outages and increase the reliability of the power system.

d. **Underground Cable System Monitoring :**There are many failures in joints and terminations of underground cable systems as well as overhead transmission line systems. However, monitoring and maintenance of underground cables is much more harder due to the harsh characteristics of the underground. WSNs will be well suited for underground cable system monitoring to reduce the maintenance costs and provide more accurate status information of the underground cables (Yang et al. 2011).

e. **Conductor Temperature and Dynamic Thermal Rating Systems :**Power utilities pay attention to the temperature values of the cables because it is an essential measurement to get the optimum cable use. The load capacity of the cables has a direct relation with the cable conductor temperature ratings and since it is one of the key values of the power system, measuring the cable conductor temperature with smart sensor nodes will be a cost effective, reliable and flexible solution (Yang et al. 2011).

f. **Animals and Vegetation Control :**Animals and Vegetation Control is necessary to achieve expanded, safe and reliable operations for the power grid. Reducing avian interactions, taking precaution to prevent animals from damaging cables will reduce the blackouts, short circuit problems and WSNs technology will be the perfect choice to detect animals and avian interactions (Yang et al. 2011).

2.8.3 Generation Side

a. **Real-time generation monitoring:** In existing power grid, some methods are used to store the energy, such as pumped hydro, compresses air and flywheel, however they are inconvenient to store the renewable energy generated from solar and wind farms (Erol-Kantarci & Mouftah 2011). Making the energy storage decisions is quite possible with the real-time generation monitoring systems in which WSNs will be a preferred solution due to their low-cost characteristics (Erol-Kantarci & Mouftah 2011).

b. **Remote monitoring of wind farms:** Wind farms are one of the most important renewable energy resources whose performance can be easily affected by some external conditions, such as outdoor pressure and temperature values,the orientation of wind, bird collisions, etc. (Erol-Kantarci & Mouftah 2011). These external factors may have a less effect on the performance of wind farms, they can be monitored wisely. Capturing the audio and vision data in an cost-effective manner will ease the identification of external parameters on the performance of the wind farms (Erol-Kantarci & Mouftah 2011).

c. **Remote monitoring of solar farms:** Temperature value, radiation, DC voltage, weather conditions are some of the external parameters that have a direct effect on the performance of the renewable energy generation of the solar farms (Erol-Kantarci & Mouftah 2011). WSN-based remote monitoring systems will evaluate the external effects on solar farms and better influence the performance of them.

d. **Power Quality Monitoring :**The importance of the quality of power has been increased due to the bad affects of the disturbances in power quality to the safe operation of control units, the sensitivity of the electric appliances to the power quality and the deregulation of the electrical power market, etc. Power quality monitoring, which enables a continuity and increase in power quality, collects the voltage and the current data and sends these data to remote centers for further decision-making processes.

WSNs provide a low cost, efficient and reliable data communication system for power quality monitoring applications.

e. **Distributed Generation:** In (Bag et al. 2010), an application of low cost IPv6 based wireless sensor network in distributed generation is proposed. IEEE 802.15.4 link layer technology is used and all the sensor nodes are capable to communicate with other IP-based devices. The main focus is to improve the power management process by correcting the distributed generators reference signals.

Table 2.4: The Requirements of Smart Grid Applications, Asuncion & Newman (2007),Yan et al. (2012)

Application	Security	Bandwidth	Reliability	Latency
Substation Automation	High	9.6-56kbps	99.0-99.99 percent	15-200 ms
Overhead Transmission Line Monitoring	High	9.6-56kbps	99.0-99.99 percent	15-200 ms
HEM	High	9.6-56kbps	99.0-99.99 percent	300-2000 ms
AMI	High	10-100kbps per node, 500kbps for back-haul	99.0-99.99 percent	2000 ms
Wide-Area Situational Awareness Systems (WASA)	High	600-1500Kbps	99.0-99.99 percent	15-200 ms
Demand Response Management	High	14-100kbps per node	99.0 percent	500 ms-several minutes
Outage Management	High	56kbps	99.0 percent	2000 ms
Distribution Automation (DA)	High	9.6-56kbps	99.0-99.99 percent	20-200 ms
Distribution Management	High	9.6-100kbps	99.0-99.99 percent	100 ms-2 sec
Asset Management	High	56kbps	99.0 percent	2000 ms
Meter Data Management	High	56kbps	99.0 percent	2000 ms
Distributed Energy Resources and Storage	High	9.6-56kbps	99.0-99.99 percent	300 ms-2 sec
Vehicle to Grid (V2G)	High	9.6-56kbps	99.0-99.99 percent	2 sc-5 min
Electrical Vehicles (EVs) Charging	High	9.6-56 kbps	99.0-99.99 percent	2 sc-5 min

Table 2.5: WSN challenges and design objectives, Sahin & Gungor (2012)

Challenges	Design Objectives
Interoperability	Standard-based WSN Protocols and Products
Memory Consumption	Low-Overhead and Simple Protocols
Power Management	Energy Efficient Protocols and Energy Harvesting Solutions
Dynamic Pricing and Configuration Updates	Adaptive Protocols
Security	Secure Design and Protocols
Quality-of Service (QoS)	QoS-Aware Protocols and Cross-Layer Designs
Unreliability of Wireless Links	Link Quality-Aware Routing and MAC Protocols
Data Management	Data Aggregation and Compression
Large Scale	Scalable Protocols
Heterogeneous Communication Techniques	Cross-Layer Design and Hybrid Protocols

3. LITERATURE SURVEY

The increasing interest on smart grid communications have lead the academia to study on designing reliable and secure routing protocols for communication technologies used in smart grid environments. For WSN technology to be used in smart grid environment, some specific QoS requirements should be met to provide reliable data transmissions, since smart grid environment may pose some challenges, e.g., fading, obstacles, link quality variations to wireless data communications.

To overcome these challenges, dynamic-QoS-treatments, e.g., short delay, high reliability or high bandwidth for various smart grid applications, should be adopted to data communications of WSNs. In the literature, there have been some routing protocols which address the energy limitations and wireless link quality variations to provide efficient and reliable data transfers. This Section discusses some of these schemes.

Link quality estimation is one of the key requirements of WSN, since getting the proper information about the link quality is very important to choose the best path for the wireless communications (Krogmann et al. 2009) and better utilize the limited resources of sensor node, e.g., battery, processing and memory limitations. Hence, a routing protocol which is well aware of the reliability and link quality of the specific application is needed to be able to meet the requirements for efficient and reliable data transfers. Here are some of the routing algorithms which take into account these specific requirements.

The work in LaI et al. (2003) proposes the design of a routing protocol for energy-constrained wireless sensor networks. The design parameters of an energy-efficient routing protocol is specified by finding the ways how to measure, characterize, and utilize the wireless link quality. Their motivation is to obtain a good cost metric to find the link quality of the sensor network with a few measurements that will cost less energy consumption of the sensor nodes.

The work in Shin, Ramachandran & Ammar (2007) aims to understand the reasons for unreliable wireless communications and data packet losses which are well summarized as the followings; signal attenuation caused by the distance, asymmetry in wireless links, nonuniform radio signal strength, fading and multi-path effects and interference due to hidden terminal problem. Moreover, they provide suggestions on the enhancements to well-known protocols to increase the reliability levels of packet delivery.

In Krogmann et al. (2009), Krogman et. al. points out that most of the researches on link quality estimations (LQEs) have avoided the sensitivity of the protocols to the LQEs errors which results in inaccurate LQEs and error propagation in LQE-based routing metrics. Hence, they propose two classes of link quality-based routing metrics, one is related to end-to-end reachability (EER) protocols and the other is about energy consumption (EC) protocols to predict their sensitivities to LQE errors. From the experiments, they showed that while EER protocols are more prone to LQE errors on large-scale and multi-hop networks, EC metrics are robust to LQE errors.

Chen et. al. proposes link quality estimation based routing protocol (LQER) which considers both energy and link quality to avoid poor link connectivity and reduce the possibility of retransmissions to be able to increase the life-time of WSNs and data reliability in Jiming Chen & Sun (2008). Before making the routing decisions, they estimate the link quality by creating a connectivity graph based on hop count field. LQER metrics provides improvements on energy efficiency of WSN, but it does not guarantee the end-to-end deadline.

The work in Deb et al. (2003) proposes a multi-path forwarding protocol, ReInForM, to provide reliability in sensor networks by sending the multi-copied packets to the sink node through multiple paths. The information of local knowledge of sensor conditions, e.g, channel error, hops to sink, out-degree, and neighborhood at each node are used to enable a lightweight and localized mechanism for reliability in information dissemination (Deb et al. 2003). However, ReInForM is inadequate in providing service differentiation in timeliness domain.

Daabaj et. al proposes a reliability-oriented routing scheme which is based on per-hop energy balancing and probability network connectivity, and provides high success rate of packet delivery and less energy consumption in Daabaj et al. (2010).

Adaptive Forwarding Scheme (AFS) is proposed to provide service differentiation based on data prioritization which is directly related to controlling the reliability of a sensor network's communication in Bhatnagar et al. (2001). The forwarding behavior of a packet is determined according to its priority level which means that the desired reliability level is proportional to its priority, in other words, to the number of copies of a packet. However, AFS needs the global topology of the network which makes it insufficient in providing QoS provisioning in timeliness domain.

RAP protocol is designed to provide real-time communication in large-scale sensor networks (Lu et al. 2002). RAP guarantees the end-to-end deadlines of the packets by providing minimum communication and processing overhead. Since, RAP is a best-effort service, it does not guarantee the reliability requirements of data packets. In Khan et al.

Table 3.1: Comparison of Routing Protocols Based on Meeting the Reliability and Delay Requirements

Protocol	Description	Reliability Requirement	Delay Requirement	Energy Aware	Network Life Time
REAR	Reliable Energy Aware Routing	Reliability-Sensitive	Not Delay Sensitive	Energy-Aware	Extends Network Life Time
RLQ	Resource-aware and link quality based routing metric	Reliability-Sensitive	Not Delay Sensitive	Energy-Aware	Extends Network Life Time
RAP	Real-Time Communication Protocol	Not Reliability-Sensitive	Delay Sensitive	out of scope	out of scope
AFS	Adaptive Forwarding Scheme	Reliability-Sensitive	Not Delay Sensitive	out of scope	out of scope
ReInForM	Reliable Information Forwarding Protocol	Reliability-Sensitive	Not Delay Sensitive	out of scope	out of scope
LQER	Link quality estimation based routing protocol	Reliability-Sensitive	Not Delay Sensitive	Energy-Aware	Extends Network Life Time
EARA	Energy-aware routing algorithm	Reliability-Sensitive	Not Delay Sensitive	Energy-Aware	Extends Network Life Time
Breath	Adaptive protocol for industrial control applications	Reliability-Sensitive	Delay Sensitive	Energy-Aware	Extends Network Life Time
EARQ	Energy aware routing for industrial control applications	Reliability-Sensitive	Delay Sensitive	Energy-Aware	Extends Network Life Time

(2010), an energy-aware routing algorithm that considers the average energy and minimum distance values and link reversing to prevent routing holes, is proposed. When a data packet is ready to be relayed, the most appropriate sensor node, with greater energy than the average energy, and with shortest distance to the destination node is selected. Each node is aware of its location from a GPS. The proposed algorithm prolong the network life time and increase the successfully packet delivery, however, the providing end-to-end delay is out of the scope.

Reliable energy aware routing (REAR) protocol is proposed in (Shin, Song, Kim, Yu & Mah 2007) which provides multi-path routing protocol and takes into consideration of residual energy-capacities of sensor nodes before establishing routing paths. In packet forwarding process, the source node broadcasts a message to find out which multi-path has higher energy level to transmit the packet. Nodes with higher energy levels respond to the broadcasted message and are selected as the relaying nodes. REAR protocols provides extending the network life time, however, does not guarantee the end-to-end deadline mechanism.

Gungor et. al. presents a resource-aware and link quality based routing metric (RLQ) which can adapt to varying wireless channel conditions, and exploit the heterogeneous capabilities in WSANs (Gungor et al. 2007). The proposed metric takes into account both the residual energy levels of sensor nodes and link quality statistics of communication links. Hence, RLQ achieves extending the network life time while providing reliable data communications. However, RLQ metric scarifies in providing end-to-end deadline of data packets.

EARQ is an energy aware routing protocol for real-time and reliable communication in wireless industrial sensor networks Heo et al. (2009). EARQ is an estimation based routing algorithm which selects the appropriate communication links to the sink node based on the estimations that are made according to the information obtained from neighbor nodes. The energy cost, delay and reliability of a path are all the estimated information that provide real-time and reliable data delivery. EARQ provides an even distribution of energy expenditure of sensor nodes which extend the network life time.

Breath is an adaptive protocol which provides energy-efficient, reliable and timely data transmissions for WSN-based industrial control applications Park et al. (2011). Breath protocol provides the desired packet delivery options and delay probabilities while achieving to prolong the network lifetime. Park et. al. provided a complete test-bed implementation of the protocol in an indoor environment to run experiments to see the performance of the protocol in reliability and timeliness domain. It is observed that Breath guarantees both reliability and delay requirements of data packets while maximizing the network lifetime by considering duty-cycle, routing,MAC, and physical layers all together Park et al. (2011).

In Sen (2010) presents a routing protocol which addresses different level of QoS, e.g., energy-efficiency, reliability, low latency and fault tolerance under different application scenarios without reconfiguration and redeployment of the wireless sensor nodes.

4. MATERIALS AND METHODS

Recently, WSNs have been used in different smart grid applications, including power fraud detection, wireless automatic metering, overhead transmission line monitoring, load control, fault diagnostics, demand response, outage detection, and distribution automation. All these applications have different QoS requirements in terms of reliability, latency, bandwidth, as shown in Table I. On the other hand, field tests show that smart grid systems have also harsh and complex environmental conditions, dynamic topology changes, connectivity problems, interference and fading (Gungor et al. 2010). All these effects cause great challenges in the reliability of WSN communications in smart grid applications. Furthermore, most WSN-based smart grid applications include a large number of wireless sensor nodes spread over the deployment field. In these applications, the lack of predetermined network infrastructure requires the WSNs to establish multi-hop connections and maintain network connectivity autonomously. Hence, reliable multi-hop routing and QoS differentiation have become an essential issue to design WSN-based smart grid applications.

Although there has been an increasing interest in smart grid applications based on WSNs, wireless multi-hop routing in different smart grid environments is still a vastly unexplored area. To the best of our knowledge, there exists no work on performance evaluations of reliable multi-hop routing protocols specifically for harsh smart grid spectrum environments. To address this need, in this thesis, the performance of QoS-aware single-path and multi-path multi-hop routing protocols is investigated for different smart power grid environments, e.g., 500kV outdoor substation, main power control room and underground network transformer vaults. Importantly, all these performance evaluations are based on our previous work (Gungor et al. 2010) including real-world field tests using IEEE 802.15.4 compliant wireless sensor nodes deployed in different smart grid environments. Specifically, we evaluated different types of routing protocols in terms of latency, reliability, and overhead to better understand the advantages and disadvantages of each routing protocol type in different smart grid spectrum environments. In addition, we also present potential applications of WSNs in smart grid along with the related research challenges. Consequently, the main contributions of this study can be summarized as follows:

a. The research challenges of WSN-based smart grid applications have been presented.

b. Multi-path and single-path QoS-aware routing algorithms which aim service differentiation in reliability and timeliness domains have been explored. The performance evaluations of these routing algorithms under harsh smart grid environmental conditions have been studied to better develop future routing protocols specifically for smart grid environments.

c. The performance evaluations are based on our previous work where real-world field tests were conducted using IEEE 802.15.4 compliant wireless sensor nodes deployed in different smart grid environments, e.g.,500kV substation, an industrial power control room, and an underground network transformer vaults (Gungor et al. 2010). Log-normal shadowing channel model has been implemented in J-SIM simulator (*DRCL J-Sim* 2005) to realistically model the wireless channel in different smart grid environments.

4.1 OVERVIEW OF EVALUATED ROUTING PROTOCOLS

The main objective of this thesis is to analyze the behavior of a multi-path and multi-speed (MMSPEED) routing protocol in different line-of-sight (LOS) and non-line-of-sight (NLOS) smart power grid environments, e.g., 500kV outdoor substation, main power control room and underground network transformer vaults. MMSPEED routing protocol is a novel packet routing mechanism that guarantees QoS provisioning in two quality domains, e.g., reliability and timeliness domains (Felemban et al. 2006). It provides several packet delivery options for timeliness domain and probabilistic multi-path forwarding for reliability domain.

4.1.1 MMSPEED

MMSPEED routing protocol provides service differentiation and QoS provisioning in the timeliness and reliability domains for wireless sensor networks (Felemban et al. 2006). The significant contribution of MMSPEED routing protocol is to achieve improving the capabilities of a wireless sensor network to well scale while enabling different data flows to meet their reliability and timeliness requirements. To achieve the above goals, MMSPEED uses probabilistic multi-path forwarding technique which controls the number of packet delivery paths to meet the required reliability level, and adopts SPEED protocol to provide multiple delivery speed options to differentiate the QoS in timeliness domain. With these advances, it provides three important achievements that could not be guaranteed at the same time by the existing routing protocols, e.g., service differentiation in both timeliness and reliability domains, localized packet delivery without global topology information and avoiding less reliable transmissions over wireless links (Felemban et al. 2006). Geographic routing mechanism is adopted to achieve localized packet routing without end-to-end path set-up. Hence, it is assumed that sensor nodes are aware of their geographical location and their neighbours' locations within their radio range. In the timeliness domain, to be able to provide multiple speed options for data packets,

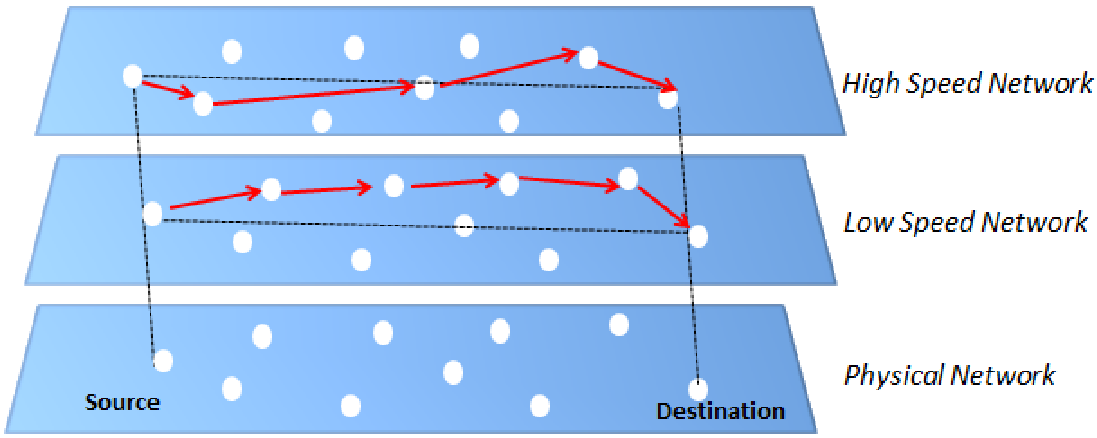


Figure 4.1: Virtual representation of overlay of multiple speed layers top of a physical network ,Felemban et al. (2006)

MMSPEED introduces virtual overlay of multiple speed layers on top of a single physical network as depicted in Figure 4.1. To achieve the virtual layering, MMSPEED uses two important methods; virtual isolation concept and dynamic compensation. Lower-speed packets may adversely affect the performance of higher-speed packets. Hence, to minimize these effects, virtual isolation makes a classification for packets according to their speed levels and place them into the priority queues. Moreover, dynamic compensation is used to compensate the local decisions to provide the end-to-end deadline requirements of data packets. For this purpose, MMSPEED calculates a minimum required speed level, $ReqSpeed(x)$ for a packet x to be able to meet its deadline requirement, $deadline(x)$, hence, the source node selects a proper speed level for a packet x based on its distance to the destination, d, e.g., $dist_{s,d}(x)$. The $ReqSpeed(x)$ is calculated as follows,

$$ReqSpeed(x) = \frac{dist_{s,d}(x)}{deadline(x)} \tag{4.1}$$

Then, the most appropriate speed layer l is picked as follows,

$$Speed_l = min_{j=1}^{L}\{Speed_j | Speed_j >= ReqSpeed(x)\} \tag{4.2}$$

where L is the number of speed options. Later, a neighbour node i whose progress speed estimation is $Speed_{s,i}^{d} = (dist_{s,d} - dist_{i,d})/delay_{s,i}$ is higher than $Speed_l$ is selected by the proper speed layer to relay the packet.

However, the packet may face with longer delays than the original estimations while travelling among many hops. This situation can be noticed by an intermediate node m by comparing expected latency to the destination using the current speed and remaining time to the deadline. Since there is no globally synchronized clock, this comparison can be made by measuring $elapsedtime$ at each node and attaching this information to the packet, hence the further node, $m^{'}$, can measure the remaining time to deadline without any additional information and update the deadline. After the new deadline is set to the packet, node m can compensate this sufficiency by resetting the speed level with the following,

$$ReqSpeed(x) = \frac{dist_{m',d}(x)}{deadline(x)} \tag{4.3}$$

With the above mentioned techniques, MMSPEED provide network-wide speed options for a packet to meet its end-to-end deadline requirement.

In the reliability domain, MMSPEED adopts the idea of utilizing the alternative longer paths may increase a packet's reaching probability to the destination. Hence, MMSPEED controls the number of communication paths according to the reliability level of a packet. MMSPEED uses two important methods to achieve the above goal; multi-path forwarding and dynamic compensation. Each node uses local error estimations and geographic hop distances of its neighbour nodes to estimate which immediate nodes it should forward the packets and how many forwarding paths it should use to meet its reliability requirements. These decisions are locally made and they are prone to mistakes, hence to compensate these decisions, dynamic compensation technique is used to meet the reliability requirements of each packet as depicted in Figure 4.2. A detailed explanation can be made as

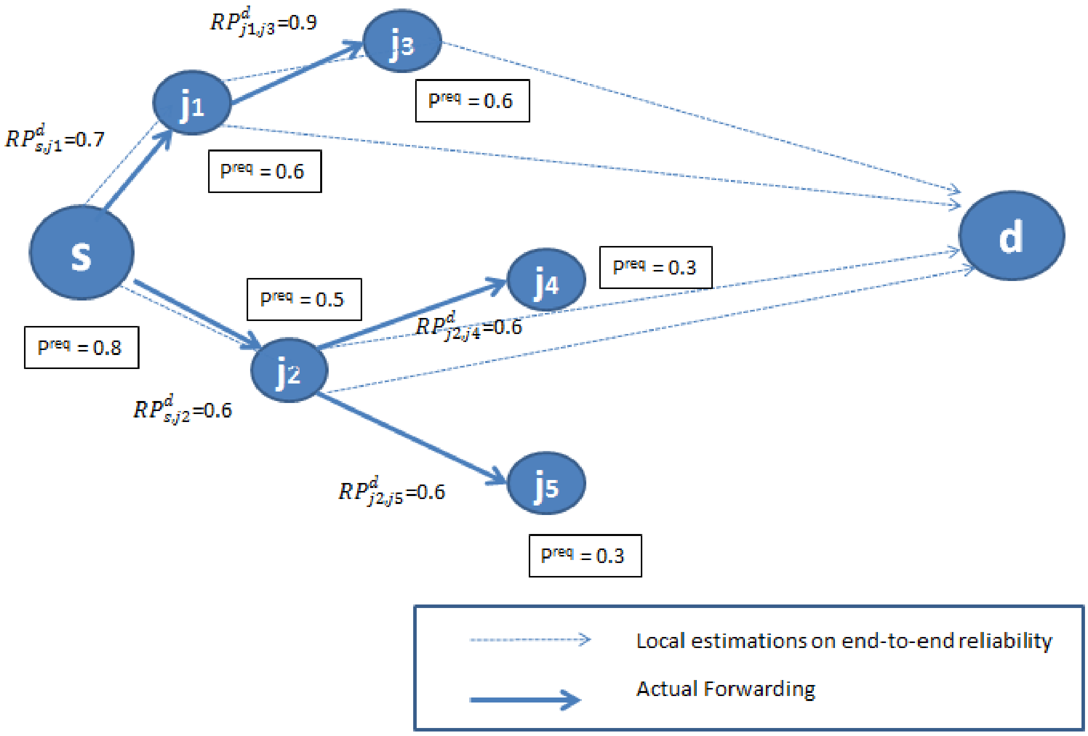


Figure 4.2: Multi-path forwarding with dynamic compensation, Felemban et al. (2006)

follows. Each node i is capable of calculating the recent average of packet loss percentage $e_{i,j}$ to the immediate node j. The total packet losses contain intentional packet drops for congestion control and errors on the channel. Hence, node i can easily estimate the reachability level of a packet to the destination d through neighbour node j as follows,

$$RP^d_{ij} = (1 - e_{ij})(1 - e_{ij})^{\lceil dist_{j,d}/dist_{i,j} \rceil} \tag{4.4}$$

where $dist_{j,d}/dist_{i,j}$ is the hop count estimation between node j and destination d. This equation is the reachability estimation of a packet via a single node j. Furthermore, to be able to meet the end-to-end reachability of a packet, more than one path may be needed. Hence, to determine how many paths needed for a required reliability level, the following adjustments should be made.

$$TRP = 1 - (1 - TRP)(1 - RP_{i,j^d}) \tag{4.5}$$

where TRP is the total reaching probability of a packet, $(1 - TRP)$ is the probability in case of none of the paths can relay the packet successfully, $(1 - RP_{i,j^d})$ is the probability in case one path trough node j will relay the packet to the destination unsuccessfully, hence, $(1 - TRP)(1 - RP_{i,j^d})$ is the probability that all of the paths will fail relaying the packet to the destination node, finally, $1 - (1 - TRP)(1 - RP_{i,j^d})$ is the probability that at least one path will certainly relay the packet to the destination. With TRP estimation, the multiple forwarding node selection can be accomplished, however, the estimations are based on local decisions which may be incorrect. Hence, dynamic compensation should take place to prevent incorrect decisions. For instance, in Figure 4.2, the source node s wants to relay a packet with $p^{req} = 80\%$. However, it cannot use a single path since the RP^d_{s,j_1} and RP^d_{s,j_2} values of immediate nodes j_1 and j_2 are not higher than the p^{req} value of node s. Hence, node s should calculate the TRP to find if two paths are enough to send the packet with the required reliability level.

$$TRP = 1 - (1 - RP^d_{s,j_1})(1 - RP^d_{i,j_2}) = 1 - (1 - 0.7)(1 - 0.6) = 0.88, \tag{4.6}$$

From the equation, TRP value is higher than the required reliability level. Hence, source s can relay the copies of the packet to node j_1 and j_2. To be able to meet the reliability condition, multi-path routing algorithm assigns $p^{req} = 0.6\%$ and $p^{req} = 0.5\%$ for nodes j_1 and j_2. With the local estimations, j_1 and j_2 try to find the neighbour node whose p^{req} values are higher than the assigned reliability requirements. j_1 finds a node j_3 with $p^{req} = 0.9$ which is higher than the assigned requirement level, hence, it relays the packet to node j_3. On the other hand, j_2 cannot find a node whose p^{req} is higher than $p^{req} = 0.5$, hence it needs to calculate the TRP to find the required number of paths for forwarding the packet.

Two immediate nodes j_4 and j_5 with $p^{req} = 0.3$ and $p^{req} = 0.3$, respectively, are chosen as the relaying nodes after the calculation of TRP which is $1-(1-0.3)(1-0.3) = 0.51$. Hence, with the dynamic compensation mechanism, the previous wrong local estimations are adjusted to correctly provide the QoS provisioning in reliability domain. In a more gloabal scope, multi-path routing algorithm provides reliability-back pressure mechanism to adjust the wrong local decisions. Nodes may not satisfy the locally estimated reliability values, hence, they start to send reliability back pressure packets to decrease the reliability expectation of other nodes.

Overall, MMSPEED protocol tries to provide service differentiation by combining above mechanisms. First of all, MMSPEED places the packet into the proper speed layer to meet the deadline requirement and then, finds multiple forwarding nodes to deliver it using MAC layer multi-cast service Felemban et al. (2006). To conclude, MMSPEED routing protocol efficiently meets the requirements of different traffic types with different reliability and timeliness requirements, provides scalability for large sensor networks and self-adaptability for network dynamics Felemban et al. (2006).

4.1.2 SPEED

SPEED protocol is a a real-time, stateless communication protocol for sensor networks which provides end-to-end deadline guarantees by maintaining the desired speed levels with a feedback control and non-deterministic geographic forwarding He et al. (2003). SPEED protocol differs from other real-time protocols, e.g. RAP **?**, with it's ability to handle long term congestion, and it differs from other reactive routing algorithms, e.g. DSR Johnson & Maltz (1996) and AODV Perkins & Royer (1999), with it's stateless structure in which only immediate neighbors information is maintained, and there is requirement for routing tables or per destination states He et al. (2003). Here are some of the advances of SPEED protocol that make it efficient and real-time protocol in providing QoS provisioning in timeliness domain He et al. (2003):

a. SPEED protocol adopts a backpressure re-routing scheme to handle large-delay links with minimum overhead.

b. Non-deterministic forwarding is used to be able to balance the data flows among the several routes which is quite a necessity in terms of bandwidth and energy utilizations.

c. SPEED makes a difference with its localized behavior. No routing tables are used in SPEED protocol, it is assumed that each sensor node knows its location, hence, there is no need to apply flooding or creating broadcasting storms to find communication paths. With this way, the scarce resources, e.g. energy, bandwidth, are better utilized.

d. In SPEED protocol, end-to-end delay of a packet is proportional to the distance of the packet destination, since uniform packet delivery option is adopted among the network.

SPEED protocol uses a packet progress speed concept that enables each node to find a proper neighbor node for relaying the data packet. Every sensor node has a packet progress speed calculate according to its distance to the destination node, and the packets are forwarded to the neighbor node that has the highest progress speed. In case of a heavy load, the packets are dropped to relieve the network and in case, there exist a congested area, a back-pressure packet is generated and sent to the previous nodes to warn them about the congested area and prevent them to sent any more packets to that area. Network scalability, end-to-end delay requirements are all provided by SPEED protocol, however, there is only one network-wide speed which is inadequate to differentiate different traffic with different deadline requirements. This inadequacy is compensated by MMSPEED routing protocol by adopting multiple delivery speed options to differentiate the QoS in timeliness domain.

Table 4.1: Mean power loss and shadowing deviation in electric power environments, Gungor et al. (2010)

Propagation Environment	**Path Loss** (n)	**Shadowing Deviation** (σ)
500 kv Substation (LOS)	2.42	3.12
500 kv Substation (NLOS)	3.51	2.95
Underground Transformer Vault (LOS)	1.45	2.45
Underground Transformer Vault (NLOS)	3.15	3.19
Main Power Room (LOS)	1.64	3.29
Main Power Room (NLOS)	2.38	2.25

4.2 PERFORMANCE EVALUATIONS

In this thesis, a multi-path and single-path routing algorithms are compared for achieving service differentiation in different smart grid environments. In the literature, there have been a few routing protocols which take in to account both reliability and latency requirements. The presented routing algorithm achieves distinguishing different QoS domains, e.g., reliability and timeliness, in smart grid environment which has harsh environmental conditions that posse additional challenges for WSN technology to provide reliability and latency requirements. Hence, the wireless channel should be modelled by taking account multiple parameters that can affect the signal quality. Since log-normal shadowing model takes into account both fading and distance affects in the surrounding of transmitters and receivers, it is the preferred propagation model in this work. Gungor et. al. have modelled the wireless channel in six different smart grid environments and presented the specific radio propagation parameters for those environments in Table 4.1. Gungor et. al. have depicted that the signal to noise ratio $\gamma(d)$ at a distance d from the transmitter is given by:

$$\gamma(d)_{dB} = P_t - PL(d_0) - 10\eta log_{10}\Big(\frac{d}{d_0}\Big) - X_\sigma - P_n \tag{4.7}$$

P_t is the transmit power in dBm, $PL(d_0)$ is the path loss at a reference distance d_0, X_σ is a zero mean Gaussian random variable with standard deviation σ, η is the path loss exponent, and P_n is the noise power in dBm.

In the light of these propagation parameters, log-normal shadowing model is implemented for different smart grid environments, and a simulation environment is generated with 100 nodes in J-SIM simulation environment developed in (Felemban et al. 2006). Some of the nodes are assigned as the source nodes and the one as a sink node. The simulations are performed for four different scenarios with different reliability and timeliness requirements to provide service differentiation:

a. Scenario 1: Deadline value is 0.3 and Reliability value is 0.5,

b. Scenario 2: Deadline value is 1.0 and Reliability value is 0.5,

c. Scenario 3: Deadline value is 1.0 and Reliability value is 0.7,

d. Scenario 4: Deadline value is 1.0 and Reliability value is 0.2,

Two flow groups are used during each simulation and the network traffic with 2, 4, 8, 12, 16 sources for each domain are generated. The following performance metrics are used for performance evaluations:

a. **Average Delay:** is the average delay time of all the packets that are successfully received by the sink node.

b. **On-Time Reliability:** is the ratio between successfully received packets that meet the deadline requirement value and the total number of packets.

c. **End-to End Delay:** represents the time to receive all data by the sink node.

d. **Control Packets:** consists of ACK, RTS, CTS and retransmission RTS that are the MAC layer control packets, location update packets and back-pressure packets.

Table 4.2: Simulation parameters, Felemban et al. (2006)

Number of nodes	100
Number of traffic flows	2, 4, 8, 12,16
Packet Length	256 Bytes
Traffic Type	CBR
Channel Model	Log normal Shadowing
MAC Protocol	802.11e EDCF

There are three main smart grid environments that Gungor et. al. have made the experimental study on the statistical characterization of the wireless channel. They measured the background noise, wireless channel characteristics, and attenuation of these environments in LOS and NLOS scenarios as depicted in Table 4.1. From the experiments, it is observed that in substation environment, high amount of noise due to the several obstacles resulted in high path loss, in underground transformers vaults, there are many equipment, such as, power transformers, network protectors, voltage regulators, circuit breakers, meters, that creates high amount of noise which adversely affect the quality of wireless communications, since main power control room is an indoor environment, there are quite less obstructions that affect the link quality as it does in other environments. Performance evaluations have been made according to these three environments, since they have different special characteristics which directly affect the performance of multi-path routing from reliability and timeliness domains.

Figure 4.3: Shadowing Model-Service Differentiation for n=2.42 and σ=3.12in in 500 kv substation(LOS)

Figure 4.3a Average Delay

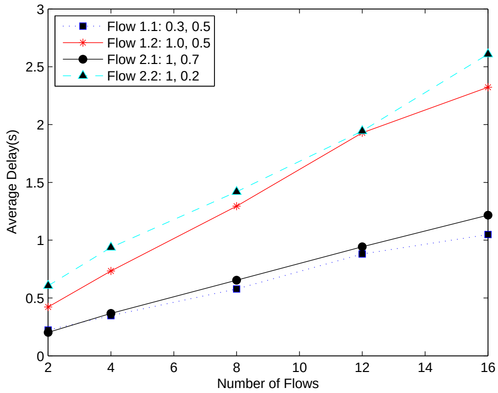
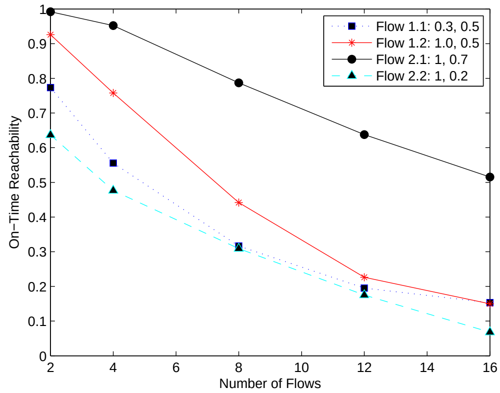


Figure 4.3b On-Time Reliability



4.2.1 Performance Evaluations from Reliability Domain Point of View

Multi-path routing uses probabilistic multi-path forwarding technique in reliability domain depending on the reliability requirement to exploit the packet delivery paths. To differentiate the reliability domain, the same deadline requirement of 1.0 is used for all flows. The flows are divided into two flow groups with different reliability requirements; flow group 2.1 has high reliability requirement of 0.7 and flow group 2.2 has low reliability requirement of 0.2. As shown, flow 2.1 and flow 2.2 lines in Figure 4.3a, Figure 4.4a, Figure 4.5a, Figure 4.6a, Figure 4.7a, Figure 4.8a show the average delays with fixed deadline requirements for each smart grid environment. Since the required packet speed is lower, it is expected to see that multi-path routing route will be farther away from the optimum path (Darabi et al. 2008). In the light of this statement, multi-path routing provides a clear differentiation with different reliability requirements. For instance, it has supported up to 25 flows under 0.7 reliability requirement and up to 10 flows under 0.2 reliability requirement in 500kV Substation(LOS) environment.

Figure 4.4: Shadowing Model-Service Differentiation for n=3.51 and σ=2.95 in 500 kv substation(NLOS)

Figure 4.4a Average Delay

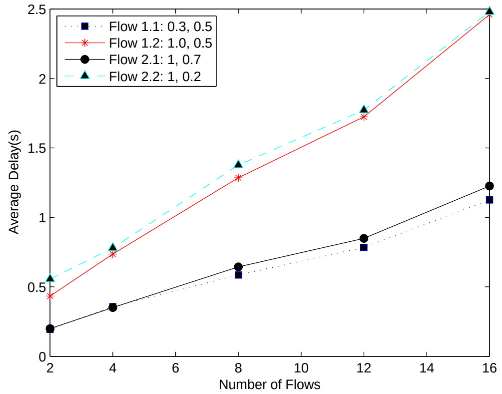
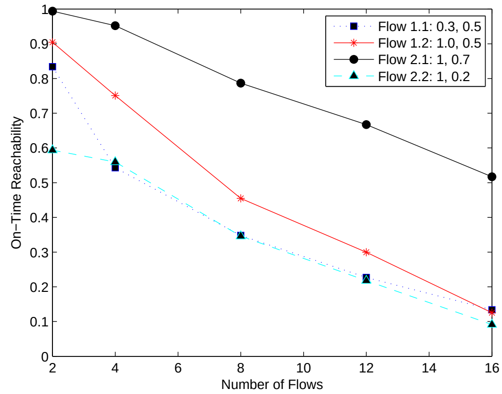


Figure 4.4b On-Time Reliability



Figures Figure 4.3b, Figure 4.4b, Figure 4.5b, Figure 4.6b, Figure 4.7b,Figure 4.8b show the on-time reachability for each group of flows, since the flow 1.1 and the flow 1.2 have the same reliability requirement of 0.5, there is no big performance differentiation in the reliability domain. However, flow 2.1 and flow 2.2 have different reliability requirements (flow 2.1 has reliability requirement of 0.7 and flow 2.2 has reliability requirement of 0.2). We expect to see a service differentiation in reliability domain. It is clearly shown that multi-path routing provides the reliability differentiation for each flow.

Figure 4.5: Shadowing Model-Service Differentiation for n=1.45 and σ=2.45 in Underground Transformer Vault(LOS)

Figure 4.5a Average Delay

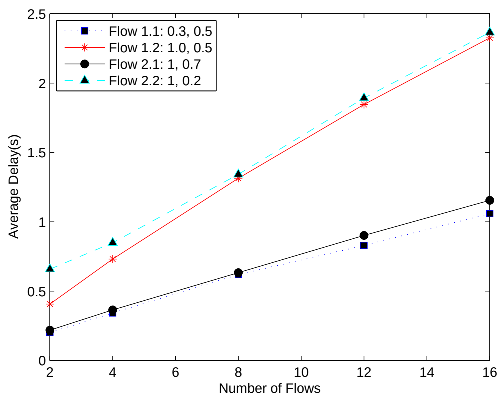
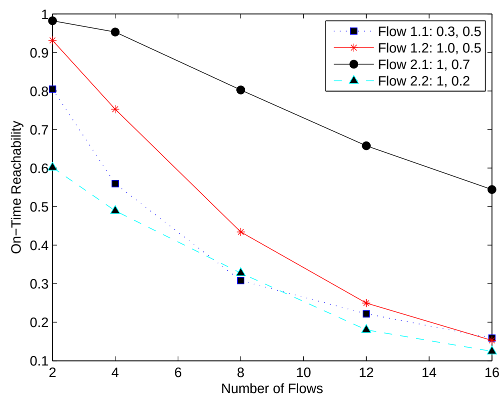


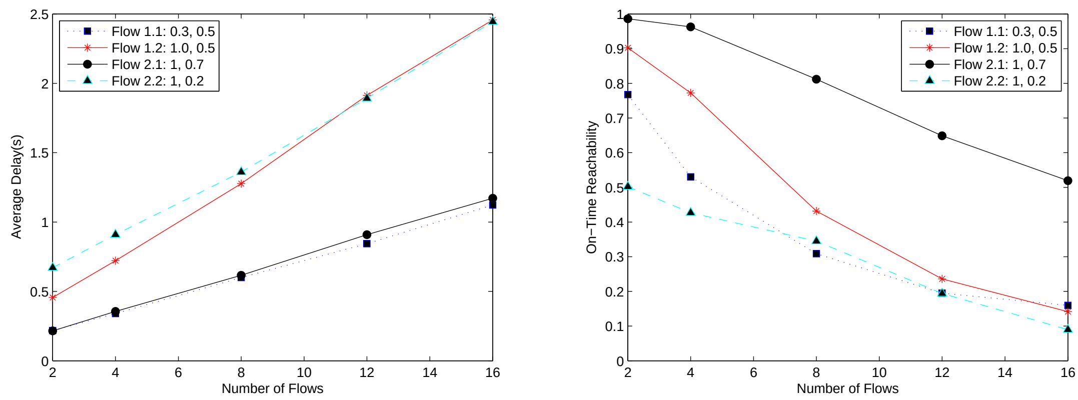
Figure 4.5b On-Time Reliability



It is observed that there is a performance degradation for line-of-sight and non-light-of-sight 500kV substation smart grid environments for on-time reachability levels, since in non-light of sight environments, the wireless performance can be limited by the obstacles. Therefore, it is obvious to see that for source group 2.2 (reliability requirement of 0.2), the on-time reachability level in 500kV Substation (LOS) environment is a little bit higher than the on-time reachability level in 500kV Substation (NLOS) environment as depicted in Figures Figure 4.3b and Figure 4.4b. However, there is no such a big performance difference in source groups 1.1 with high reliability requirement, since QoS-Aware Multi-Path Routing provides guaranteed service for high reliability requirement flow groups.

Figure 4.6: Shadowing Model-Service Differentiation for n=3.15 and σ=3.19 in Underground Transformer Vault(NLOS)

Figure 4.6a Average Delay **Figure 4.6b** On-Time Reliability



The same performance degradation is observed in underground transformers vault (LOS) and underground transformers vault (NLOS) smart grid environments. For source group 2.2(reliability requirement of 0.2), there is a quite performance degradation in NLOS underground transformers vault as depicted in Figures Figure 4.5b and Figure 4.6b. It is obvious to see such a performance differentiation between NLOS and LOS underground transformers vault, since there are a lot of equipment, e.g., power transformers, network protectors, voltage regulators, circuit breakers, meters, housed in underground transformers vault which can affect the wireless communication in NLOS environment. As it is observed in 500kV (NLOS) and (LOS) smart grid environments, for source groups 1.1 (reliability requirement of 0.2), there is no such a big performance difference in on-time reachability in (NLOS) and (LOS)underground transformers vault environments.

The performance of source 2.2 in main power room (NLOS) environment is surprisingly higher than the performance of source 2.2 in main power room (LOS). Since main power control room is an indoor environment, this performance difference can be tolerated. On the other hand, while there are no performance differentiation occurred in 500kV Sub-

Figure 4.7: Shadowing Model-Service Differentiation for n=1.64 and σ=3.29 in Main Power Room (LOS)

Figure 4.7a Average Delay

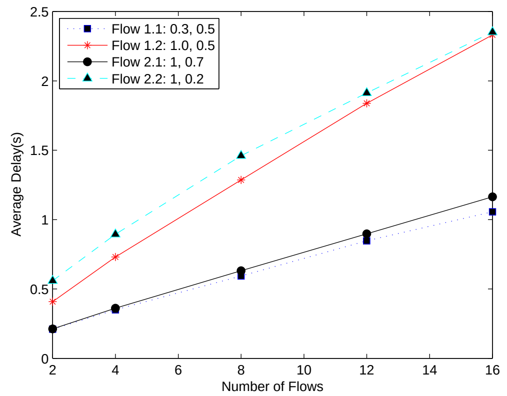
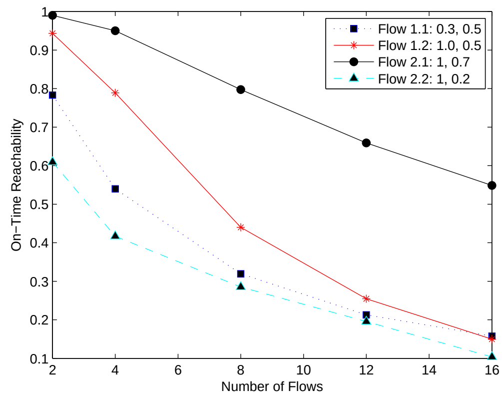


Figure 4.7b On-Time Reliability



station and underground transformers vault environments for source group 1.1, the main power control room (LOS) shows quite higher performance source group 1.1 (reliability requirement of 0.2) than the main power control room (NLOS) shows.

Figure 4.8: Shadowing Model-Service Differentiation for n=2.38 and σ=2.25 in Main Power Room (NLOS)

Figure 4.8a Average Delay

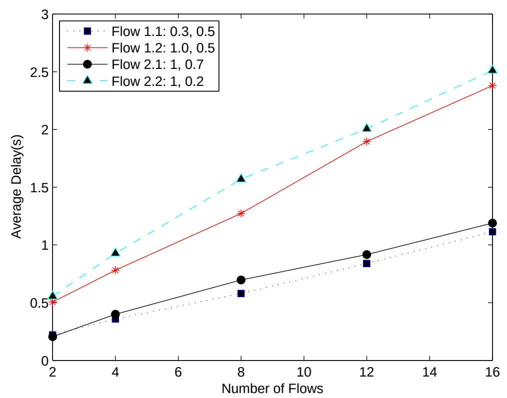
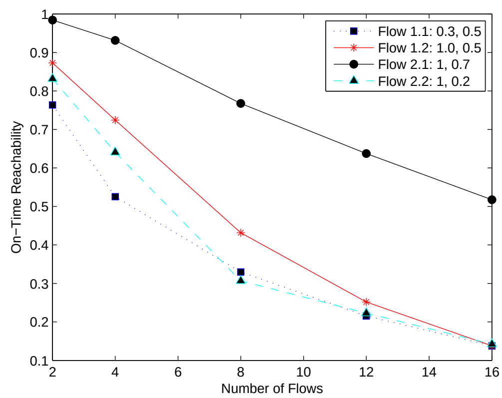


Figure 4.8b On-Time Reliability



4.2.2 Performance Evaluations from Timeliness Domain Point of View

The multi-path routing protocol adopts single-path routing to provide multiple delivery speed options to differentiate the QoS in timeliness domain. Hence, the same reliability requirement of 0.5 is used for all flows. The flows are divided into two flow groups with different deadline requirements; flow group 1.1 has short deadline requirement of 0.3 sec. and flow group 1.2 has long deadline requirement of 1.0 sec. As shown, flow 1.1 and flow 1.2 lines,as increasing number of sources, in Figures Figure 4.3a, Figure 4.4a, Figure 4.5a, Figure 4.6a, Figure 4.7a, Figure 4.8a, the flows with 0.3 sec. of deadline have showed a great performance in providing the end-to-end deadline requirements. It is very obvious that multi-path routing protocol has achieved a clear differentiation with different deadline requirements for different flow groups. For instance, it has supported up to 8 flows under 0.3 sec deadline requirement and up to 11 flows under 1.0 sec deadline requirement in 500kV Substation(LOS) environment as depicted in Figure 4.12.

Figure 4.9: Overhead of control packets versus number of flows for n=2.42 and σ=3.12

Figure 4.9a Control Packets for Reliability Domain

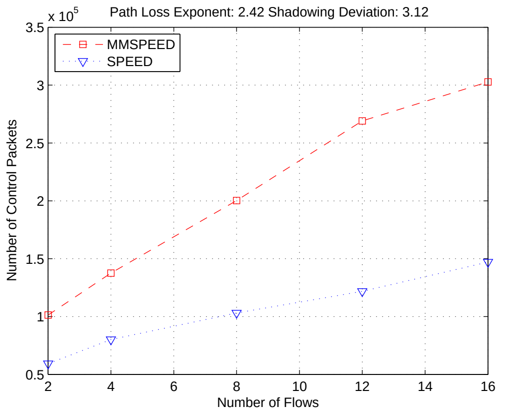
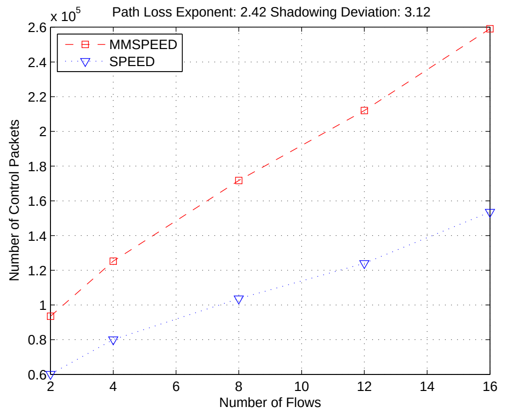


Figure 4.9b Control Packets for Timeliness Domain

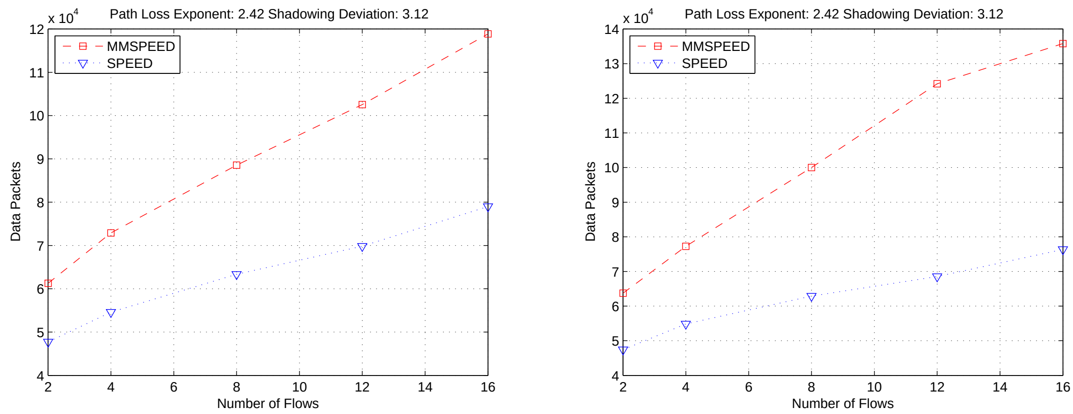


The performance differentiation of flow groups in 500kV substation LOS and NLOS is clearly distinctive as depicted in Figures Figure 4.3a and Figure 4.4a. The average delays in 500kV substation (NLOS) smart grid environment for source groups 1.1 and 1.2, are higher than they are in 500kV substation (LOS), since non-line-of-sight environment has more obstructions which may adversely increase the delay of wireless communications. Furthermore, as it can be easily predicted, source group 1.2 with higher delay requirement (delay requirement of 1.0) has higher average delay performance than source group 1.1 with low delay requirement (delay requirement of 0.3) has. The clear distinction in

average delay performances is also observed in underground transformer vault NLOS and

Figure 4.10: Overhead of data packets versus number of flows for n=2.42 and σ=3.12

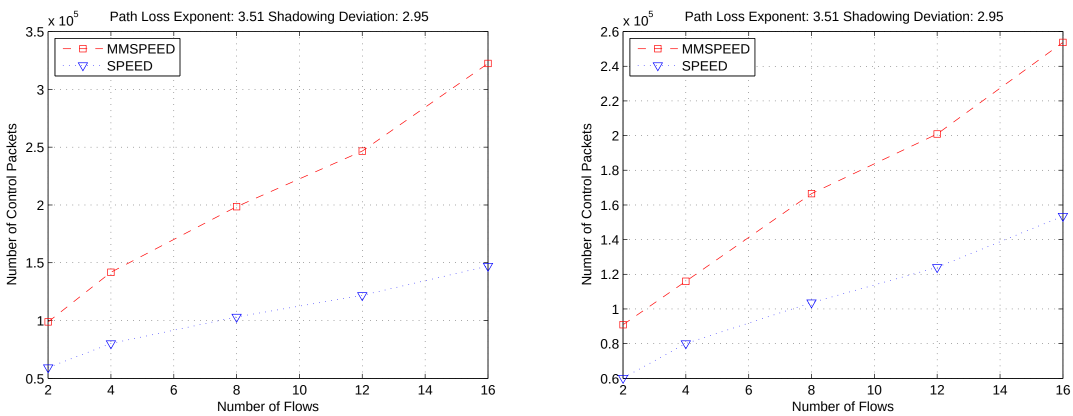
Figure 4.10a Data Packets for Timeliness Domain **Figure 4.10b** Data Packets for Reliability Domain



LOS smart grid environments. Since, the special environment of underground transformer vault poses additional obstructions, the average delays are a little bit higher than they are in other two environments. Figures Figure 4.5a and Figure 4.6a show that source groups 1.1 and 1.2 have higher average delays in NLOS environment than they are in LOS environment. Moreover, as it is observed in 500kV substation environment, the source group 1.2(delay requirement of 1.0) has a significant higher average delay that the source group 1.1 (delay requirement of 0.3) since, high delay requirement provides a flexibility to the routing algorithm to tolerate the additional delays. In main power control room,

Figure 4.11: Overhead of control packets versus number of flows for n=3.51 and σ=2.95

Figure 4.11a Control Packets for Reliability Domain **Figure 4.11b** Control Packets for Timeliness Domain



it is clearly shown that there are performance differentiation in average delays of source groups 1.1 and 1.2 in LOS and NLOS scenarios. The QoS-aware multi-path routing is able to provide lower average delay for source group 1.1 with delay requirement of 0.3 to be able to meet the timing requirement. Hence, source group 1.2 with delay requirement of 1.0 shows higher average delay than source group 1.1 as depicted in Figures Figure 4.7a and Figure 4.8a. However, as it is observed in reliability point of view, the LOS and NLOS performance evaluations are not as they are predicted. Surprisingly, source group 1.2 in LOS scenario has higher average delay that it is in NLOS scenario.

Figure 4.12: The network capacity is briefly depicted for shadowing model for smart grid environment, n=2.42 and σ=3.12

	System Performance	Delay Performance	On Time Reachability
Deadline 1.0 Reachability 0.7	Up to ~22 flows	Up to ~25 flows	Up to ~20 flows
Deadline 1.0 Reachability 0.2	Up to ~20 flows	Up to ~10 flows	Up to ~23 flows
Deadline 0.3 Reachability 0.5	Up to ~9 flows	Up to ~8 flows	Up to ~10 flows
Deadline 1.0 Reachability 0.5	Up to ~12 flows	Up to ~11 flows	Up to ~13 flows

4.2.3 Overhead Analysis

In this section, the overhead analysis of MMSPEED and SPEED protocols are presented. Two types of overhead are introduced, the first type is data packets and the second type is control packets which include location update packets, timeliness back-pressure packets, and reliability back-pressure packets. Location update packets and timeliness back-pressure packets are used by both MMSPEED and SPEED protocols, while reliability back-pressure packets are used by only MMSPEED protocol. Data overhead includes the data packet multiplication overhead required for enabling multipath routing.

The overhead of each protocol is depicted in Figures 4.10, 4.13, 4.15, 4.17, 4.19, 4.21 as increasing number of flows. The flows are divided into four source groups with different reliability and timeliness requirements. Each figure represents the overhead analysis of data or control packets in a different smart grid environment.

Figure 4.13: Overhead of data Packets versus number of flows for n=3.51 and σ=2.95

Figure 4.13a Data Packets for Timeliness Domain

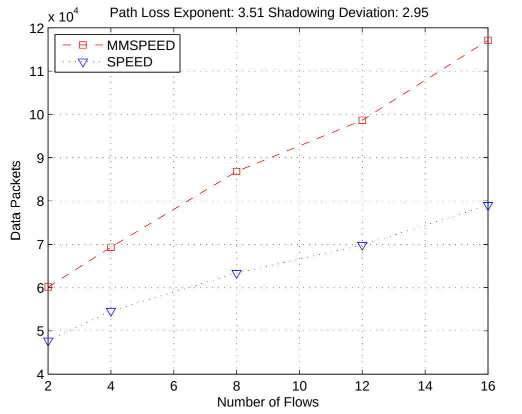
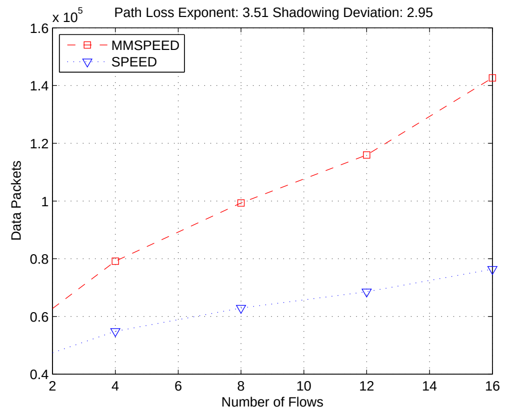


Figure 4.13b Data Packets for Reliability Domain



For six different smart grid environments, the total number of control packets and data packets of MMSPEED is larger than SPEED protocol. This can be explained as follows. The reaching capability of a packet to the final destination increases while the number of paths used for packet transmission increases, hence, multi-path routing protocol exploits the redundant paths to the final destination point even they might not be the shortest paths, just to provide end-to-end reliability of a packet Felemban et al. (2006).

For this reason, multi-path forwarding technique is adopted by the presented multi-path routing algorithm which transmits the duplicate copies of the packets to meet the reliability requirement and uses multiple hops by considering the fact that each copy of the packet meets end-to-end deadline requirement. Another sign why control packets of MMSPEED protocol are larger in number than control packets of SPEED protocol can be explained as follows. MMSPEED algorithm uses reliability back pressure packets. For instance, in a congested area, it is possible that a node may not find any possible nodes that have higher progress speed than $SetSpeed$ to relay the packets. Hence, it starts to drop packets to reduce the workload. Moreover, the node starts to send reliability back pressure packets to prevent the coming packets to the congested area. These reliability back pressure packets may increase the number of control packets in multi-path routing protocol.

Figure 4.14: Overhead of control packets versus number of flows for n=1.45 and σ=2.45

Figure 4.14a Control Packets for Reliability Domain **Figure 4.14b** Control Packets for Timeliness Domain

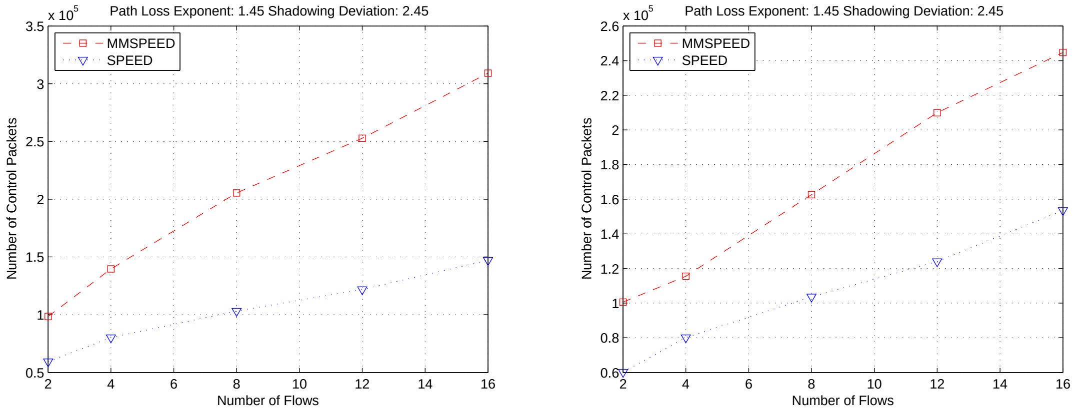
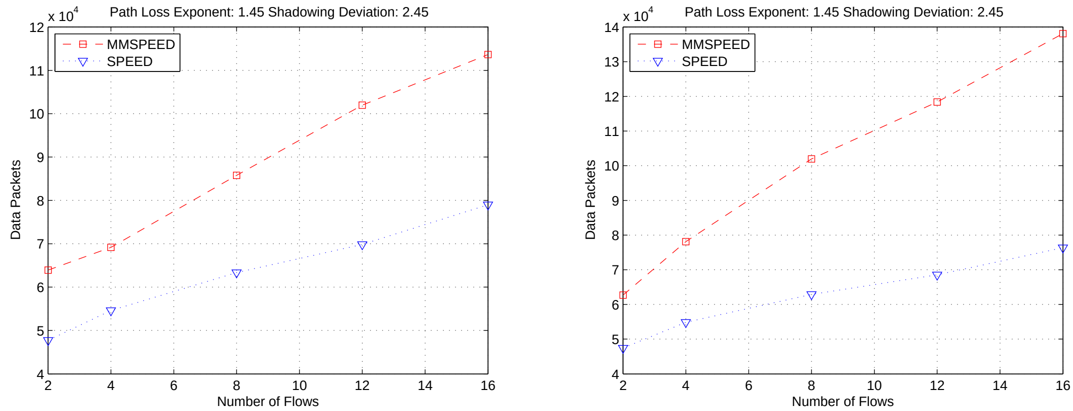


Figure 4.15: Overhead of data packets versus number of flows for n=1.45 and σ=2.45

Figure 4.15a Data Packets for Timeliness Domain **Figure 4.15b** Data Packets for Reliability Domain



Moreover, the multi-cast capability of multi-path routing in the MAC layer may create additional bits. Hence, the total number of data and transmissions of control packets are quite larger than that of single-path routing.

On the other hand, the number of timeliness back pressure packets in single-path routing algorithm is quite larger than the timeliness back pressure packets in multi-path routing algorithm. However, the total number of control packets are still larger in multi-path routing algorithm. Multi-path and single-path is a localized routing protocol which provides the network range to be easily expanded, especially in smart grid environment, this is an important feature for data communications.

Figure 4.16: Overhead of control packets versus number of flows for n=3.15 and σ=3.19

Figure 4.16a Control Packets for Reliability Domain

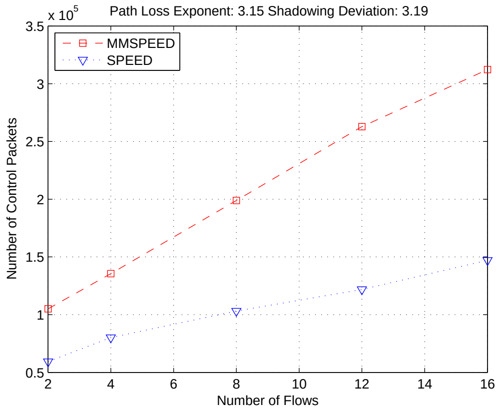


Figure 4.16b Control Packets for Timeliness Domain

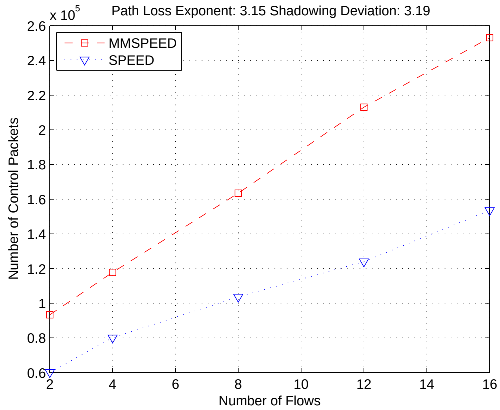


Figure 4.17: Overhead of data packets versus number of flows for n=3.15 and σ=3.19

Figure 4.17a Data Packets for Timeliness Domain

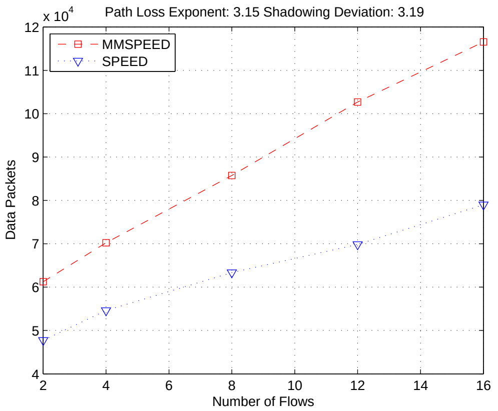
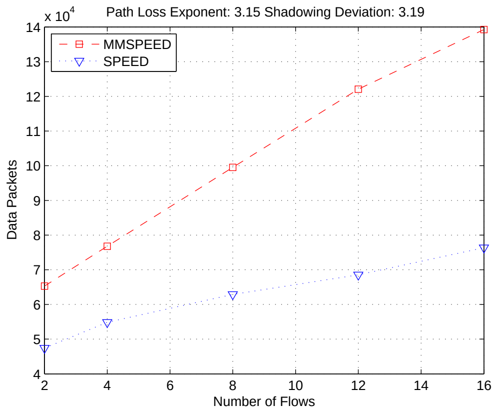


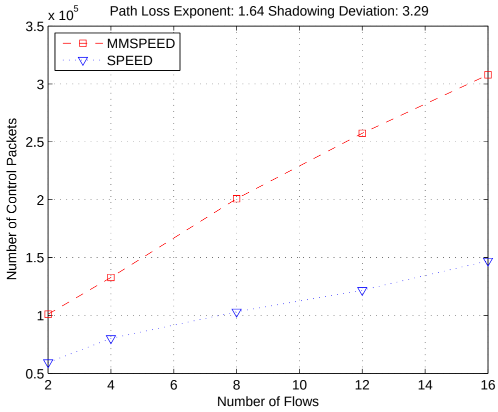
Figure 4.17b Data Packets for Reliability Domain



Hence, it is obvious to see a linear increase in control packets since location update packets are transferred periodically. On the other hand, the increase in control packets adversely affect the power consumption of sensor nodes. Multi-path and single-path routing algorithm has complex calculations and large overhead bits to accomplish multi-path forwarding and dynamic compensation, hence the overall power consumption may increase. However, multi-path and single-path routing algorithm uses enough number of multi-paths and multi-hops, hence the power consumption is not so much. For six different smart grid environments, the total number of control packets in LOS environment are quite larger than control packets in NLOS environment. The control packets are used to

Figure 4.18: Overhead of control packets versus number of flows for n=1.64 and σ=3.29

Figure 4.18a Control Packets for Reliability Domain **Figure 4.18b** Control Packets for Timeliness Domain



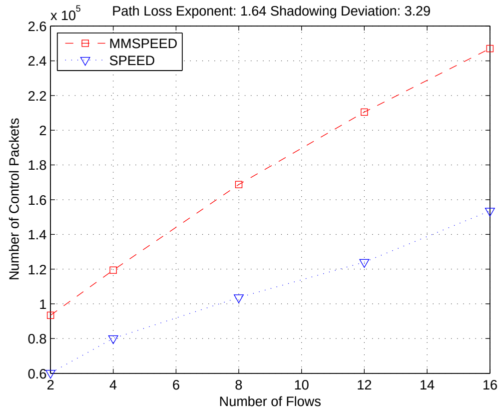
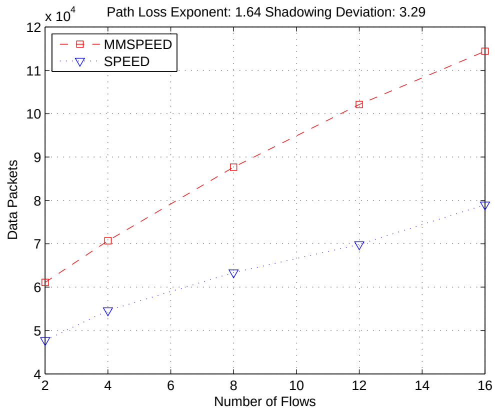
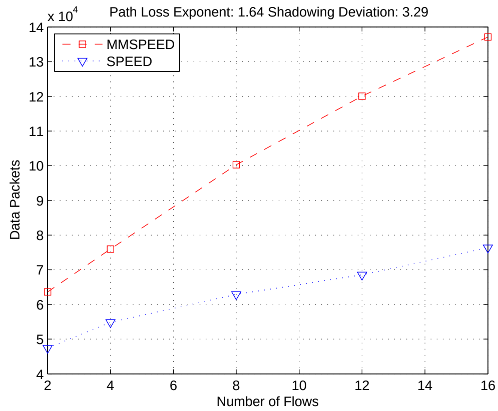


Figure 4.19: Overhead of data packets versus number of flows for n=1.64 and σ=3.29

Figure 4.19a Data Packets for Timeliness Domain **Figure 4.19b** Data Packets for Reliability Domain





reliably and successfully transmit the data packets to the destination. Since the number of successfully transmitted packets are larger in LOS smart grid environment than NLOS environment, it is very clear to see such a difference. On the other hand, such a difference is not observed for data packets. The total number data packets in NLOS environment are larger than LOS environment. This can be explained as follows. In NLOS environment, to be able to meet the QoS requirements, so much effort is needed to put since there are a lot of obstructions that may adversely affect the performance of the routing protocol. Larger number of data packets is a sign for such an effort. Multi-path routing algorithm

Figure 4.20: Overhead of control packets versus number of flows for n=2.38 and σ=2.25

Figure 4.20a Control Packets for Reliability Domain **Figure 4.20b** Control Packets for Timeliness Domain

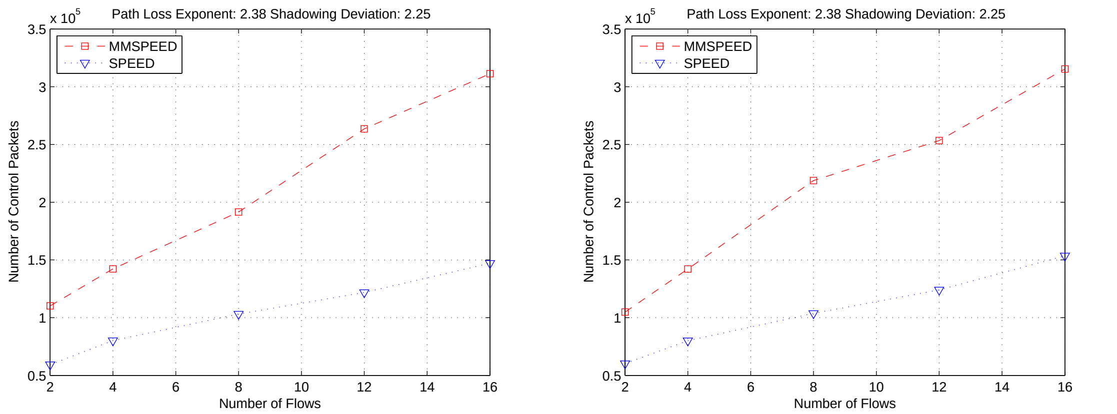
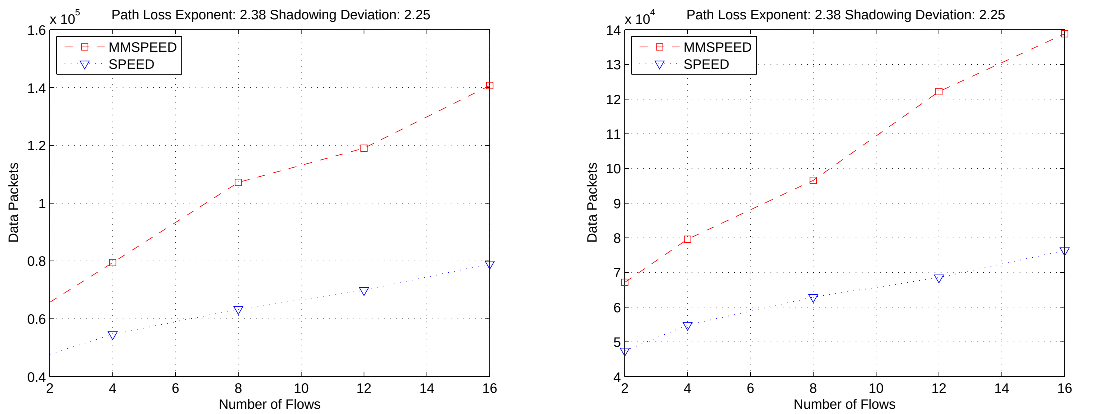


Figure 4.21: Overhead of data packets versus number of flows for n=2.38 and σ=2.25

Figure 4.21a Data Packets for Timeliness Domain **Figure 4.21b** Data Packets for Reliability Domain



in NLOS smart environments send many duplicate or retransmitted data packets by using multi-paths and multi-hops to be able to provide QoS requirements.

5. CONCLUSION

Smart grid is the key solution to modernize the existing power grid which has been causing critical problems to the humanity with its aging infrastructure, hence the integration of advanced communication techniques has an important role in this process. Afterwards, the deployment of wired communication techniques means huge investment and maintenance costs and creates the inflexibility in extending the network range. Hence, WSNs will be the perfect choice due to the low cost and rapid deployment characteristics for the smart grid environment. There are some requirements to design reliable and energy efficient WSNs and most of the routing protocols can meet just some of these requirements, however the presented multi-path routing protocol provides a great service differentiation with different QoS requirements with different traffic flows in smart grid environments.

In this thesis, research challenges of WSN-based potential smart grid applications have been summarized. Afterwards, a related work on reliability-aware and link-quality-aware routing protocols for WSNs has been studied. A multi-path and single-path routing algorithm is presented for achieving service differentiation in different smart grid environments. The presented routing algorithm achieves distinguishing different QoS domains, e.g., reliability and timeliness, in smart grid environment which has harsh environmental conditions that posse additional challenges for WSN technology to provide reliability and latency requirements. Since log-normal shadowing model takes into account both fading and distance affects in the surrounding of transmitters and receivers, it is the preferred propagation model in this work. A simulation environment is generated with 100 nodes in J-SIM simulation environment developed in Felemban et al. (2006). Some of the nodes are assigned as the source nodes and the one as a sink node. The simulations are performed for four different scenarios with different reliability and timeliness requirements to provide service differentiation. Two flow groups are used during each simulation and the network traffic with 2, 4, 8, 12, 16 sources for each domain are generated. Our simulations are based on specific radio propagation parameters obtained from real sensor node implementations (Gungor et al. 2010). In the reliability domain, multi-path routing uses probabilistic multi-path forwarding technique in reliability domain depending on the reliability requirement to exploit the packet delivery paths. Hence, multi-path routing provides a clear differentiation with different reliability requirements. For instance, it has supported up to 25 flows under 0.7 reliability requirement and up to 10 flows under 0.2 reliability requirement in 500kV Substation(LOS) environment. In timeliness domain, multi-path routing protocol adopts single-path routing to provide multiple delivery speed options to differentiate the QoS in timeliness domain. Hence, it has achieved a clear differentiation with different deadline requirements for different flow groups. For instance, it has supported up to 8 flows under 0.3 sec deadline requirement and up to 11 flows under 1.0 sec deadline requirement in 500kV Substation(LOS) environment.

In this thesis, the overhead analysis of MMSPEED and SPEED protocols are also presented. Two types of overhead are introduced, the first type is data packets and the second type is control packets which include location update packets, timeliness back-pressure packets, and reliability back-pressure packets. For six different smart grid environments, the total number of control packets and data packets of MMSPEED are larger than SPEED protocol. This can be explained as follows. The reaching capability of a packet to the final destination increases while the number of paths used for packet transmission increases, hence, multi-path routing protocol exploits the redundant paths to the final destination point even they might not be the shortest paths, just to provide end-to-end reliability of a packet. For this reason, multi-path forwarding technique is adopted by the presented multi-path routing algorithm which transmits the duplicate copies of the packets to meet the reliability requirement and uses multiple hops by considering the fact that each copy of the packet meets end-to-end deadline requirement. Moreover, the multi-cast capability of multi-path routing in the MAC layer creates additional bits. Hence, the total number of data and transmissions of control packets are quite larger than that of single-path routing.

However, there are still open-research issues for routing algorithms in this specific environment. Here is a list of future work towards this promising research area:

a. Due to the nature of multi-path routing, some additional features such as multi path, multi-speed, more power consumption may be observed, however power consumption is not our focus in this thesis, hence we can just do the estimations of the energy efficiency of the presented protocol in smart grid environment. Smart grid environment is a harsh and complex environment, hence a much more decrease on the link quality between sources and the sink can be observed. This would cause multi-path routing protocol to try to find more redundant paths to send the data packets to meet QoS requirements and more retransmissions may occur. Hence, the energy consumption will be increased. In the future, we may work on measuring the actual power consumption of multi-path routing routing protocol in smart grid environment.

b. Due to the dynamic nature of wireless channels, accomplishing an accurate link quality estimation is a challenging task. In our experiments, PRR (Packet Reception Rate) is used as a link quality estimator. In future, we may try using a different link quality estimator and improve the performance results.

c. Multi-path routing uses geographic routing mechanism based on location awareness using GPS technology which is an expensive, more energy consuming technology and it may lead some incorrect information about the location positions of the nodes at indoor coverage. Hence, some location position estimation algorithms can be used to improve the estimation results in future.

d. In future, by using adaptive transmission power control techniques, we can dynamically change the communication range of the network.

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