T.C.
BAHÇEŞEHİR ÜNİVERSİTESİ

ADAPTIVE WIRELESS SENSOR NETWORK PROTOCOLS FOR SMART GRID APPLICATIONS

M.S. Thesis

Bilal Erman BİLGİN

İSTANBUL, 2011

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Bilal Erman BILGIN

ABSTRACT

ADAPTIVE WIRELESS SENSOR NETWORKS PROTOCOLS FOR SMART GRID APPLICATIONS

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Today's electric power systems suffer from the lack of pervasive and effective communications, monitoring, and automation. To overcome these problems, a new electric power system, i.e., smart grid, has been proposed. The main idea of smart grid is to add monitoring, control, and communication capabilities to the traditional electricity delivery system to improve efficiency, reliability, and safety while reducing the energy consumption. Importantly, the smart grid will allow the electric utilities to move electricity around the electric power grid as economically as possible.

Recently, Wireless Sensor Networks (WSNs) have been widely started to use in smart grid environments. The collaborative operation of WSNs brings significant advantages over traditional communication technologies, including self-organization, rapid deployment, low cost, flexibility and aggregated intelligence via parallel processing.

Besides, the ZigBee Smart Energy profile has been developed, which is the application profile based on IEEE 802.15.4 standard and offers an affordable way for communicating energy-related information in smart grid environments. The major features of ZigBee, including low cost, low power, low bandwidth, low complexity and easy deployment and implementation make ZigBee ideal for monitoring, data collection and analyzing for smart grid applications.

However, high packet losses and link capacity variations due to harsh power system environments pose great challenges in the reliability of wireless communications in smart grid systems. Therefore, to increase network reliability and thus to improve smart grid system performance, there is an urgent need for reliable communication protocols.

In this thesis, firstly the performance of ZigBee has been evaluated then an Adaptive Forward Error Correction (AFEC) mechanism has been developed to address the challenges in the reliability of wireless communications, and finally, a multi-channel scheme has been applied for different smart grid environments, including an indoor main power control room, an outdoor 500 kV substation environment, and an underground network transformer vault environments.

Importantly, these performance evaluations are based on a comprehensive set of real-world field tests using IEEE 802.15.4 compliant wireless sensor nodes deployed in smart grid environments at Georgia Power, Atlanta, GA, USA. Comparative performance evaluations are performed in terms of network throughput, packet delivery ratio, end to end delay, and energy consumption.

Keywords: Smart Grid, Wireless Sensor Networks, Adaptive Error Control, ZigBee, Multi-Channel, NS-2

ÖZET

AKILLI ŞEBEKE UYGULAMALARI İÇİN UYARLANABİLİR KABLOSUZ ALGILAYICI AĞLARI PROTOKOLLERİ

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Günümüzün elektrik enerjisi sistemleri yaygın ve etkili iletişimin, izlemenin ve otomasyonun eksikliğinden sıkıntı çekmektedir. Bu problemlerin üstesinden gelebilmek için yeni bir elektrik sistemi olan akıllı şebekeler önerilmiştir. Akıllı şebekelerin ana fikri, geleneksel elektrik dağıtım sistemlerinde enerji tüketimini düşürürken verimliliği, güvenilirliği ve güvenliği arttırmak içim izleme, kontrol ve iletişim yetenekleri eklemektir. Önemli vurgulamak gerekir ki, akıllı şebekeler elektrik dağıtım şirketlerine elektriğin elektrik enerji şebekeleri etrafında mümkün olduğu kadar ekonomik şekilde taşınmasına izin verir.

Son zamanlarda, kablosuz algılayıcı ağları akıllı şebeke ortamlarında oldukça kullanılmaya başlanmıştır. Kablosuz algılayıcı ağların kolay yerleştirilmeleri, ucuz maliyetleri, esnekliği, paralel işlemeyle bütünleşmiş akıllılığı gibi yardımcı operasyonları, geleneksel iletişim teknolojileri üzerinde belirli avantajlar getirmiştir.

Ayrıca, IEEE 802.15.4 standartına dayalı olan ve akıllı şebeke ortamlarında enerji ilişkili bilgi iletişimi için ekonomik bir çözüm öneren bir uygulama profili olan ZigBee Akıllı Enerji Profili geliştirilmiştir. Akıllı şebeke uygulamalarında ZigBee'nin düşük maliyet, az enerji, az bant genişliği, düşük karmaşıklık, kolay yerleştirilmesi ve kolay kodlanabilir gibi ana özellikleri ZigBee'yi izleme, veri toplama ve analiz için ideal kılar.

Bununla beraber, çetin enerji sistemi çevrelerinden dolayı yüksek paket kayıpları ve bağlantı kapasite çeşitliliği akıllı şebeke sistemlerinde kablosuz iletişimin güvenilirliğinde büyük zorluklar yaratır. Bundan dolayı, ağ güvenilirliğini ve dolayısıyla akıllı şebekelerin performansını arttırmak için, güvenilir iletişim protokollerine acil ihtiyaç vardır.

Bu tezde, bir iç ana enerji kontrol odası, bir dış 500 kv trafo merkezi ortamı ve bir yer altı ağ iletişim ortamı gibi farklı akıllı şebeke ortamları için ilk olarak ZigBee'nin performansı test edilmiştir, sonra kablosuz iletişimlerin güvenilirliğindeki zorlukları çözmek için değiştirilebilir FEC mekanizmaları geliştirilmiştir ve son olarak, çoklu kanal şemaları uygulanmıştır.

Önemli vurgulamak gerekir ki, bu performans değerlendirmeleri Atlanta ABD'de bulunan Georgia Enerji'deki akıllı şebeke ortamlarına yerleştirilmiş olan IEEE 802.15.4 kablosuz algılayıcı ağlarını kullanarak bulunmuş karşılaştırmalı gerçek test değerlerine dayandırılmıştır. Karşılaştırılmalı performans değerleri ağ veri hacmi, paket teslim oranı, sondan sona gecikmeye ve enerji tüketimine dayanılarak uygulanmıştır.

Anahtar Kelimeler: Akıllı Şebekeler, Kablosuz Algılayıcı Ağları, Uyarlanabilir Hata Kontrolü, ZigBee, Çok Kanallı, NS-2

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LIST OF ABBREVIATIONS

Acknowledgement	: ACK
Adaptive Forward Error Correction	: AFEC
Advanced Metering Infrastructure	: AMI
Automatic Repeat Request	: ARQ
Acquitted Reception Rate	: ARR
Beacon Interval	: BI
Contention Access Period	: CAP
Contention Free Period	: CFP
Carrier Sense Multiple Access with Collision Avoidance	: CSMA-CA
Field Area Networks	: FANs
Forward Error Correction	: FEC
Full Function Devices	: FFD
Guaranteed Time Slots	: GTS
Home Area Networks	: HANs
Industrial, Scientific and Medical	: ISM
Link Quality Assessments	: LQA
Link Quality Estimators	: LQE
Link Quality Indicator	: LQI
Link Quality Measurements	: LQM
Low Rate Wireless Personal Area Networks	: LR-WPAN
Neighbor Area Networks	: NANs
Organization for Economic Corporation and Development	: OECD
Packet Reception Ratio	: PRR
Reduced Function Devices	: RFD
Received Signal Strength Indicator	: RSSI
Required Number of Packet	: RNP
Signal to Noise Ratio	: SNR
Transmission and Distribution	: T&D

Vehicle-to-Grid	: V2G
Wireless Multimedia Sensor and Actor Networks	: WMSANs
Wireless Sensor Network	: WSN
Wireless Sensor Networks	: WSNs

1. INTRODUCTION

1.1 BACKGROUND

The increasing in energy consumption and generation has continually grown and more intelligent processes will be introduced into the electric power delivery networks. According to Energy Information Administration, there is a 1.3 and 3.5 percent increase each year in energy consumption for OECD (Organization for Economic Corporation and Development) and non-OECD nations, respectively (U.S. Department of Energy, 2008). It is envisioned that the electric power grid will move from an electromechanically-traditional-controlled system to an electronically -smart- controlled network in the coming future.

The increment of the energy consumption leads to black outs, voltage sags and overloads, which significantly decrease the power quality and reliability. In addition to these problems, the existing power grid suffers from the lack of pervasive and effective communications, monitoring, and automation. These drawbacks cause region-wide system breakdown due to the cascading effects initiated by a single fault (Güngör, et al., 2010), (U.S. Department of Energy, 2004). The blackouts and power quality issues cost the U.S. businesses more than $100 billion on average each year (Bilgin and Güngör, 2010), (Güngör,et al., 2010), (U.S. Department of Energy, 2004).

To overcome these problems, recently a new approach, called smart grid as shown in Figure 1.1 (pge.com) and Figure 1.2, has been emerged (Bilgin and Güngör, 2010), (Ullo, et al., 2010), and (Erol-Kantarci and Moftah, 2010). As shown in Figure 1.1, smart grid has 5 different segments. First one is energy infrastructure segment. It is a physical infrastructure that distributes energy. Second segment is communication infrastructure. This segment helps to transmit critical data of smart grid. Third segment is communication and information technology segment. Providing modeling, analysis, web presentment, and commercial transaction is in this segment. Fourth segment is business applications that create business value. Fifth segment is security segment that helps data integrity for customers and utilities.

Smart grid infrastructure from power generation to customer side is shown in Figure 1.2. There are many control and automation center in this infrastructure, including control center, substation automation system, distribution control and automation systems, and etc.

An illustrative framework of the smart grid is shown in Figure 1.3 (pge.com). As shown in Figure 1.3, the existing and envisioned applications of smart grid span a very wide range in consumer, transmission and distribution side, and consumer side of smart grid. The information technologies that used in smart grid are servers, data storage, web presentment, etc. WiMax, Fiber/MPL, RF mesh, WSNs, HANs, and cellular infrastructures are used. In this thesis, we used WSNs as communication infrastructure. There are different energy infrastructures for different environments.

The main idea of smart grid is to add monitoring, control, and communication capabilities to the traditional electricity delivery system to improve efficiency, reliability, and safety while reducing the energy consumption. Importantly, the Smart Grid will allow the electric utilities to move electricity around the electric power grid as economically as possible.

With the integration of smart grid technologies with the power grid, the reliability and security of the power system are expected to increase, while simultaneously enabling the end-users to make informed decisions about their energy consumption, resulting in large-scale implementation of load control and demand response programs (Bilgin and Güngör, 2010).

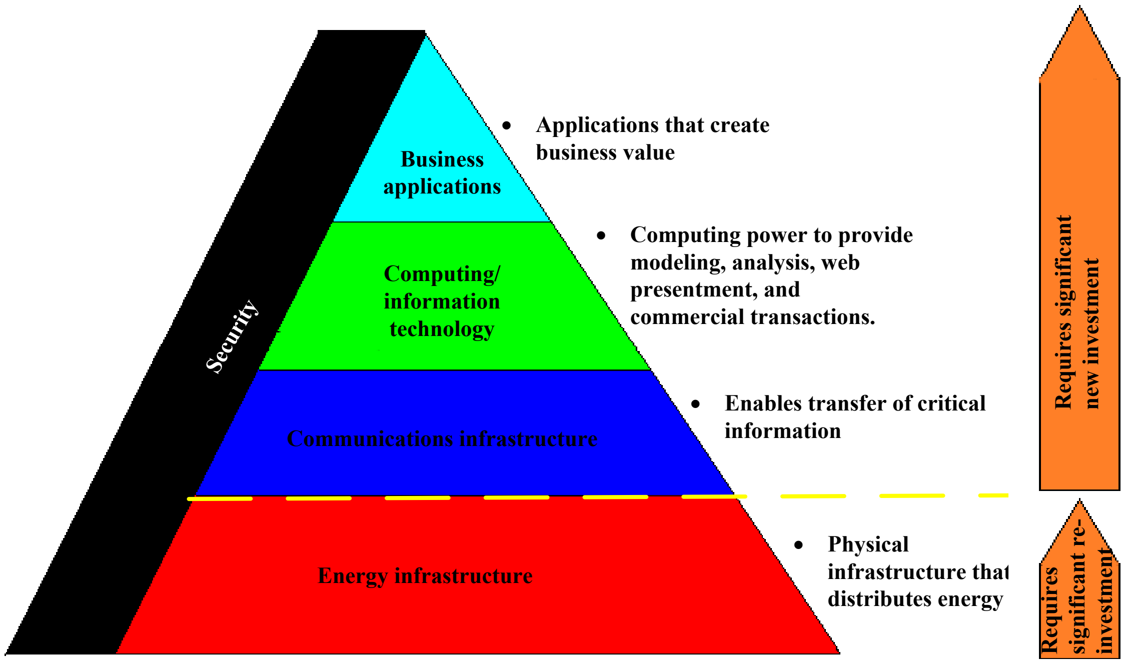

Figure 1.1 : What is smart grid?
Reference: www.pge.com

Recently, making research and development on smart grid applications and technologies have been started in Australia, Canada, China, South Korea and USA. The largest power grid modernization investment in the U.S history, i.e., $ 7.1 billion in grant awards, has recently announced by the U.S. Government in 2010. Also China Government announced that $7.3 billion would be spent into creation of a cleaner, more energy efficient Smart Grid in 2010.

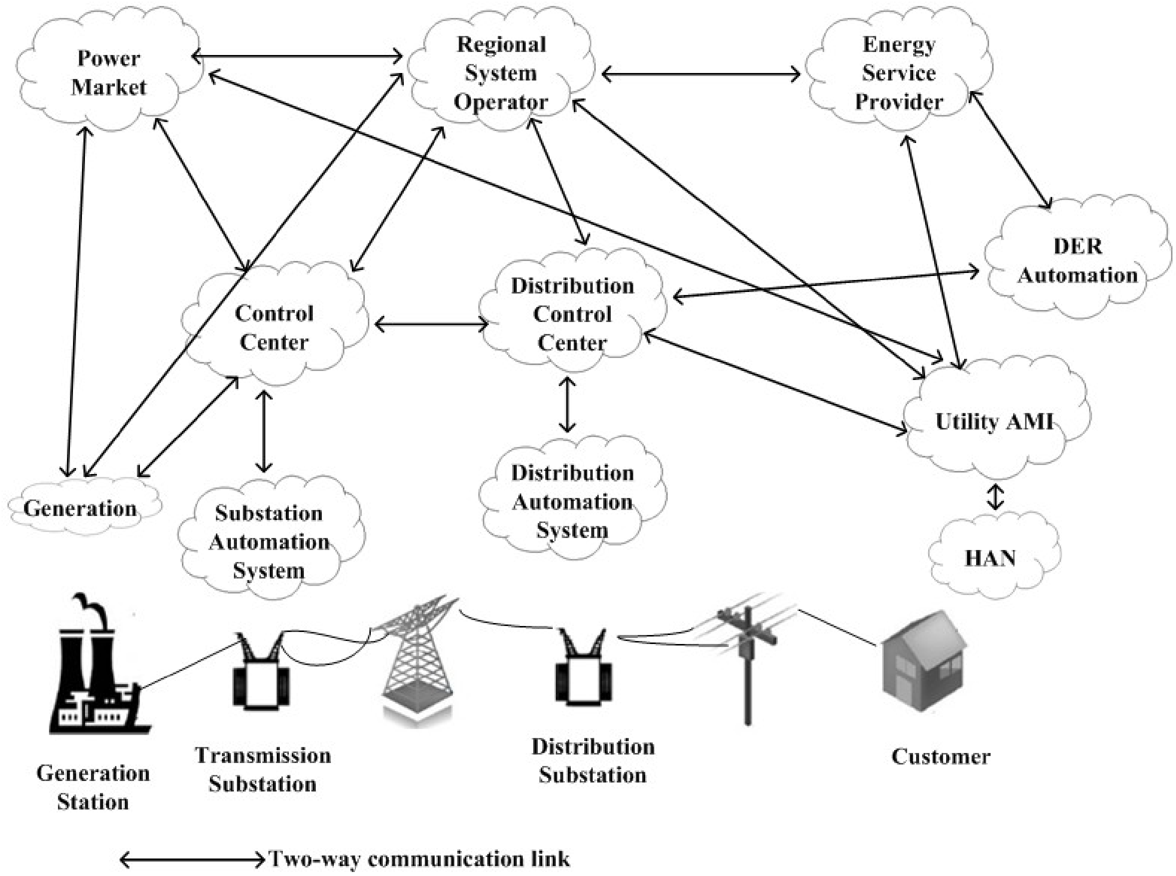

Figure 1.2 : Smart grid infrastructure

However, the electric power system environments are very harsh. This harsh environment may cause link failures and challenges in the reliability of wireless communications in smart grid applications. Therefore, adaptive WSNs protocols should be perform in smart grid applications to increase the network reliability and the system performance.

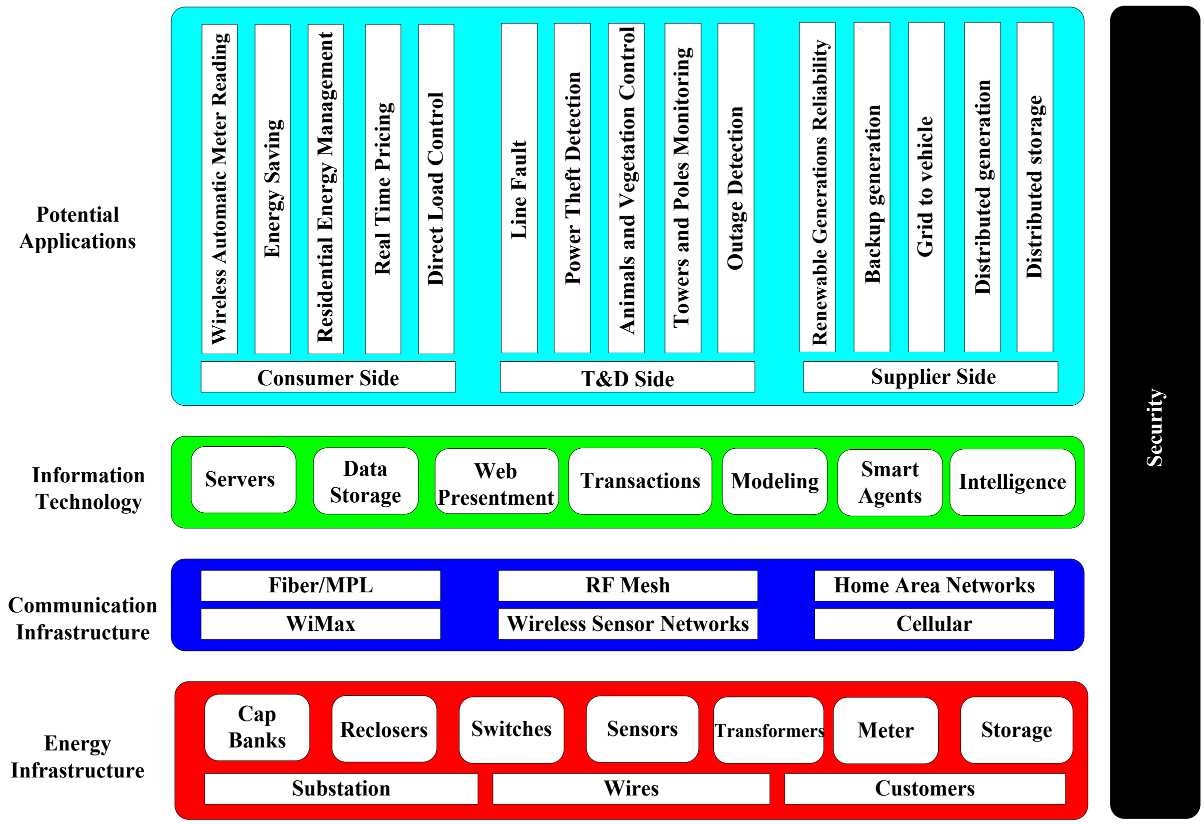

Figure 1.3 : Smart grid framework
Reference: www.pge.com

1.2 TRADITIONAL GRIDS VS. SMART GRIDS

There is a comparison between today's grid and smart grid according to principal characteristics of the electric power systems, including self-repairing, motivates and includes the end user, resists attack, provides power quality for 21st century needs, accommodates all generation and storage options, enables markets, optimizes assets and operates, efficiently in Table 1.1 (U.S. Department of Energy, 2008). An illustrative framework of the today’s power grid and future power grid are shown in Figure 1.4 and Figure 1.5 respectively (pge.com).

As shown in Figure 1.4, today's power grid has limited communication and computing capability. This reduces reliability, security, etc. If there is an error on any side of grid system, it may take lots of time to understand the problem. Also, there is no energy storage option or adding renewable energy on the today's power grid system. So increase in energy consumption causes problems.

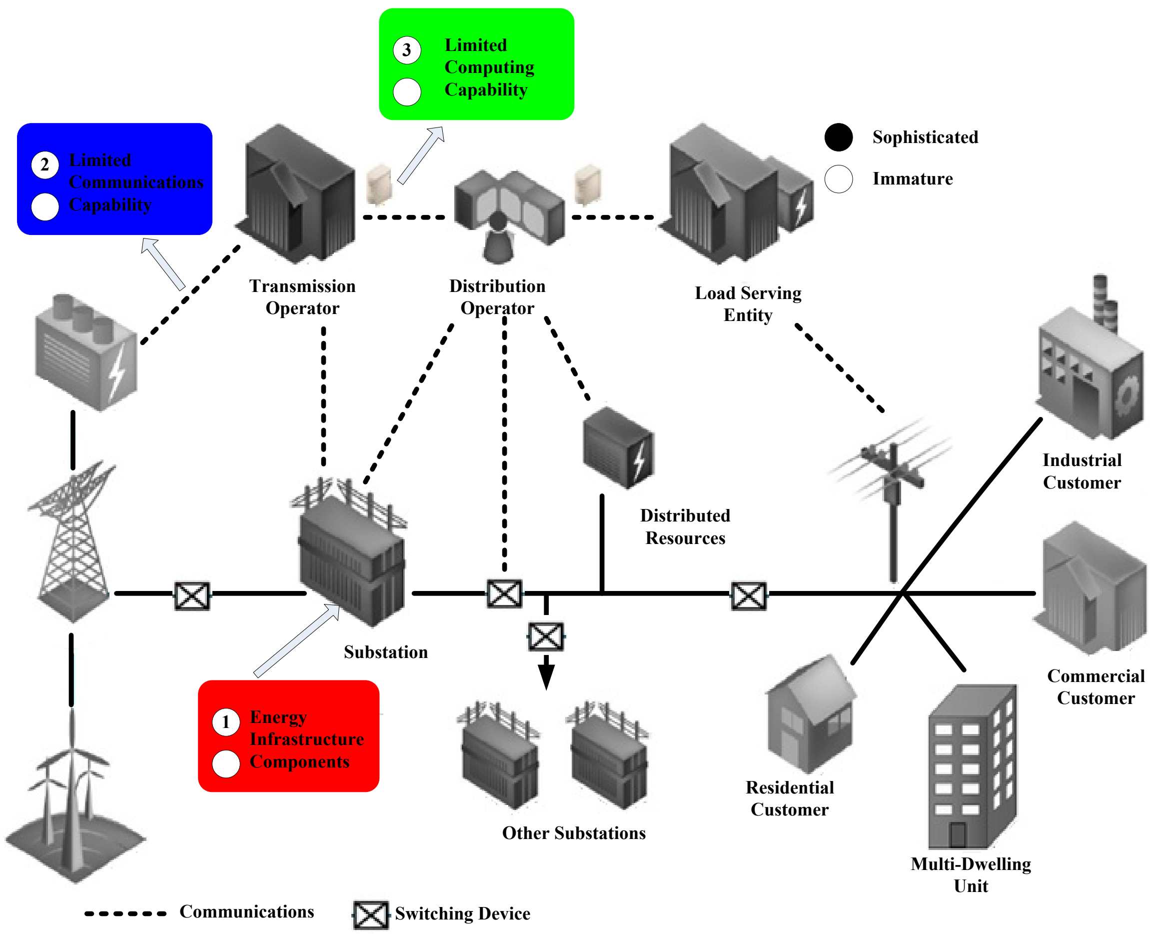

Figure 1.4 : Today's power grid infrastructure
Reference: www.pge.com

As shown in Figure 1.5, future power grid has more communication capability that increases the system performance and reliability. There are distributed computing systems. There is two way communications in this infrastructure using smart sensors that enables transmit data from utilities to customer and also from customer to utilities at the same time.

Moreover, there are advanced applications in future grid, including AMI, energy storage, using renewable energies, and etc.

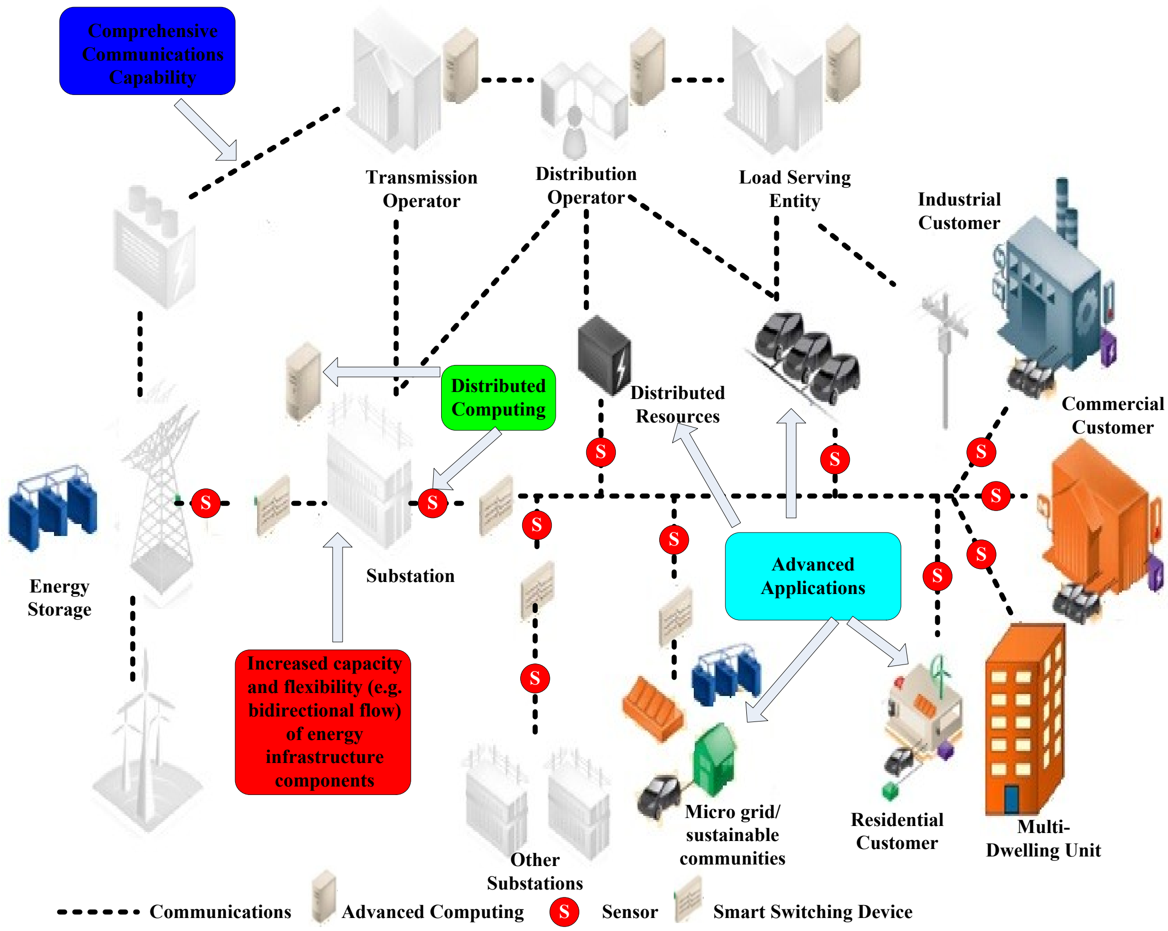

Figure 1.5 : Future power grid infrastructure
Reference: www.pge.com

Table 1.1 : Comparison between today's grid and smart grid

Characteristics	Today's Grid	Smart Grid
Self-repairs	Reacts to avoid further damage. Focus is on protection of assets.	Online monitoring detects and reacts to problems automatically. Focus is on prevention.
Motivates & includes the end user	End users do not have any information about power system.	End users are informed, involved and active.
Resists attack	It is open to attacks and natural disasters.	It is flexible to attack and natural disasters.
Provides power quality for 21st century needs	Black outs problems are more important than power quality problems.	Power quality is determined according to industry standards and consumer needs.
Accommodates all generation and storage options	Comparatively number of large generating plants is small.	There are too many diverse distributed generation and storage devices to complement the large generating plants.
Enables markets	Working to find the best operating models in limited wholesale markets is still going on. Transmission congestion separates buyers and sellers.	The integration of mature wholesale with reliability coordinators is good. It minimizes the transmission congestion and constraints.
Optimizes assets and operates efficiently	The integration of asset management processes and technologies with limited operational data is not deeply. Time based maintenance.	The integration of asset management processes and technologies with limited operational data is deeply. Condition based maintenance.

Reference: www.energy.gov

As shown in the comparison table, smart grids have more advantages of electric power systems than traditional grids. Smart grid systems improve the reliability of electric power systems, provide data integrity, provide more power quality, and etc.

1.3 RESEARCH CHALLENGES

Although smart grid brings many advantages to electric power system, there are some researches challenges need to be integrated and deployed. These challenges are as follows:

- Large-scale stochastic renewable generation
- Electric energy storage
- Distributed generation
- Plug-in hybrid electric vehicles
- Demand response
- Ensuring security
- Collecting and analyzing massive amounts of data
- Maximizing return on investment
- Connecting large number of devices
- Transmitting data over multiple media
- New synchronized measurement technologies
- New sensors
- New system integrity protection schemes

These are general challenges of smart grid and challenges about sensor network are represented in second chapter.

1.4 THESIS OUTLINE

During this thesis, a general outline will be drawn to the performing adaptive WSNs protocols in the different smart grid environments.

In this study, we firstly explored the WSN-based smart grid applications in chapter two. Then, the performance of ZigBee in different smart grid environment has been evaluated in chapter three. After that, in chapter four, AFEC mechanism has been performed to overcome the problems in the reliability of wireless communications in smart grid environments. In chapter five, a multi-channel scheme has been applied for different smart grid environments. And finally we conclude the thesis in chapter six.

The data that used in performance evaluations are based on a comprehensive set of real-world field tests using IEEE 802.15.4 compliant wireless sensor nodes deployed in smart grid environments at Georgia Power, Atlanta, GA, USA.

2. WIRELESS SENSOR NETWORK-BASED SMART GRID APPLICATIONS

2.1 BACKGROUND OF WSN

Recent advances in sensor technologies and wireless communication have enabled the development of sensor nodes in many applications, including military sensing, physical security, traffic surveillance, industrial and manufacturing automation, environment monitoring, and building and structures monitoring (Akyildiz, I.F., et al., 2002).

Sensor nodes which are multifunctional and low in cost, power have been started to use in short distance with the recent advances in wireless communications and electronics. Although sensor networks have been used in many applications, including monitoring, security, health, and recently in smart grid applications, technical challenges such as fault tolerance, harsh and uncertain environments, scalability, hardware, and bandwidth constraints affect sensor networks (Yang and Lambert, 2007).

Control systems and monitoring are typically realized through wired communications in the traditional electric power grid. However, this is very expensive solution because of required communication cables to be installed and regularly maintained. Control systems and online monitoring systems have become cost-effectively with the recent advances in WSNs in the smart grid environments. In these systems, important parameters, including voltage, current, temperature, and other related data are monitored and then either transmitted to a centralized station or processed locally in a data processing system by the nodes that are deployed on the critical equipments of the smart grid. In this regard, WSNs play a vital role in creating a highly reliable and self-healing smart electric power grid.

Other wireless communication standards, including Wi-Fi, Z-wave, and ZigBee, also have been started to use in smart grid applications. In smart grid applications, including Home Area Networks (HANs), Neighbor Area Network (NANs), and Field Area Networks (FANs), Wi-Fi has been used. Wi-Fi technology has high data rate. This feature may be ideal for smart grid application but it requires higher energy. Z-wave is another communication standard which based on short range and low data rate protocol protocols and supported by Z-wave alliance. Z-wave is used in home control and management, energy conservation, home safety and security systems, home entertainment. Although it's applications span a very wide range and 200 worldwide manufacturer supporters, it is not an open source protocol. ZigBee which is an open platform and based on IEEE 802.15.4 standard offers an affordable way for communicating energy-related information, including price, energy consumption, in smart grid environments. These features of ZigBee make it ideal for smart grid applications (Bilgin and Güngör, 2010).

2.2 WSN IN SMART GRID ENVIRONMENTS

The existing smart grid application based on WSN is summarized as follows:

2.2.1 Conductor Temperature and Dynamic Thermal Rating Systems

Conductor operating temperatures is important and so the temperatures measurements need to be directed to electric utilities. Also to increase the power carrying capabilities there is need for real time monitoring of electric cables thermal conditions. Online temperature monitoring systems which measure the conductor temperature with sensors is used in power donuts and power lines. These sensors are self-powered (Yang and Lambert, 2007).

2.2.2 Wireless Automatic Meter Reading

By using Wireless Automatic Meter Reading (WAMR) systems, there is no need for human readers and online pricing model. So this feature helps to electric utilities to reduce their operational cost. The requirement of two way communications can be addressed by the

WSNs by providing low-cost and low power wireless communications (Güngör, et al., 2010).

2.2.3 Line Fault and Power Theft Detection

Current or earth faults, including environmental problems, earthing of phase line, may cause economic problems. For example, the blackouts and power quality issues cost the U.S. businesses more than $100 billion on average each year. The main reasons of blackouts and power quality issue are lack of online monitoring and wrong coordinated of protection devices. For example, still in many areas of the United States, outage is realized only if a customer calls to report it. By using WSNs on critical equipments an online monitoring control system can be provided.

In some countries power theft is a major problem. Power theft can be in several ways, including meter tampering, billing irregularities and illegal connections. With the usage of WAMR power theft can be tackled or minimized (Devidas and Ramesh, 2010).

2.2.4 Energy Saving

It is commonly known that unit price of electric is higher in peak hours according to off-peak hours. To decrease the energy consumption in peak hours, transfer of power to customer can be limited. If customer reaches the critical limit a warning message can be send to the customer. And if the used energy exceeds in the peak hours, electric of that customer can be cut. Not to exceed the use of electric in peak hours, customer should use only the required devices. This method helps to save large amount of energy and also decrease the energy bills (Devidas and Ramesh, 2010).

2.2.5 Residential Energy Management

Recently, some commercial products that help customer to reduce energy bills and consumption, including Google PowerMeter, Microsoft Hohm and Intel Home Dashboard

Concept, have been developed and started to deployed. These products give personalized tips, allow seeing energy consumption online and providing security and remote control (Erol-Kantarci and Moftah, 2010).

2.2.6 Animals and Vegetation Control

Branches of trees and predaceous animals cause problems, including damaging cable, short circuit, and etc. on power distribution systems. These problems leads to black outs and reducing in reliability. Detection of animals and vegetation is achieved by WSNs (Devidas and Ramesh, 2010).

2.2.7 Underground Cable System

In the underground power lines, various failures occur in joints and terminations. However, maintenance of the system last much longer according to overhead lines. There are some existing technologies, including coaxial cable sensors, inductive sensors, acoustic emission techniques, fiber optic distributes sensor, and etc. to monitor and diagnose the underground cables (Devidas and Ramesh, 2010).

2.2.8 Towers and Poles Monitoring

Outages and higher repair costs are occurred by failures on poles or tower. Timely manner monitoring and control is important to maximize the system performance and equipment life. As mentioned, WSNs offers timely manner monitoring and control and this makes them a vital component in power distribution system (Devidas and Ramesh, 2010).

2.2.9 Real Time Pricing

With the integrating WAMR, to learn the real time energy consumption of customers have been enabled. This lets to customer learn real time pricing. Moreover, this enables shifting loads during peak times.

2.2.10 Outage Detection

Existing distribution networks suffers from lack of online monitoring. Therefore, there is no any outage detection that works real time. In other words, reliability is low in current system. With the two way communication of WSNs, reliability can be increased by implementing outage detection and online monitoring systems.

2.2.11 Direct Load Control of Home Appliances

By connecting Reduced Function Nodes (RFNs) to the home appliances power supply switches can be controlled. These RNFs are connected to the Fully Function Nodes (FFNs) have some advanced functions, e. g. routing. These functions help to control the load of HANs automatically.

2.2.12 Renewable (Green) Generations Reliability

Recently, Wireless Multimedia Sensor and Actor Networks (WMSANs) applications have been started to use in smart grid systems, especially in renewable generation systems, including wind farms, solar farms.

In wind farms, critical parameters that affect the power quality, including pressure, humidity, and temperature can be monitored by using WMSANs. Both audio and image can be collected for these important parameters to detect collision and to identify the fault.

In solar farms, to monitor sky and weather conditions WMSANs can be used. These sensors can collect information about panels, radiation, current and voltage. The collected information can be used to predict the energy.

2.2.13 Mobile Broadband Wireless Access

MBWA which offers real time peak data rate can be used in broadband communication for plug-in electric vehicles, monitoring and SCADA systems.

Table 2.1 : Sensor network applications in smart grid

Applications	**Power Grid Segment**
Real Time Pricing	Consumer Side
Wireless Automatic Meter Reading	Consumer Side
Residential Energy Management	Consumer Side
Direct Load Control of Home Appliances	Consumer Side
Outage Detection	T&D Side
Line Fault and Power Theft Detection	T&D Side
Animals and Vegetation Control	T&D Side
Underground Cable System Monitoring	T&D Side
Towers and Poles Monitoring	T&D Side
Conductor Temperature and Dynamic Thermal Rating Systems	T&D Side
Wind Farm Monitoring	Generation Side
Solar Farm Monitoring	Generation Side
Traditional Power Plant Monitoring	Generation Side

2.3 RESEARCH CHALLENGES FOR WSN IN SMART GRID SYSTEMS

The major technical challenges of WSNs in smart grid applications can be outlined as follows:

2.3.1 Reliability

Due to the some problems, including lack of power or physical problems, some sensor nodes may fail. Packet failure and link capacity also affect the reliability of WSNs. But these failures should not affect the network. Each WSNs based smart grid application needs different reliability requirements. So it is important to determine the required specifications in terms of reliability (Güngör, et al., 2010).

2.3.2 Harsh and Uncertain Environments

The environment of power system is very harsh. This environmental condition increase packet error rates and also cause defects of some sensor nodes and thus decrease the reliability and system performance of the smart grid system. In this situation, it is important to develop some adaptive error control mechanism for this harsh environment (Güngör, et al., 2010).

2.3.3 Hardware and Bandwidth Constraints

Sensing unit, processing unit, transceiver unit and power unit are the four basic components of sensor nodes. The hardware constraints of sensor nodes are limited power, computation and memory capacity. Larger flash memory on a separate chip and tiny multi-threading distributed operating systems can be used for these constraints (Bilgin and Güngör, 2010).

2.3.4 Standardization of Sensors

There are many sensor manufacturers that provide solutions the existing systems. Sensor nodes that belong different venders should be interoperable with each other. Also open standards such as IEEE 802.15.4 should be used in the wireless communication. They help to decrease the cost (Bilgin and Güngör, 2010).

2.3.5 System Performance And Data Integrity

Since a WSN is the combination of the large number of wireless sensor nodes, large streams of data may overload the system. Also same data packets may be transmitted to the receiver. This affects the battery life of sensor nodes (Bilgin and Güngör, 2010).

2.4 WIRELESS CHANNEL MODEL

To overcome the problems of current electric power system, recently a new approach, called smart grid, which updates traditional power grids by carrying electricity using digital technology, has been emerged. The main idea behind smart grid is to add monitoring, control, and communication capabilities to the national power delivery system to improve the productivity of the system while reducing the energy consumption. The smart grid will also allow the people to use electricity as economically as possible.

In our previous study (Güngör, et al., 2010), we have modeled wireless channel in different smart grid environments, i.e., outdoor 500kV substation environment, underground transformer vault environment, and main power room environment (as shown in Figure 2.1) through a comprehensive set of real-world field tests using IEEE 802.15.4 compliant wireless sensor nodes as shown in Figure 2.2 (Güngör, et al., 2010). Specifically, the log-normal shadowing path loss model has been used. This model is used for large and small coverage systems and moreover, experimental studies have shown that it provides more accurate multi-path channel models than Nakagami and Rayleigh models for indoor wireless environments with obstructions (Rappapport, T., 2002).

In log normal shadowing path loss model, the signal to noise ratio γ (d) at a distance d from the transmitter is given in Equation 2.1:

$$\boldsymbol{\gamma(d)_{dB} = P_T - P_L - 10_{\eta} log_{10} \frac{d}{d_0} - X_{\sigma} - P_{\eta}} \quad \textbf{(2.1)}$$

where P_T is the transmit power in dB_m , P_L (d_0) is the path loss at a reference distance d_0, η is the path loss exponent, X_σ is a zero mean Gaussian random variable with standard deviation σ , and P_η is the noise power in dB_m. Experimentally determined log-normal channel parameters for different power system environments are given in Table 2.2.

(a) (b) (c)

Figure 2.1 : Experimental sites a) outdoor 500 kV substation environment b) Indoor main power room, and c) Underground network transformer vault environments

Table 2.2 : Log normal shadowing channel parameters

Propagation Environment	**Path Loss (η)**	**Shadowing Deviation (σ)**
500 kV Outdoor Substation	2.42	3.12
Underground Transformer Vaults	1.45	2.45
Main Power Room	1.64	3.29

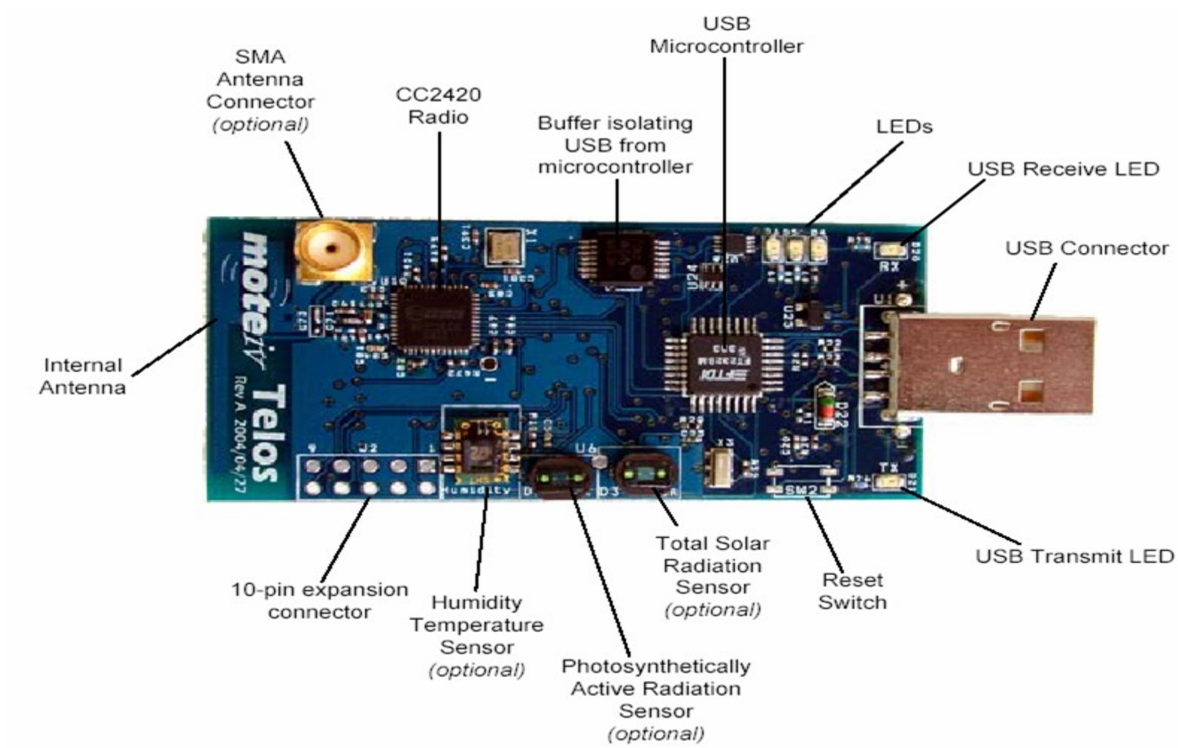

Figure 2.2 : TMote-Sky node used in channel modeling at smart grid environments

2.5 RELATED WORK ON SMART GRID COMMUNICATIONS

The major distinguishing characteristic of smart grid on communication is that it supports two-way and real-time communication whereas traditional power grids only support one-way and typically not real-time communication (Javadi and Javadi, 2010), (Cupp and Beehler, 2010). Two-way communication helps smart grid systems for real-time information and power exchange simultaneously and thus, increases the quality of power to the consumer in these systems (Aggarval, et al, 2010).

There are numerous studies on smart grid communications in the literature (Aggarval, et al, 2010), (Hauser, et al, 2005), (Hammons, 2006), (Chen, et al, 2010), (Luan, et al, 2010). These studies are mostly focus on network architecture and performance analysis, e.g., latency, bandwidth analysis, requirements for smart grid communications, new communication architecture for smart grids, and communication of Wireless Automatic Meter Reading (WAMR).

The requirements for robust communication infrastructure were explored and fortified (Aggarval, et al, 2010). The authors Hauser, et al. (2005) proposed new communication architecture for smart grids, i.e., GridStat, to overcome the problems in existing communication infrastructure, e.g., the types of controls and protection limitation. This architecture also makes it easier to implement the control and monitoring applications for smart grid systems. The author Hammons (2006) described the requirements of future communication networks at the power distribution level. Also, they explore the network design issues related to smart grid. There are also some studies about wireless communication standards for smart grid applications, including ZigBee, Wi-Fi, Z-wave, (U.S. Department of Energy), (Heile, 2010), (zigbee.org). ZigBee is new wireless technology based on IEEE 802.15.4 standard, which offers low-cost and low-power communications. There are some devices that are developed by the ZigBee Alliance for Advanced Metering Infrastructure (AMI) (Heile, 2010). Wi-Fi has also been used in smart grid applications, such as Home Area Networks (HANs), Neighbor Area Network (NANs), and Field Area Networks (FANs). Wi-Fi supports higher data rate than ZigBee, but it causes higher power consumption. Z-wave is short range and low data rate protocol supported by Z-wave alliance. There are over 200 worldwide manufacturer supporters, but the standard is not open source. The common existing application of Z-wave is remote home control and management, energy conservation, home safety and security systems, home entertainment (wikipedia.org/wiki/Zwave), (zwavealince.org/modules/AllianceStart).

The authors Erol-Kantarci and Moftah (2010) discussed the potential applications and challenges of Wireless Multimedia Sensor and Actor Networks (WMSANs) for smart grid. They suggest that security and safety of the power grid can be increased using multimedia content. They also discussed the opportunities WMSANs in energy generation, T&D facilities. Also, they described the challenges of WMSANs in power grids including QoS provisioning, latency, and battery, etc.

Although all these studies proposed important and necessary foundation in smart grid communication, there is no study about error control and correction based on a comprehensive set of real-world field tests using IEEE 802.15.4 compliant wireless sensor nodes in different smart grid environments. As mentioned before, the reliability of wireless communications in smart grid applications is affected due to the harsh electric power system environments. Therefore, it is clear that there is an urgent need for reliable communication protocols in smart grid applications to increase the smart grid system performance and communications reliability.

2.6 RELATED WORK ON WIRELESS LINK QUALITY MEASUREMENTS IN WSNS

There are numerous studies on wireless sensor networks about Link Quality Assessments (LQA), Link Quality Measurements (LQM), and Link Quality Estimators (LQE) (LaI, et al., 2003), (Baccour, et, al., 2009), (Jian and Hai, 2009), (Krogmann, et al., 2009), (Liu, et al., 2009), (Keshavarzin, et al., 2004), (Liang, et al., 2010) and (Baccour, et, al., 2010), (Liu, et al., 2010). These studies were performed in either indoor – factory and office – or outdoor environments. Some of these studies are simulation of the existing LQEs protocols (LaI, et al., 2003), (Baccour, et, al., 2009) and the others are about development of new LQE algorithms (Liang, et al., 2010), (Kolar, et. al, 2010). Also, the problem of co-existence between IEEE 802.11b and IEEE 802.15.4 networks has received a significant interest from the research community (Kolar, et. al, 2010), (Wapf and Souryal, 2009), (Tang, et al., 2007), (Guistiniano and Bianchi, 2007).

In these studies, different sensor platforms have been used, and each of them has had their specific frequency bands, protocols, channel modulation, and power levels. Despite their differences, their observations have mostly agreed on the following three aspects.

First, these studies have shown that there are three different packet reception regions in a wireless link, i.e., connected (effective), transitional, and disconnected (LaI, et al., 2003), (Baccour, et, al., 2009), (Jian and Hai, 2009), (Krogmann, et al., 2009), (Liu, et al., 2009), (Keshavarzin, et al., 2004), (Liang, et al., 2010). Second, wireless link quality varies over space and time significantly. Based on these empirical studies and measurements, it is also found that the coverage area of sensor radios is neither circular nor convex, and packet losses due to fading and obstacles are common at a wide range of distances and keep varying over time. Finally, link asymmetry and radio irregularity were observed in several studies (LaI, et al., 2003), (Baccour, et, al., 2009), (Jian and Hai, 2009), (Krogmann, et al., 2009), (Liu, et al., 2009), (Keshavarzin, et al., 2004), (Liang, et al., 2010). Link asymmetry occurs when a node can successfully send packets to another node but not vice versa, even if both nodes are set to the same transmit power.

In the related literature, the Link Quality Estimators (LQEs) can be classified in two main categories according to these studies i) hardware-based link-quality estimators and ii) software-based estimators (Baccour, et, al., 2010). In hardware-based link-quality estimators, some link quality metrics, such as Received Signal Strength Indicator (RSSI), Link Quality Indicator (LQI), and Signal to Noise Ratio (SNR), are used to avoid the large number of periodic control packets (Baccour, et, al., 2009), (Jian and Hai, 2009) and (Baccour, et, al., 2010), (Liu, et al., 2010). In software-based link-quality estimators, the metrics, such as Packet Reception Rate (PRR), Required Number of Packet transmission (RNP), and Acquitted Reception Rate (ARR), are used to count or estimate either packet reception ratio or average number of packet transmissions (Baccour, et, al., 2009), (Baccour, et, al., 2010). There are also some link-quality studies based on IEEE 802.15.4 standard (Hoffert, et al., 2005), (Jurcik, et al., 2007), (Rao and Marandin, 2006), (Rao and Marandin, 2006) and (Faruqe, and Helmy, 2010), (Zhuang, et al., 2010), (But, et al., 2010), (Ilyas, et al., 2009). However, none of them were applied in power distribution environments.

Although all these studies provide a valuable and solid foundation in WSNs, none of them addresses a statistical characterization of the wireless channel and link quality in indoor, outdoor and underground electric power system environments. In addition, the advances in sensor radio hardware as well as spatiotemporal link quality variations in electric power systems call for performance evaluations on IEEE 802.15.4-compliant sensor platforms deployed in different electric power system environments. These evaluations not only provide valuable insights about IEEE 802.15.4-compliant sensor network platforms, but also guide design decisions and tradeoffs for WSN-based smart grid applications.

3. PERFORMANCE EVALUATIONS OF ZIGBEE IN POWER DISTRIBUTION SYSTEMS

3.1 IEEE 802.15.4 OVERVIEW

Recently ZigBee Smart Energy profile has been developed, which is the application profile based on IEEE 802.15.4 standard and offers an affordable way for communicating energy-related information, such as price, energy consumption, in smart grid environments. It is an open platform facilitating the development of interoperable power-related devices from multiple vendors to automate the use of energy (Yi, et al, 2010), (zigbee.org). It also designed to specify communications to support behavior and does not reconstruct the existing home automation standards. Moreover, it makes homes greener by giving consumers information and automation. This information and automation help to reduce consumers' consumption and save money.

Two types of ZigBee networks, including Neighborhood Area Networks (NANs) for meters and communication with devices within the home, are required for metering and energy management in Smart Energy Management (zigbee.org). An illustrative architecture of the ZigBee Smart Energy has been showed in Figure 3.1.

The ZigBee Smart Energy Features are metering support, demand response and load control, pricing support, text message support (zigbee.org).

In metering support, meters can be used as electric, water and gas meter. Meters can read different measure units, including kg, lbs. Beside meters can log historical reading information. They enable to see real time consumption.

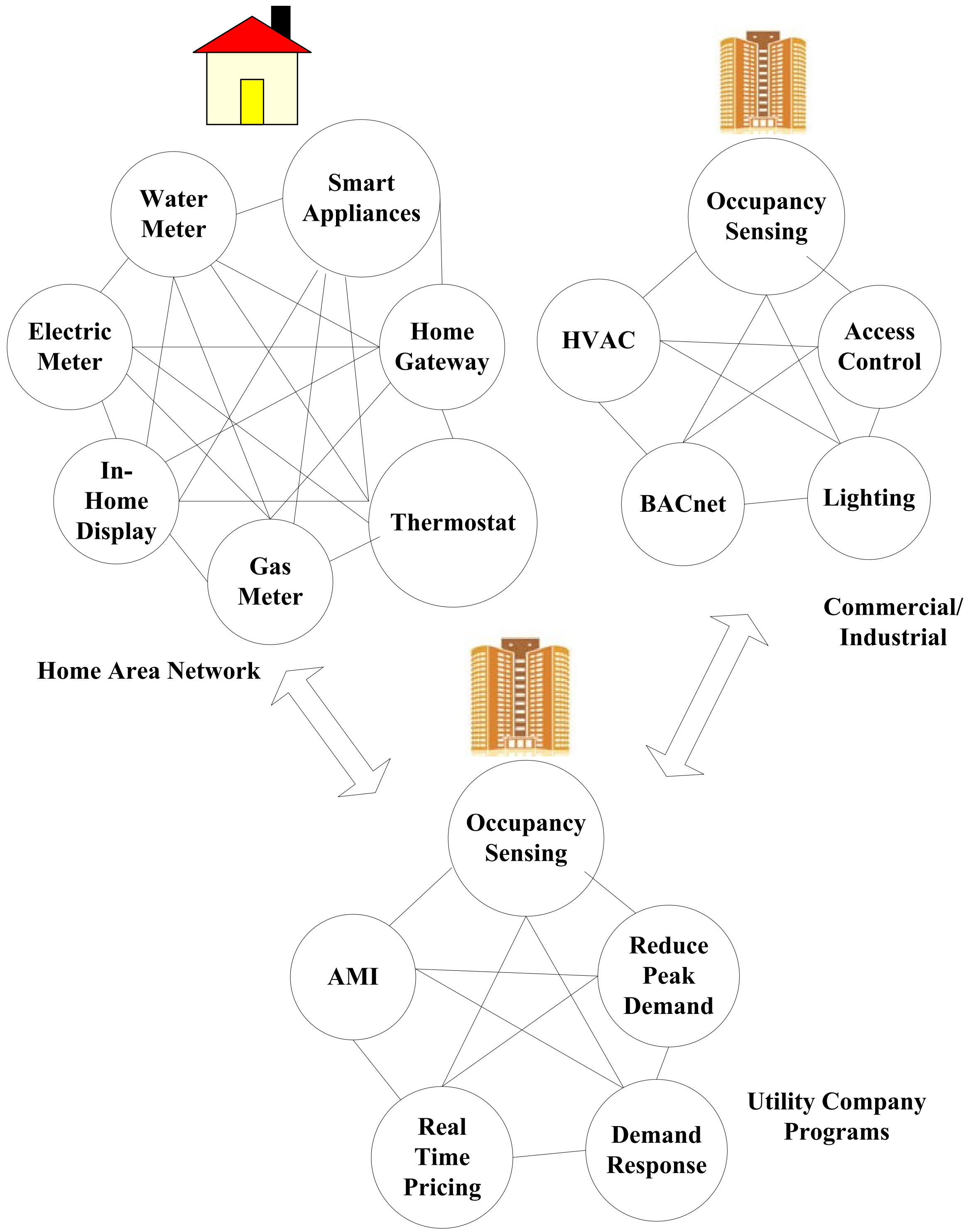

Figure 3.1 : An illustration of ZigBee smart energy

In demand response and load control, devices that are in HAN can be scheduled and canceled. Temperature, usage times, emergency signals, and etc. can be controlled. If the critical energy consumption level is exceeded in peak hours, devices may switch off.

In pricing support, using ISO 4217 standard different currencies for electric, water and gas commodities can be supported.

In text message support, if there is a problem or in peak hours, some messages are transmitted to ZigBee devices for consumers. Devices can show international characters. Real time consumption can be transmitted to the devices.

The existing ZigBee Smart Energy profile device types are Energy Services Portals (ESPs) which are used in meters, Programmable Communicating Thermostat (PCT) which is a programmable thermostat that can receive information wirelessly, Load Control Devices (LCDs) which control and monitor devices, including appliances, lighting, water heaters and dumb devices such as refrigerator magnets, glowing orb, etc. All these products are manufacturer independent. So this allows customer and utilities to purchase these products cheaper. The benefits of ZigBee Smart Energy have been summarized in Table 3.1.

In this section, since ZigBee is based on IEEE 802.15.4 standard, we describe the main features of IEEE 802.15.4 standard. In general, IEEE 802.15.4 is a wireless communications standard for Low Rate Wireless Personal Area Networks (LR-WPAN) (Ullo, et al., 2010), (Yi, et al, 2010), (zigbee.org). It is low in cost, power consumption, and data rate. Two basic network topologies are defined in this standard, i.e., star topology and peer-to-peer topology as shown in Figure 3.2.

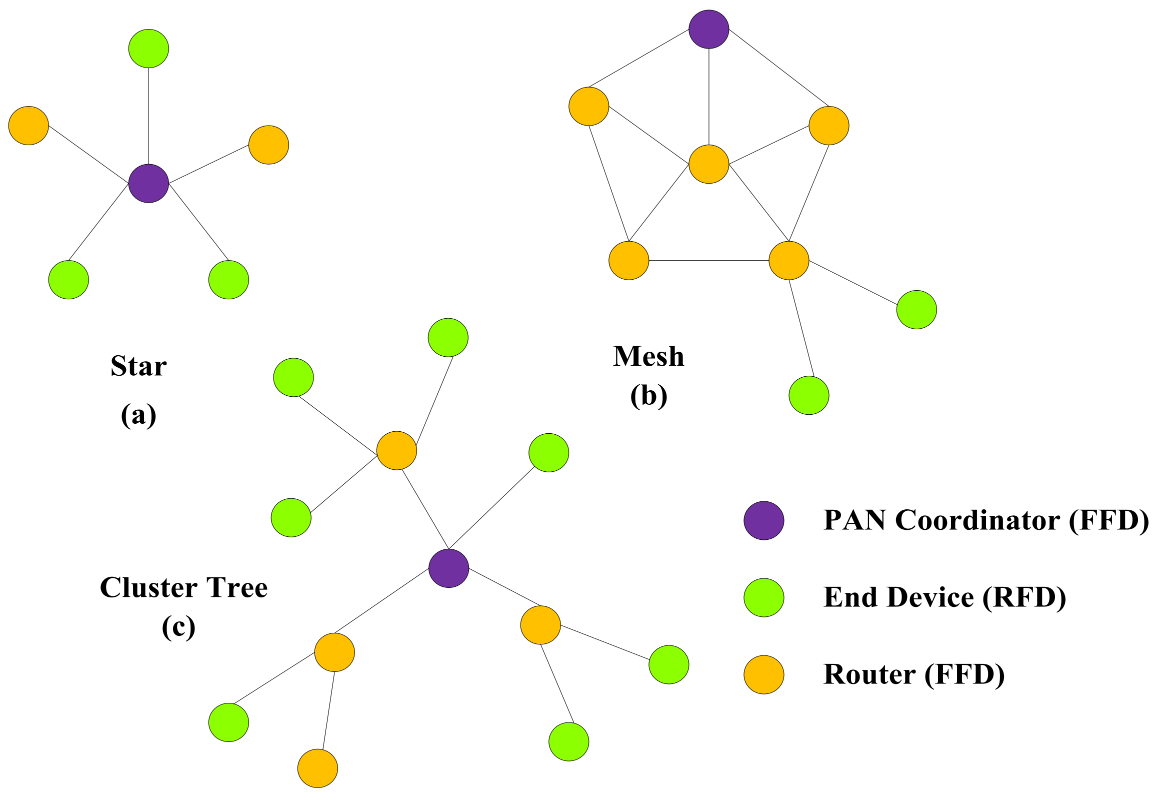

Figure 3.2 : Network topologies a) star topology, b) mesh topology, c) cluster tree

IEEE 802.15.4 standard is based on PHY and MAC layers as shown in Figure 3.3.

Table 3.1 : Benefits of ZigBee smart energy

Affordable	Vendors offer lower cost because of open standard so price of products starts to decrease.
Easy to Use	Wireless technology decreases the wire cost. 2.4 GHz spectrum makes simpler installation, operation, adoption and customer service.
Reduces Energy Consumption	Improves reliability. Reduces customer cost. Real-time usage information drives decision.
Reduces Environmental Impact	No need to extra generation plants. Improvement in footprint emissions and regulatory compliance Decreasing in impact on environment.

3.1.1 PHY Layer

The interface between MAC layer and physical radio channel is provided in this layer. Some of the tasks of PHY layer are:

- **Channel Frequency Selection:** It helps transceiver to select the channel upon receiving request.
- **Transceiver Activation and Deactivation:** According to receiving request transceiver is turned into transmitting, receiving or sleep mode.
- **Energy Detection:** The receiving signal power is estimated.
- **Link Quality Indication:** For each received packet LQI measurement is performed.
- **Clear Channel Assessment:** For energy detection or CSMA-CA CCA is performed.
- **Data transmission and reception:** Modulation and spreading techniques are used in this part (Zheng and Lee, 2004).

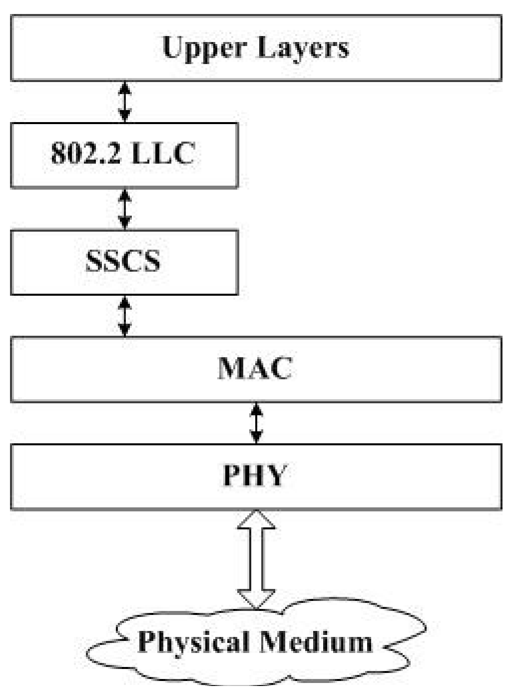

Figure 3.3 : IEEE 802.15.4 protocol stack

The IEEE 802.15.4-conformant devices can utilize one of three frequency bands for operation as shown in Figure 3.4. The first one is 868 MHz band with 20 kbps in Europe. The second one is 914 MHz band with 40 kbps in the USA. The last one is 2.4 GHz band with 250 kbps in the worldwide (Rao and Marandin 2006), (Rao and Marandin, 2006), (Yang, et al., 2007), (Andersson and Cornell, 2010). There are 27 channels in IEEE 802.15.4, 1 of them is in 868 MHz band, 10 of them is in 915 MHz band and 16 of them in 2.4 GHz band.

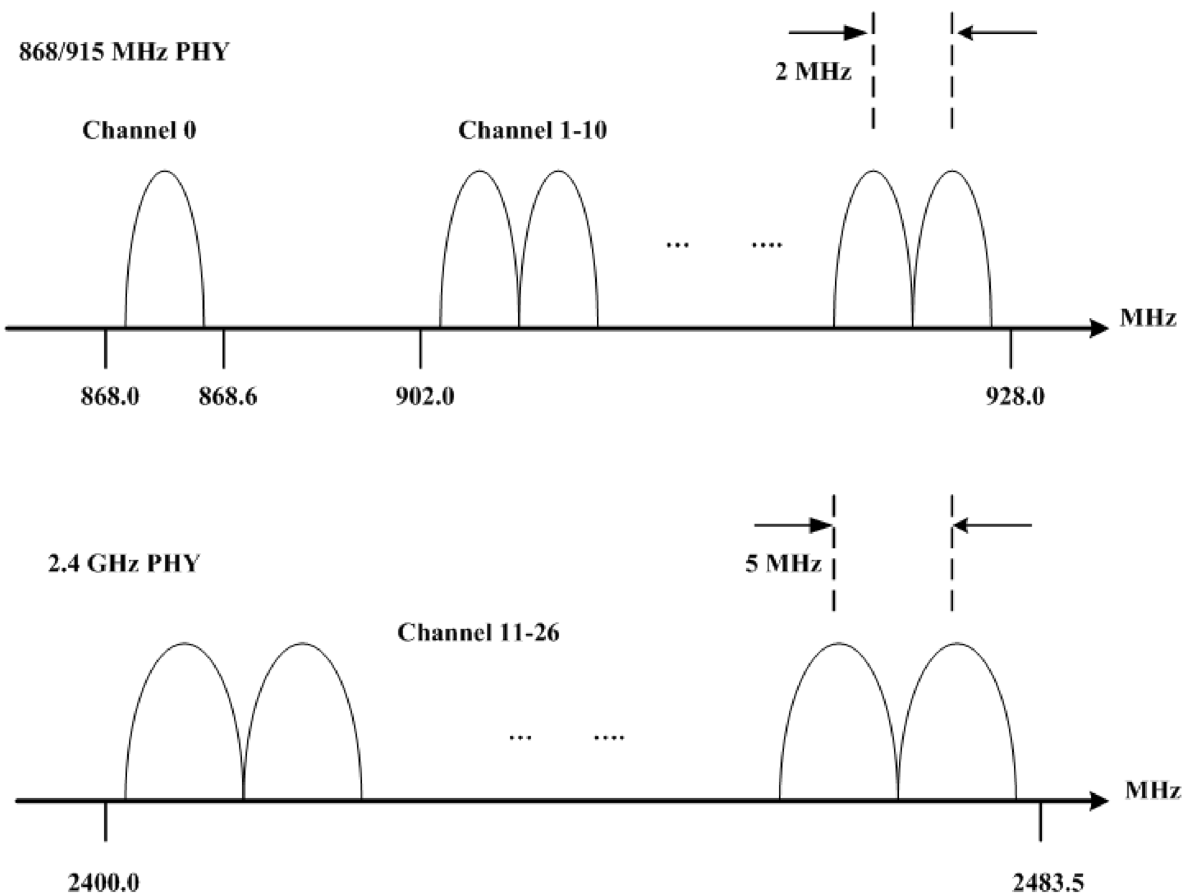

Figure 3.4 : IEEE 802.15.4 channel structure

3.1.2 MAC Layer

Interface between service specific convergence sublayer and PHY layer is provided in this layer. Some of the tasks of PHY layer are:

- **Generating Beacons:** According to superframe structure coordinator determines its working mode.
- **Synchronizing Beacons:** Beacons are synchronized with coordinator.
- **Managing Channel Access with CSMA-CA:** Using CSMA-CA method nodes try to access channel and since the IEEE 802.15.4 supports acknowledgements (ACK), it provides message ACKs.

3.1.3 Beacon and Superframe Structure

Overall, the MAC layer offers two operational modes:

- **Beacon-Enabled:** In beacon enabled mode, in every Beacon Interval (BI) a beacon is transmitted by the PAN coordinator to synchronize devices to enable the communication and to define the superframe structure as shown in Figure 3.5 (Hoffert, et al., 2005), (Jurcik, et al., 2007), (Rao and Marandin 2006), (Rao and Marandin, 2006), (Andersson and Cornell, 2010).
- **Nonbeacon-Enabled:** In nonbeacon-enabled mode unslotted CSMA-CA channel access mechanism is used to transmit data packets.

Furthermore, the IEEE 802.15.4 superframe structure has two different periods:

- **Active Period:** Active period contains 16 equal time slots and nodes communicate in this period. The active periods divided into 2 sections after the beacon:
  i. Contention Access Period (CAP): In the CAP, nodes compete to access to network and communicate with each other using CSMA-CA.

ii. Contention Free Period (CFP): In the CFP, Guaranteed Time Slots (GTS) is provided for the nodes. During these periods, devices access to channel without any contention. Devices may communicate in one way in these GTS. They may either transmit or receive data in one GTS period.

- **Inactive Period:** In the inactive period, devices may not communicate with the PAN coordinator and go to sleep mode to conserve energy.

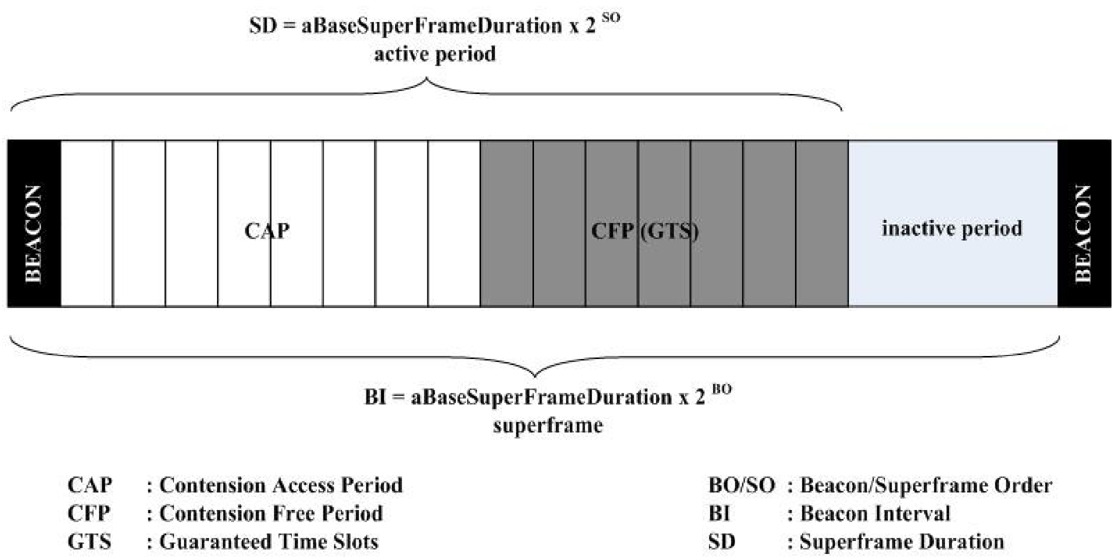

Figure 3.5 : IEEE 802.15.4 superframe structure

3.1.4 Function Devices

Moreover, the IEEE 802.15.4 standard has two types of devices (Hoffert, et al., 2005), (Rao and Marandin 2006):

- Full Function Devices (FFDs): FFDs can communicate with devices in the network and also act as PAN coordinator and initiate a PAN.
- Reduced Function Devices (RFDs). RFDs can only directly communicate with FFDs

64-bit IEEE address or a 16-bit short address is used in all devices in IEEE 802.15.4 network. Maximum 65536 devices can be in IEEE 802.15.4 network (Lee, 2005).

3.2 PERFORMANCE RESULTS

In this section, the performance evaluations of IEEE 802.15.4 in different power distribution environments, including indoor power control room, outdoor 500 kV substation and underground network transformer vault environments, are shown. This paper is based on our previous study (Güngör, et al., 2010), where the wireless channel in different smart grid environments has been modeled through a comprehensive set of real-world field tests using IEEE 802.15.4 compliant wireless sensor nodes in different electric power system environments at Georgia Power, Atlanta, GA, USA.

In this study, comparative performance evaluations have been conducted using ns-2 simulator based on experimentally determined log-normal channel parameters for different smart grid environments. For these performance evaluations, we have used ns-2 implementation of the IEEE 802.15.4 standard (Rao and Marandin 2006). The parameters used in our performance evaluations are listed in Table 3.2.

In the performance evaluations, we investigate the following performance metrics:

- ***Network Throughput*** represents the amount of data transmitted between transceiver in a specific time period.
- ***End to End Delay*** is the average time to receive all data on the destination side.
- ***Delivery Ratio*** is the ratio between the number of successful packets and the total number of transmitted packets.
- ***Energy Consumption*** represents the average percentage of the consumed energy by nodes.

Table 3.2 : Simulation parameters

Number of nodes	15
Number of traffic flows	8
Network topology	Star
Packet length	70 bytes
Traffic type	CBR
Queue Type	Drop Tail
Data rate	20 Kbps
Frequency band	868 MHz
Channel model	Log-normal Shadowing
MAC protocol	CSMA
Data rate	1 – 5 pkts/sec

Based on these performance metrics and simulation parameters, we present the performance results in Figure 3.6 to 3.9. Figure 3.6 shows the network throughput in different smart grid environment. Generally, when the data rate increases, network throughput also increases. But there are some inconsistent values such as when data rate is 4 pkts/sec for main power room and underground transformer vault, throughput decreases and then starts to increase again. And when the data rate is 5 pkts/sec for 500 kV substation environment, throughput decreases. Figure 3.7 shows the average end to end delay at receiver side. Average delay values are inconsistent but generally we can say it increases when the data rate increases. Figure 3.8 shows the delivery ratio in different smart grid environments. In our simulations, delivery ratio values decrease with the data rates and we observe that the delivery ratio ranges from 15% to 55% with varying packet rates. Figure 3.9 shows the energy consumption in different smart grid environments. In general, energy consumption values changes with increasing data rate.

It is also interesting that energy consumption values are not consistent for different smart grid. The other interesting point is in 500 kV substation and main power room environments the network achieves almost the same network throughput value at data rate of 2 pkts/sec and almost the same end to end delay time at data rate of 3 pkts/sec. In addition, the energy consumption in all three environments are the same at data rate of 3 pkts/sec. Also main power room environment and underground transformer vault environment have nearly same energy consumption values after the 2 pkts/sec data rate.

Overall, all these performance evaluations show that the ZigBee can only be used for low-data rate and low-power smart grid applications not having real-time deadlines.

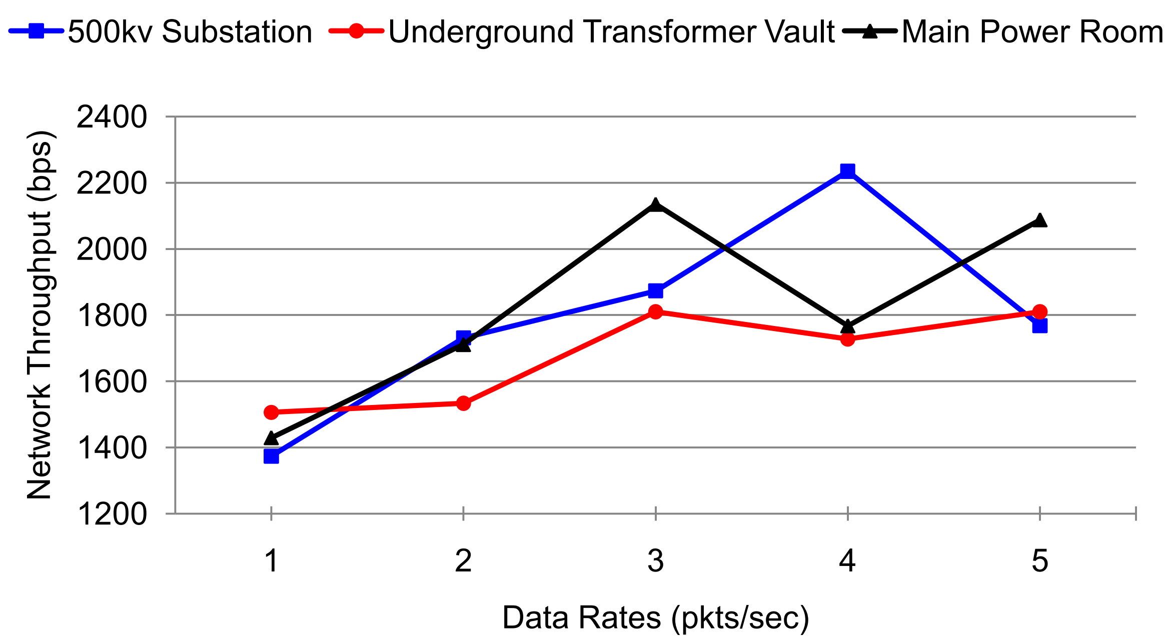

Figure 3.6 : Network throughput

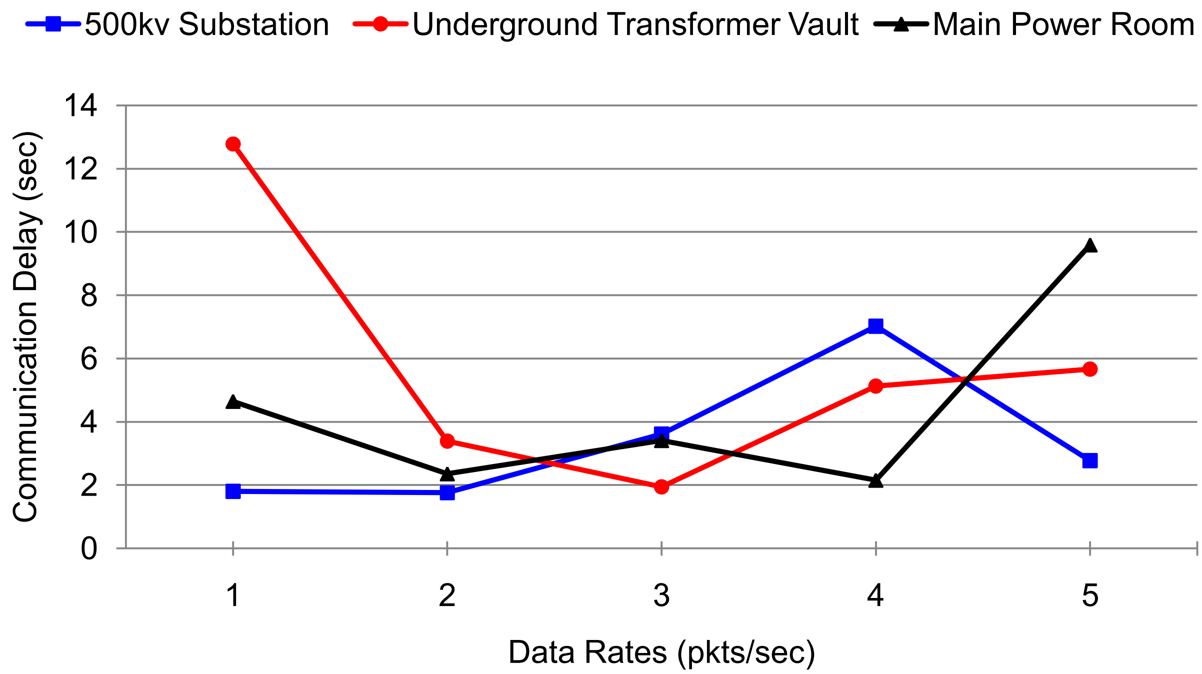

Figure 3.7 : End to end delay

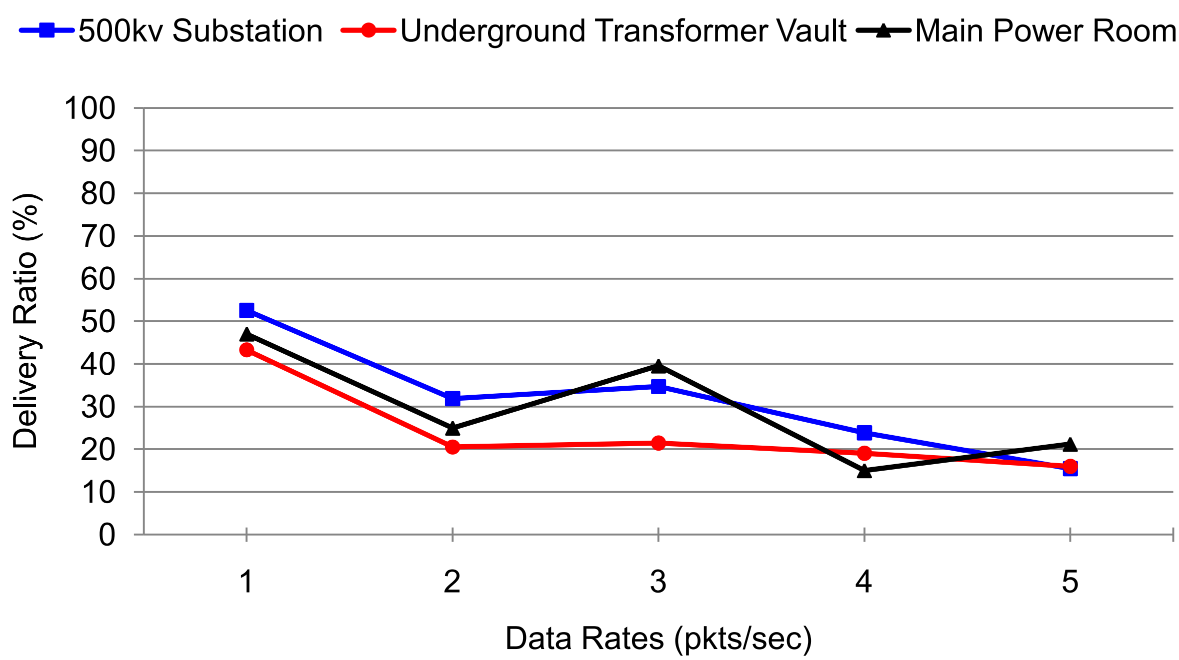

Figure 3.8 : Delivery ratio

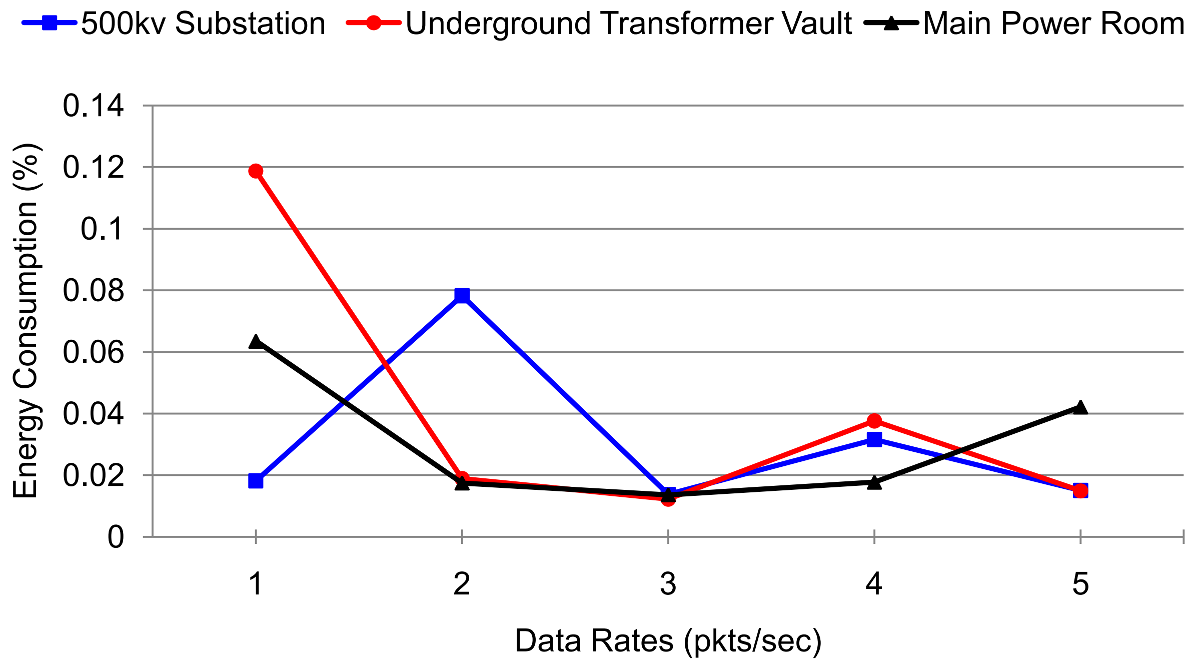

Figure 3.9 : Energy consumption

4. ADAPTIVE FORWARD ERROR CORRECTION IN WSNS FOR SMART GRID APPLICATIONS

Packet errors and link-quality variations are inevitable in WSN-based smart grid systems (U.S. Department of Energy), (Güngör, et al., 2010), (Bilgin and Güngör, 2010), (Güngör, et al., 2006). Furthermore, these link-quality variations and packet error rates are not static during network operation; they may get lower or get higher instantly by bursty errors and RF interferences. To minimize the effects of these circumstances, it's not surprising that the adaptiveness, which is the key factor of widely accepted mechanism designed for WSNs, is also very important for error control techniques in WSN-based smart grid applications. In these adaptive techniques, redundancy is tuned according to network condition or channel status. Since the redundancy changes dynamically, it helps to improve the system performance and does not cause unnecessarily network overhead.

The existing error control mechanisms are Automatic Repeat-reQuest (ARQ), Forward Error Correction (FEC), and Hybrid ARQ (HARQ) (Vuran and Akyildiz, 2009), (Jeong and Ee, 2006), (Meer, et al., 2003), (Zorzi and Rao, 1997). Also there are some adaptive mechanisms. We will propose an adaptive mechanism for smart grid environments. To the best of our knowledge, this study will be the first reported study at smart grid systems about applying adaptive error control mechanisms.

4.1 AUTOMATIC REPEAT REQUEST

In ARQ mechanism, transmitter transmits a packet to the receiver and waits for Acknowledgement (ACK) packet. According to this ACK packet, transmitter retransmits the packet if the packet is erroneous; otherwise transmitter transmits a new packet. Receivers only understand that there is an error on transmitted data but they do not try to correct the error in ARQ systems. Receivers refer to retransmission (Vuran and Akyildiz, 2009), (Kleinschmidt, et al., 2009), (Meer, et al., 2003), (Zorzi and Rao, 1997).

Number of retransmissions and time for waiting ACK packets cause long delays and decrease the system performance. Moreover, this mechanism causes additional energy cost and increase the overhead.

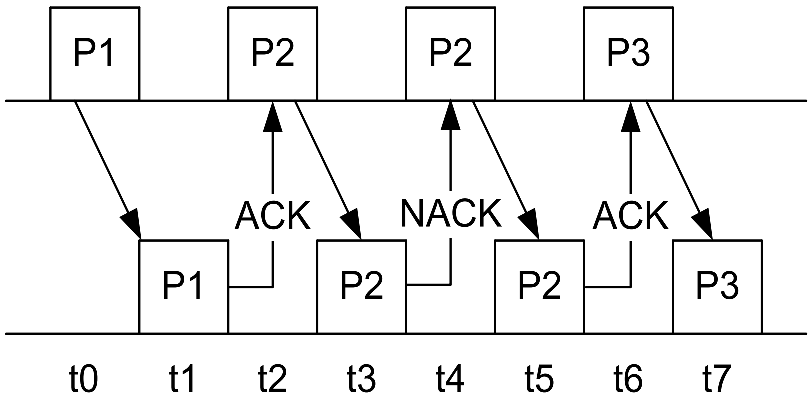

Figure 4.1 : Stop and wait ARQ

Figure 4.1 shows that packet flow from transmitter to receiver. Packet P1 is transmitted at time t_0 by sender and sender waits idle until ACK is received. Then sender transmits the other packets P2, P3 respectively. At time t_4 sender received Negative Acknowledgement (NACK) from receiver for packet P2. So it retransmits the packet P2.

4.2 FORWARD ERROR CORRECTION

FEC mechanism, when the transmitter transmits a new packet, it adds some redundant bits to the packet and after this operation transmit the data. Receiver tries to correct erroneous data by using several algorithms if an error occurs on the data. This is the main difference between FEC and ARQ. FEC technique tries to correct the data without retransmission (Vuran and Akyildiz, 2009), (Kleinschmidt, et al., 2009), (Jeong and Ee, 2006), (Meer, et al., 2003).

This mechanism does not cause delays in the message flow since there are no retransmissions of data when the channel is bad. Since there is no retransmission thus this situation helps reducing power consumed in the process.

The amount of redundant bits is important in this mechanism. Because if transmitter adds unnecessarily redundant bits, it causes unnecessarily network overhead and this increases the network overhead and decreases the system performance.

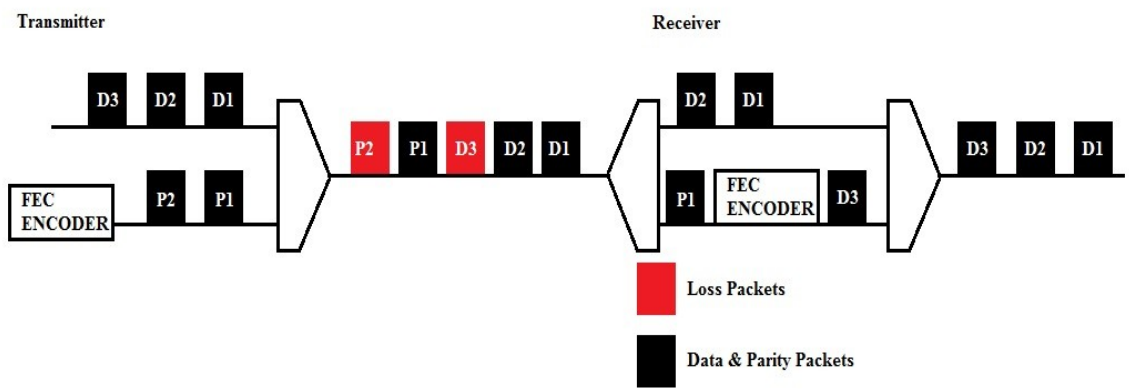

Figure 4.2 : Static FEC mechanism

In Figure 4.2, the FEC Encoder adds P2, P1 to D3, D2 and D1 at transmitter side and transmitter transmits the data like that. At the receiver side decoder decodes the coming data and finds the original data D3, D2 and D1.

4.3 HYBRID ARQ

The HARQ mechanism is the combination of the ARQ and FEC mechanisms. This mechanism takes advantages of ARQ and FEC mechanisms. This mechanism has two different transmission mechanisms.

4.3.1 Type I

This technique is the simplest way of Hybrid ARQ. Before transmitter transmits the data, firstly it adds Error Detection (ED) bits and FEC bits to the data then transmits the data with extra bits. After that the receiver firstly decodes the ED. Then if the quality of the channel is good all data should be received perfectly. So the receiver does not need to use FEC bits to correct the received data. But if the quality of the channel is not good enough and both ED and FEC bits cannot correct the received data, receiver detects this situation and the received data block is discarded and receiver requests retransmission of the discarded data like the way ARQ perform (Ahn, et al., 2005), (wikipedia.org/wiki/Hybrid_automatic_repeat_request).

4.3.2 Type II

This technique is different from Type I HARQ. Transmitter firstly transmits the only data. If any erroneous data is received, receiver sends a NACK to transmitter and does not discard the data. This point is main difference between Type I and Type II. In Type II when the transmitter receives a NACK packet, it does not transmit the data again, it either sends stronger FEC code or some incremental FEC code.

The main problem of the Type I is that it wastes the bandwidth because of repeatedly resending the same data. The main problem of the Type II is if either data or some of FEC codes cannot reach the receiver, Type II becomes inefficient. The other problem is it is hard to implement to some heavily noisy wireless networks due to the convolution code add all transmitted incremental FEC codes.

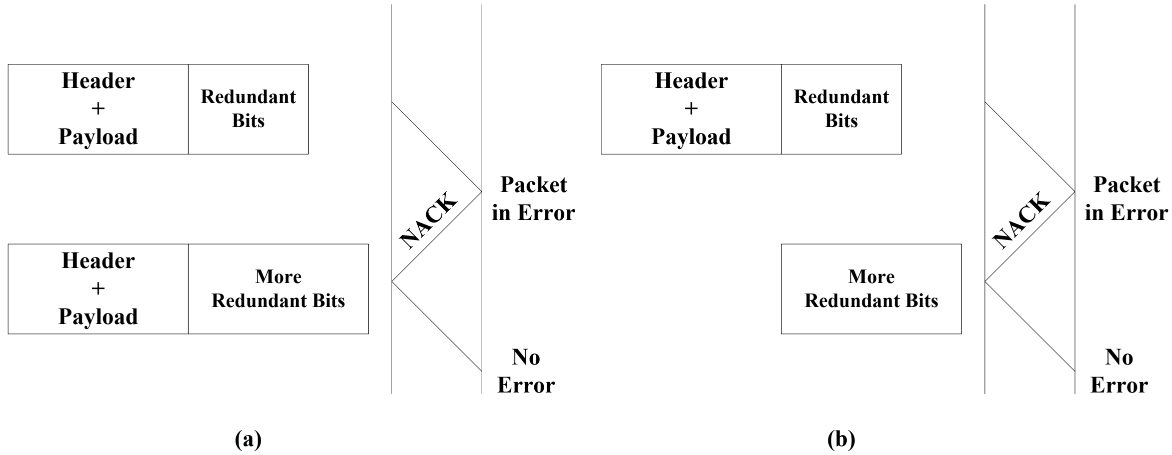

Figure 4.3 : Hybrid ARQ a) Type I b) Type II

Figure 4.3 shows that the type I type II mechanisms. In type I, if there is an error transmitter increases the number of redundant bits and retransmits the data. In type II, if there is an error transmitter increases the number of redundant bits and only transmits the redundant bits.

4.4 ADAPTIVE FORWARD ERROR CORRECTION

As we mentioned in this section, the existing error correction mechanisms have some problems. They causes network overhead, decreases system performance, causes additional power cost and etc. The smart grid systems have very harsh environment. These traditional mechanisms may not give high communication reliability in this harsh environment.

Specifically, the AFEC mechanism aims to exploit the advantages of both FEC and ARQ schemes by adaptively increasing the error resiliency of a data packet through retransmissions. In the AFEC mechanism, first, a data packet coded with a lower error correction capability is transmitted. If the packet is received successfully, then the transmitter tries to access the channel to transmit other data packet in its queue. If the data packet is received in error, a retransmission is requested by the receiver. Then, the transmitter re-transmits the packet coded with a more powerful FEC code. Here, the proposed adaptive error control mechanism assumes that channel conditions are relatively severe and thus, increases the number of redundant bits gradually to improve the error correction capability. This adaptive operation continues until the maximum number of re-transmissions is reached. Here, it is also important to note that the AFEC mechanism improves the error resiliency compared to the ARQ schemes by transmitting redundant bits through the wireless channel. Therefore, lower signal to noise ratio (SNR) values can be supported to achieve reliable communication compared to uncoded transmissions.

In this thesis, we proposed an AFEC for different smart grid environments. The main objective of the proposed mechanism is to achieve high communications reliability without causing unnecessary network overhead in smart grid environments. To achieve this objective, in the proposed mechanism, if the wireless channel state is good (or bad) the number of redundant bits in FEC-enabled data packet is decreased (or increased). Similarly, if network load is high (or low), more (or less) redundant bits are added to the data packets. In this way, we try to balance the trade-off between providing high communication reliability and keeping the communication overhead at minimum.

The networks that have harsh environment conditions like smart grid environment, using AFEC mechanism instead of traditional error correction mechanisms, gives high system and delay performance also increases the network and energy efficiency since it does not cause unnecessarily network overhead.

4.5 PERFORMANCE RESULTS OF AFEC

This paper is based on our previous study, where the wireless channel in different smart grid environments has been modeled through a comprehensive set of real-world field tests using IEEE 802.15.4 compliant wireless sensor nodes (see Figure 2.1) in different electric power system environments at Georgia Power, Atlanta, GA, USA (see Figure 2.2).

Based on these field tests, in Figures 4.4 to 4.7, we present our experimental results to elaborate the relationship between Packet Reception Rate (PRR) and network overhead vs. different packet error rates. Here, packet reception rate represents the ratio of the number of successful packets to the total number of transmitted packets and network overhead represents the ratio of the number of redundant bits to the total number of transmitted bits.

In the performance evaluations, sensor nodes are equipped with a single transmitter/receiver with a CSMA-based medium access control (MAC) layer. A constant bit rate (CBR) traffic is utilized in simulation experiments. Moreover, for each simulation, we run 10 experiments with different seeds and take the average of the measured values. Unless specified otherwise, we use the simulation parameters listed in Table 4.1

Table 4.1 : Simulation parameters

Traffic Type	*CBR*
Channel Model	*Log-Normal Shadowing*
MAC protocol	*CSMA*
Max. number of retransmissions	*3*
Number of source nodes	*6*
Max. buffer length	*40*
Packet Rate	*1 pkts /sec*

In our performance evaluations, three different algorithms, i.e., Adaptive FEC (AFEC), Static FEC, and No FEC, have been compared in terms of packet reception rate (PRR) and network overhead. Here, packet reception rate represents the ratio of the number of successful packets to the total number of transmitted packets and network overhead represents the ratio of the number of redundant bits to the total number of transmitted bits. Furthermore, the Static FEC and No FEC mechanisms represent the case where a fixed number of redundant bits are added to the data packet, and the case where no FEC coding is employed in the network, respectively. Here, note that when the code size of the Static FEC mechanism is determined, the FEC code size, which leads to the best performance in terms of PRR, is selected. Here, our motivation is to explore whether the best PRR performance can be reached using the proposed AFEC mechanism, while introducing network overhead only when necessary (only when channel conditions become severe).

In Figures 4.4 to 4.7, we present our simulation results to elaborate the relationship between packet reception rate (PRR) and network overhead vs. different packet error rates when different FEC mechanisms are employed in different smart grid environments. Specifically, Figures 4.4 and 4.5 show the network overhead of the AFEC, Static FEC and No FEC mechanisms in terms of different packet error rates in 500kV outdoor substation, and underground network transformer vaults, respectively. In these figures, it is important to note that the Static FEC mechanism introduces a constant overhead irrespective of the channel conditions (error rates). In other words, the deterministic (or static) selection of the FEC code size introduces unnecessary network overhead by mismatching the FEC strength to the underlying channel conditions. On the other hand, the overhead of the proposed adaptive FEC mechanism is dynamically adjusted based on the channel conditions. For example, in Figures 4.4 and 4.5, it is depicted that the overhead of the AFEC mechanism is only increasing when channel error rates increase. This adaptive operation becomes an important advantage when energy and bandwidth limitations of WSNs are considered and hence, plays a vital role in creating highly reliable and energy-efficient WSN-based smart grid systems.

Figures 4.5 and 4.6 also show that the packet reception rates (PRR) of the AFEC, Static FEC and No FEC mechanisms in terms of different packet error rates for 500kV outdoor substation and underground network transformer vault environments, respectively. In these figures, we observe that both Static and Adaptive FEC (AFEC) mechanisms achieve high PRR ratios compared to the case, where No FEC mechanism is applied. Overall, we observe that the proposed AFEC mechanism achieves high PRR (higher than 95%) by dynamically adjusting the number of redundant bits while increasing network overhead only when channel conditions become severe. Consequently, to overcome varying link conditions and thus, to meet application-specific requirements, adaptive error control mechanisms need to be utilized in WSN-based smart grid systems.

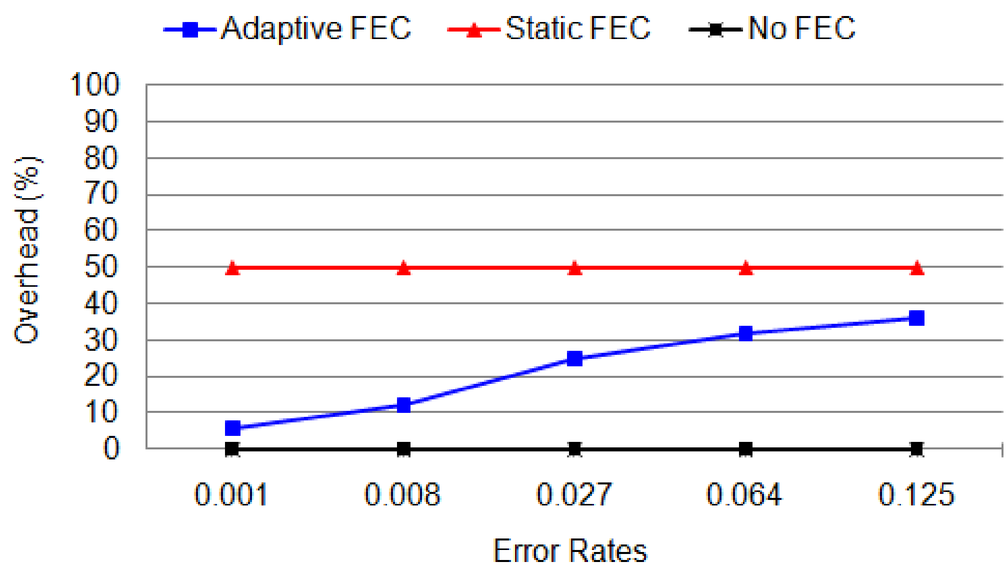

Figure 4.4 : Overhead vs. error rates in outdoor 500 kV substation

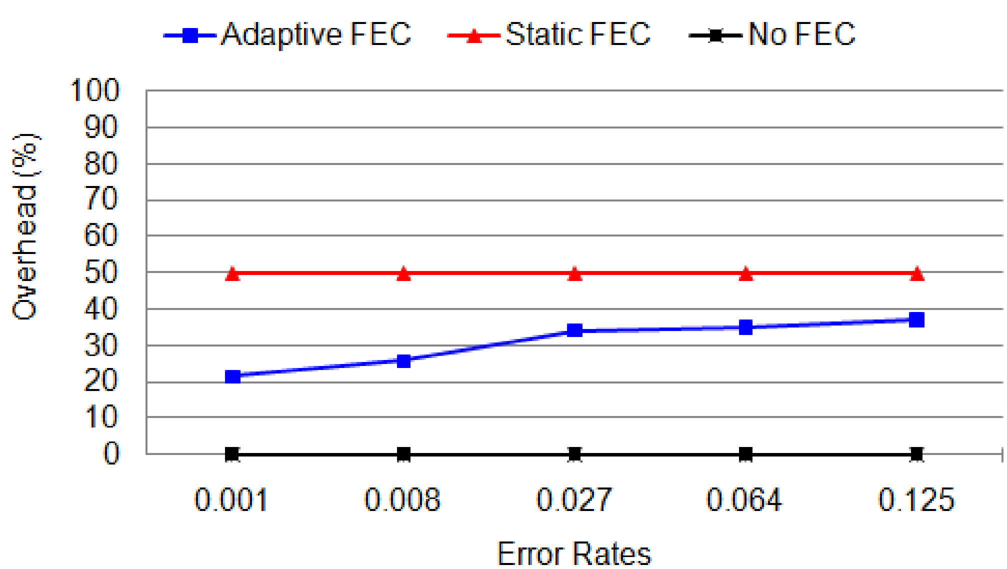

Figure 4.5 : Overhead vs. error rates in underground transformer vault

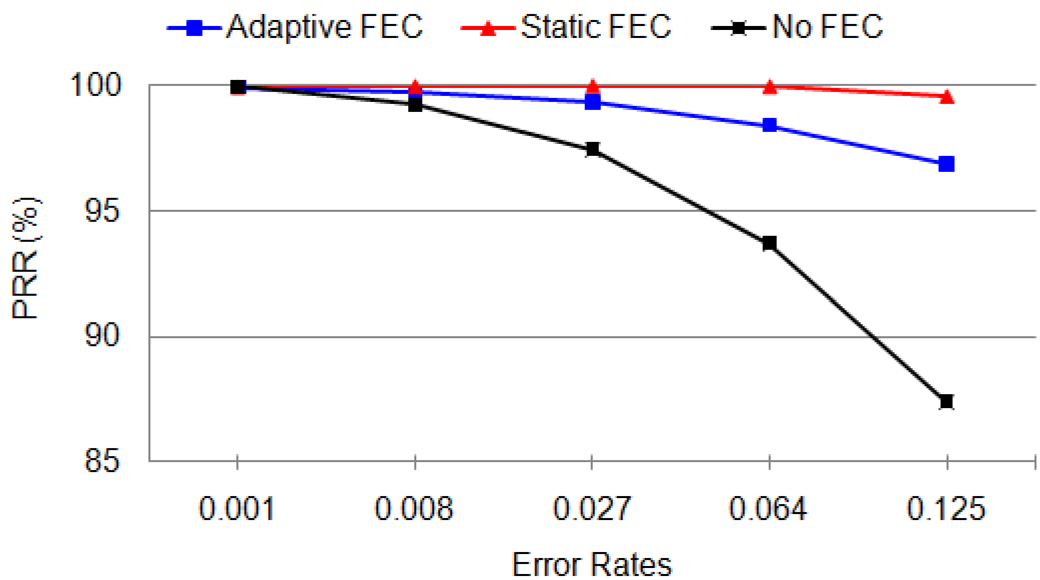

Figure 4.6 : PRR vs. error rates in outdoor 500 kV substation

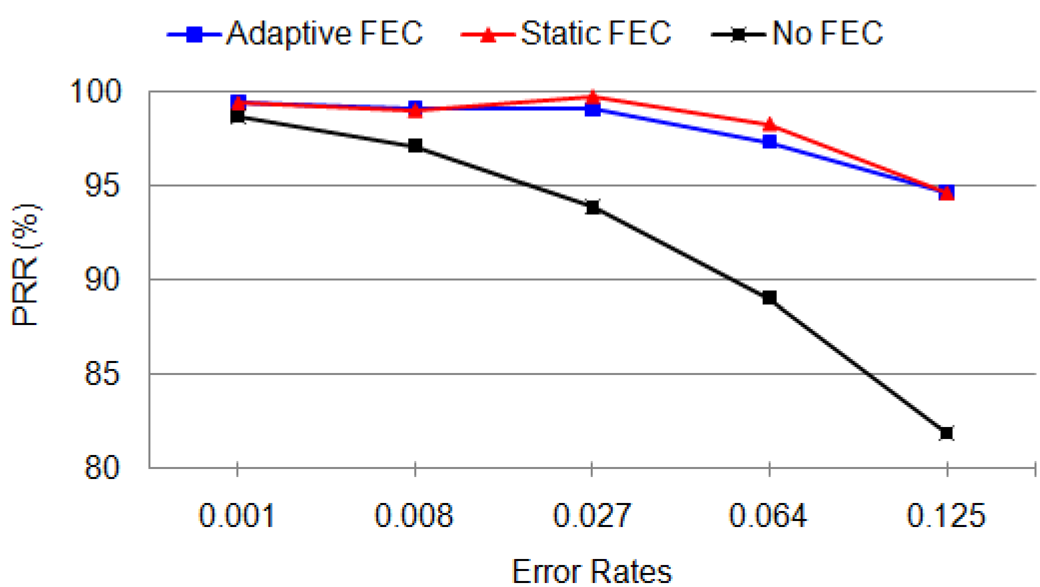

Figure 4.7 : PRR vs. error rates in underground transformer vault

5. PERFORMANCE EVALUATION OF MULTI-CHANNEL MULTI-INTERFACE ALGORITHM IN SMART GRID APPLICATIONS

5.1 OVERVIEW OF EXISTING MULTI CHANNEL ALGORITHMS

With the recent advances in WSNs lead to increase the network capacity of wireless networks. Although there are multiple non-overlapping channels in the 2.4 GHz and 5 GHz spectrum, i.e. IEEE 802.11 b/g has 3 and 802.11 a has 12 non-overlapped frequency channels, most of IEEE 802.11 based multi hop networks use only one channel today. In this situation, the aggregate bandwidth provisioned by the standards cannot be used by these networks. To utilize the all available channels, routing protocols and channel assignment algorithms need to be addressed. Moreover, to enable the communication on different channels, specific hardware should be used.

Although there are significant advances in physical layer technology, in wireless LAN level of sustained bandwidth is not same as wired LAN. Maximum data rate of 802.11 a/g is 54 Mbps. All overheads, packet errors and losses almost halved the data rate.

Wireless Mesh Networks (WMNs) which is special usage of multi-channel architecture are becoming popular in smart grid applications, including AMI, SCADA. WMNs require reliable, efficient, timely packet delivers.

Different from single-channel MAC solutions, recently some algorithms for multi-channel utilization in WSNs have been proposed to improve overall network performance (Akyildiz, Melodia and Chowdhury, 2007). In this section, the related work on existing WSN multi-channel schemes is briefly described and compared in terms of broadcast support, medium access type, channel assignment, and channel switching time as shown in Table 5.1.

The authors Raniwala and Chiueh (2004) proposed a centralized channel assignment algorithm. In this algorithm, by equipping nodes with multiple NICs using multiple frequency channels in an ad hoc network is allowed. Moreover, more channels are used on each node than the number of interfaces. Authors also evaluated their algorithm performance by using shortest path routing and randomized multi-path routing.

A link layer protocol called MMAC is proposed to utilize multiple channels (Chereddi, et. al., 2006). To ensure connectivity and to exchange information for all nodes, time is divided into the beacons. Nodes transmit their data in a random interval time to avoid contention. Channel that will be used is defined according to information in the transmitted data. The channel information of source node's neighborhood is in the transmitted data. Destination node decides to use the least used channel and add this information to its ACK packet. Thus, this algorithm tries to enable equal load on all channels.

Two multicast algorithms called LCA and MCM, is proposed for multi-channels to improve the system performance in terms of throughput (Zeng, et al., 2010). Their algorithms try to minimize the hop count of the trees and number of relay nodes. In the LCA algorithm, level information is obtained by using BFS which is decrease and conquer approach. Then it tries to construct a multicast tree according to level information. Then nodes select the channels according to their levels. In the MCM algorithm, the first step is similar with LCA, except deleting the edges of nodes which are in the same level. Than it tries to decrease number of relay nodes to prevent more transmission.

A channel assignment algorithm called HRC is proposed (Zhou, et al., 2009). In this algorithm, they try to use whole network capacity and to measure link capacity in more effective and practical way.

A routing protocol called MR-LQSR is proposed to calculate the bandwidth loss rate of links (Padhye and et al., 2004). In proposed protocol, WCETT which is a new metric is used as the path metric. In the WCETT metric, path is found according to east summation of ETT and path throughput is dominated by bottleneck channel. Authors try to increase number of node to better explore the performance of WCETT.

A multi-channel MAC protocol for WSNs is proposed (C. Xun and et al. 2006). In this study, they firstly classified energy waste. Their protocol assumes that there are n channels with the same bandwidth and one of them is control channel and the rest of them are data channels. Each node is equipped with a half-duplex transceiver and these transceivers can be switched by nodes. The communication frame consists of two periods. One of them is active period which has 4 stages, including synchronous beacon, transmission request, channel schedule and data convey. Second period is sleep period. They make simulations in OMNET++ and according to results they increase the network performance in terms of energy efficiency, lifetime and throughput.

Multi-channel assignment is formulated as an optimization problem and showed that it is a NP-Hard problem (Q. Yu. And et al., 2010). According to authors this is the first attempt in WSNs. To reduce the interference, unlike the static assignment protocols, authors used both topology information and routing information. They proposed a distributed Game Based Channel Assignment based on Best Response to solve optimization problem. According to simulation results in OMNET++, they increase the delivery ratio, throughput and decrease the channel access delay and energy consumption.

An algorithmic framework is proposed to reduce the packet losses that occur by WLANs and commercial microwave devices (Chowdhury and Akyildiz, 2009). Sensor nodes identify the type of interferer and its operational channel in this proposed method. The basic ideas of this method are classifying interference according to channel power measurements and choosing the transmission channel. They reduce the energy consumption to the 30-50%.

A multi-channel MAC protocol, called MC-LMAC, is developed with the aim of improving network throughput of WSNs through communications over multiple channels (Incel and et al., 2011). This protocol utilizes a scheduled access scheme, where each node allocates a time slot beforehand and utilizes this time slot without contention. In this protocol, at the beginning of each time slot, all the sensor nodes are necessary to listen on a common channel to share control information, which causes some network overhead.

The multi-frequency MAC protocol, called MMSN, has been proposed for WSNs (Zhou and et al., 2006). The MMSN protocol is a slotted CSMA protocol and at the start of each time slot, nodes need to contend for the medium before they can transmit. In the related literature, it is shown that contention based protocols have a lower communication delay at lower traffic loads, which is the general case in WSNs. However, when the network load is high, there is a higher waste of network bandwidth from packet collisions and exponential backoffs. On the other hand, schedule-based communication has the inherent advantage of a collision-free medium access while introducing synchronization overhead.

A tree-based multi-channel protocol (TMCP) is presented for data collection applications (Wu, et al., 2008). The main objective of this protocol is to divide the network into multiple subtrees with minimizing the intra-tree radio interference. In other words, network is divided into subtrees by the protocol and different channels are assigned to the nodes that located on different trees. Overall, the TMCP is designed to support convergecast traffic and it is difficult to have successful broadcasts because of network partitions.

Y-MAC is another schedule based multi-channel MAC protocol for WSNs (Kim, Shin and Cha, 2008). In this protocol, time slots are to the receivers. At the start of each time slot potential transmitters for the same receiver contend for the shared medium. If it is necessary to transmit multiple packets, then the transmitter and the receiver pass to a new channel based on a predetermined sequence. Other potential transmitters also follow the hopping sequence of the receiver.

HyMAC is another multi-channel MAC protocol for WSN (Mastooreh, Hamed and Antonis, 2007). Similar to MC-LMAC protocol, HyMAC is also a hybrid of TDMA and FDMA protocols. However, the Breath First Search (BFS) algorithm is used to assign frequencies and time slots on a tree topology.

Table 5.1 : Summary of multi-channel MAC protocols in WSNs

	MC-LMAC (Incel and et al., 2011)	**Y-MAC (Kim, Shin and Cha, 2008)**	**MMSN (Zhou and et al., 2006)**	**TMCP (Wu, et al., 2008)**	**HyMAC (Mastooreh, Hamed and Antonis, 2007)**
Broadcast Support	Available	Available	No Information	Available	No Information
Medium Access Type	Schedule Based	Slotted CSMA	No Information	Schedule Based	Schedule Based
Channel Assignment	By Transmitters	By Receivers	Cluster Based	Dynamic	By Transmitters
Channel Switching Time (Slot)	1	More Than 1	0	1	1

Although all these studies provide solid and valuable foundations in multi-channel WSNs, none of them focuses on employment of multi-channel WSNs for smart grid applications. Hence, there is a need for performance evaluations of multi-channel WSNs in smart power grid spectrum environments.

5.2 MULTI CHANNEL ALGORITHM USED IN SIMULATIONS

A multi-channel multi-interface architecture called Hyacinth is proposed (see Figure 5.1) (Raniwala and Chiueh, 2005). We also inspired by this architecture in our simulations. The architecture proposed for WMNs. Load on each channel is filtered and this information is used to balance load on other links by the routing protocol of this architecture. The aim of the channel assignment and routing algorithms is to maximize the system performance. Available bandwidth is defined according to the load on interfering nodes.

The channel assignment is done in two ways: i) neighbor-interface binding, ii) interface-channel assignment. In the first way, NICs divided into two disjoint sets. UP-NICs are used to communicate with the parent nodes and DONW-NICs are used to communicate with child nodes. In the second way, nodes assign the channels to DONW-NICs. Nodes exchange channel information with each other to achieve this. Based on the exchanged information node assigns the least used channel to its DONW-NICs.

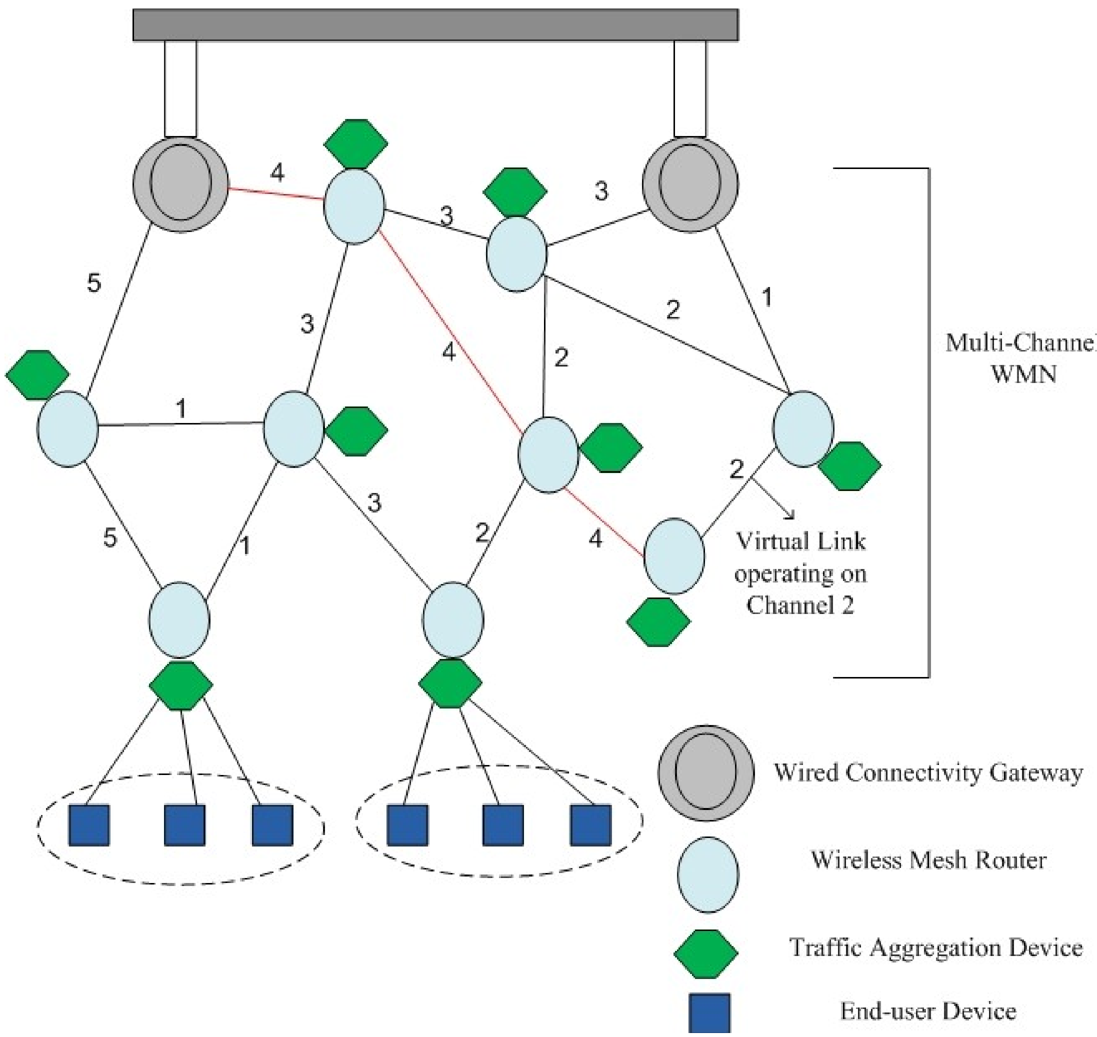

Figure 5.1 : Hyacinth network topology

The routing metrics of this architecture are hop count, gateway link capacity and path residual capacity. These cost metrics are used in the routing to determine the final topology.

By finding the differences between the aggregate usage of the channels in the neighborhood and the total capacity, the capacity of wireless link can be calculated.

5.3 PERFORMANCE RESULTS

In the performance evaluations, a constant bit rate (CBR) traffic is utilized. Moreover, for each simulation, we run 10 experiments with different seeds and take the average of the measured values. When we consider multi-channel communications, it is important to note that some of the IEEE 802.15.4 frequencies overlap with IEEE 802.11b frequencies as shown in Figure 5.2. This overlapping increases the effects of external interference on link quality. In our field tests (Güngör, et al., 2010), we observe that only channels 25 and 26 in IEEE 802.15.4 spectrum are not affected by the IEEE 802.11b interference. Thus, to minimize the IEEE 802.11b interference in smart grid applications, e.g., wireless automatic meter reading systems, the default IEEE 802.15.4 channel can be set to 25 or 26. Due to this overlapping with IEEE 802.11b spectrum, we used two channels (channel 25 and 26) in our multi-channel simulation experiments. In these performance evaluations, multi-channel MAC for WSNs has been compared according to following performance metrics:

- ***Average Delay*** is the average time to receive all data on the destination side.
- ***Packet Loss*** is the amount of data which not received by the receiver in a specific time period.
- ***Packet Reception Rate*** is ratio of the number of successful packets to the total number of transmitted packets.
- ***Network Throughput*** is the amount of data transmitted between transceiver in a specific time period.

In this study, comparative performance evaluations have been conducted using ns-2 simulator based on experimentally determined log-normal channel parameters for different smart grid environments. In the performance evaluations, a constant bit rate (CBR) traffic is utilized in simulation experiments. We run simulations with different seeds 10 times and take the average of the measured values. The parameters used in our performance evaluations are listed in Table 5.2.

Table 5.2 : Simulation parameters

Number of Nodes	4
Traffic Type	CBR
Packet Length	250 bytes
Traffic Type	CBR
Data Rate	20 -200 Kbps
Channel Model	Log-Normal Shadowing
Number of Simulation Runs	10

Based on these metrics, we present the performance results in Figure 5.3 to 5.6 to elaborate the relationship between PRR and packet loss vs. number of transmitted packet and throughput and average delay vs. different offered load when different number of channel are employed in different smart grid environments. Figure 5.3 shows the packet reception rate (PRR) vs. offered traffic load in different smart grid environments with different number of channels. In this figure, we observe that using single channel causes a sharp decrease at PRR values when traffic load exceeds 50 packets/sec. Especially, if offered load is 120 packets/second, the PRR values decrease lower than 40% for single channel case. However, when multiple channels are utilized, the PRR ratios do not change until offered load becomes 100 packets per second. Figure 5.4 shows the number of lost packets vs. offered load in different smart grid environments. When multiple channels are used, there is almost no packet loss until the offered load becomes 100 packets/sec. After this threshold, the number of packet loss starts to increase. However, when single channel is used, packet losses start to increase after the traffic load of 50 packets/sec..

Figure 5.5 shows network throughput vs. offered load in different smart grid environments. When single channel is used, the throughput increases until the offered load is 50 packets/sec. Then, it remains stable after this traffic load. On the other hand, when multiple channels are used, throughput increases until the offered load is 100 packets / sec. Then it remains stable even if offered traffic load is increased. Figure 5.6 shows the average delay vs. offered load in different smart grid environments. Using more than one channel helps to decrease the average delay on the destination side. As for single channel case, the average delay exceeds 700 ms when offered load exceeds 80 packets per second. When we use multiple channels, the average delay on the destination side does not exceed 10 ms until the offered load becomes 100 packet per second. This experiment clearly shows that multiple channel communications will be the preferred solution for time- critical WSN-based smart grid applications.

Overall, we observe that when we increase the number of used communication channel, we achieved more PRR ratios and this helps increasing in throughput. Throughput increases almost twice as much. Increasing in channel number also helps decreasing in average delay and packet loss. When we compare the values of average delay and packet loss, almost there is no any delay and loss if we use two channels. It is also interesting that performance metrics values are almost same for Underground Transformer Vaults and Main Power Room environments even if we run simulations with different seed values. In the end, all these performance evaluations show that increasing number of channel in the wireless communication affects the system performance positively.

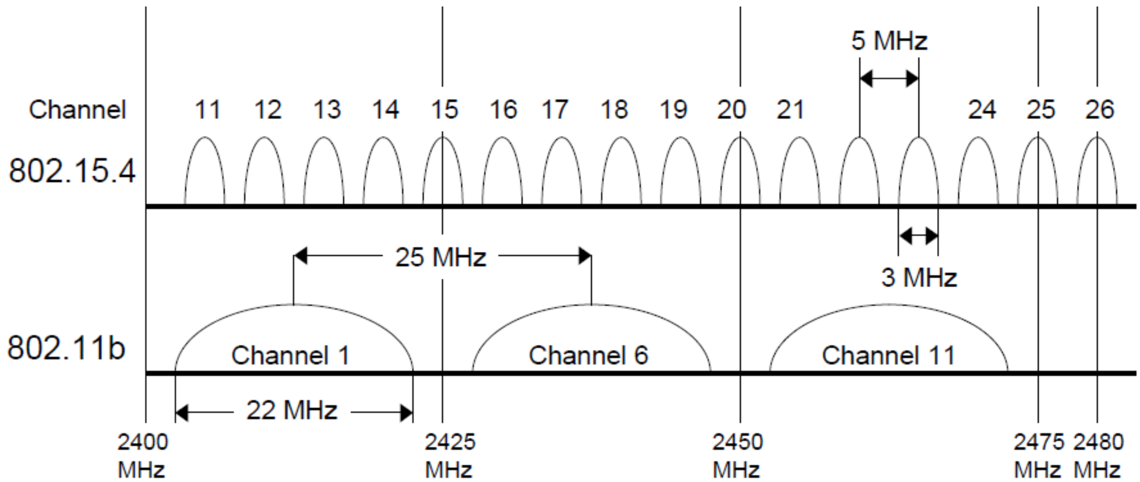

Figure 5.2 : 802.15.4 and IEEE 802.11b spectrum usage

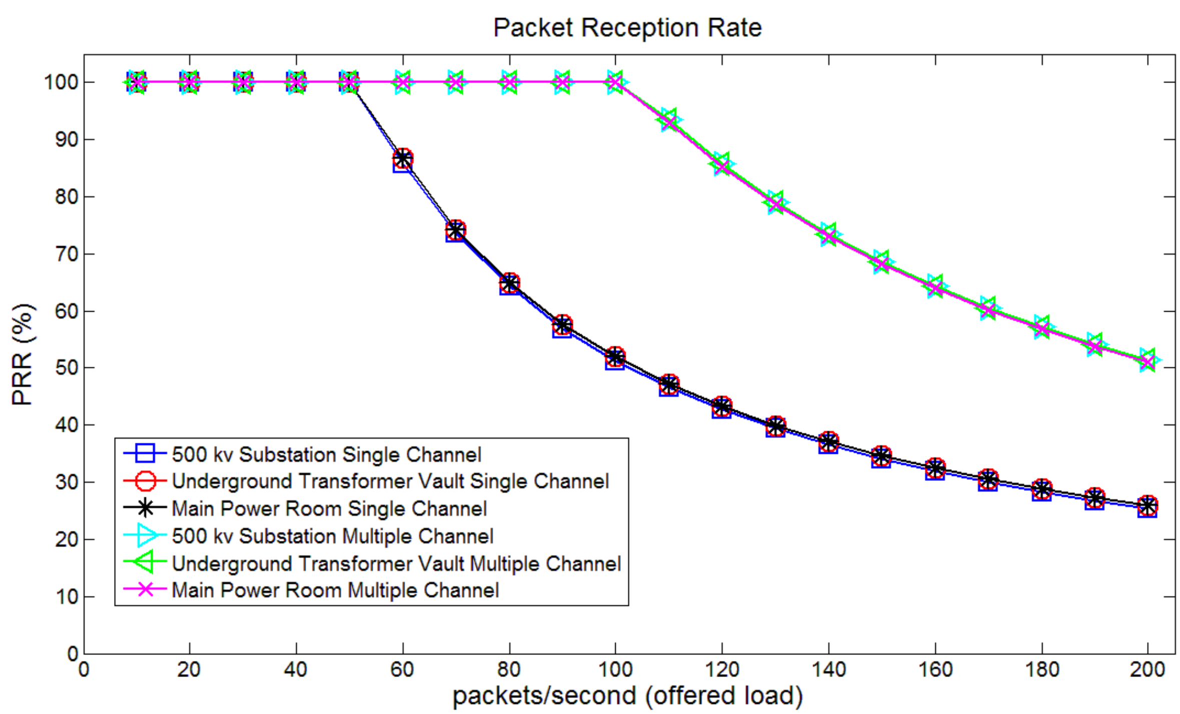

Figure 5.3 : Packet reception rate vs. number of transmitted packet

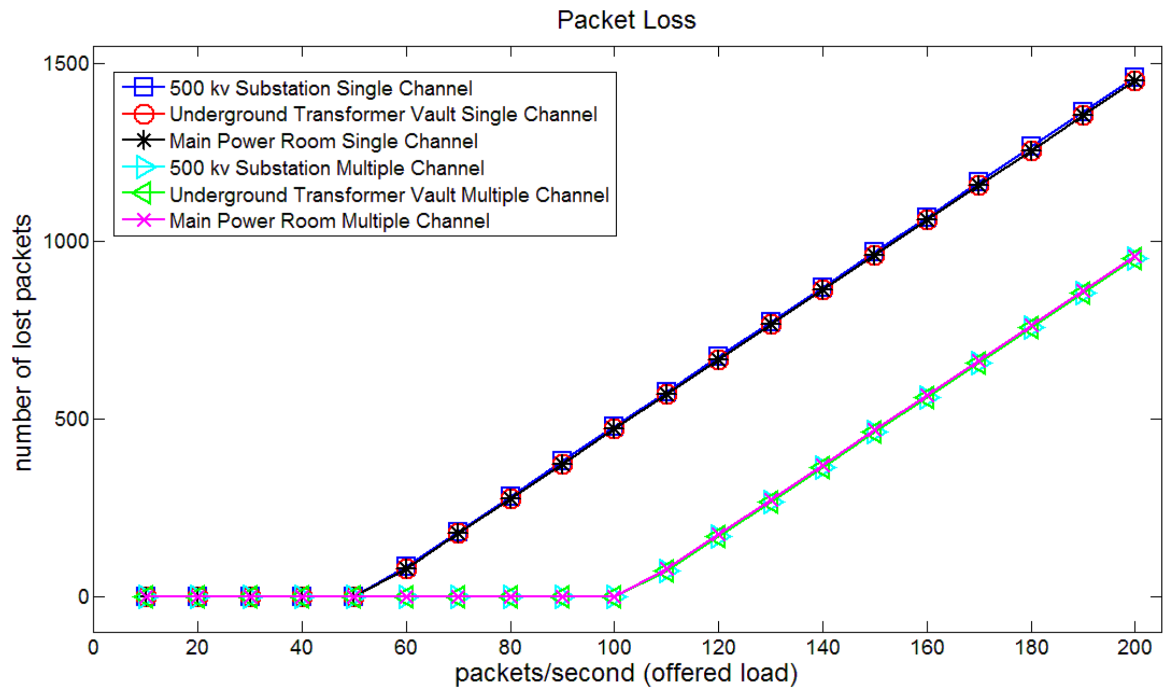

Figure 5.4 : Packet loss vs. number of transmitted packet

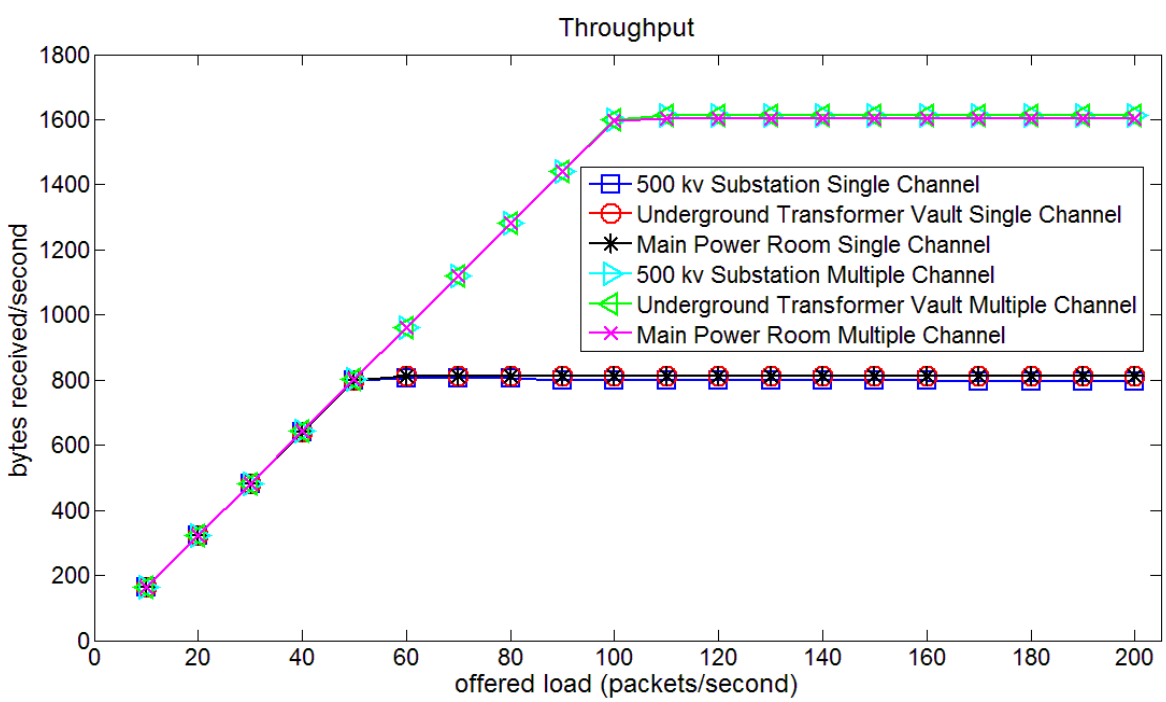

Figure 5.5 : Throughput vs. offered load

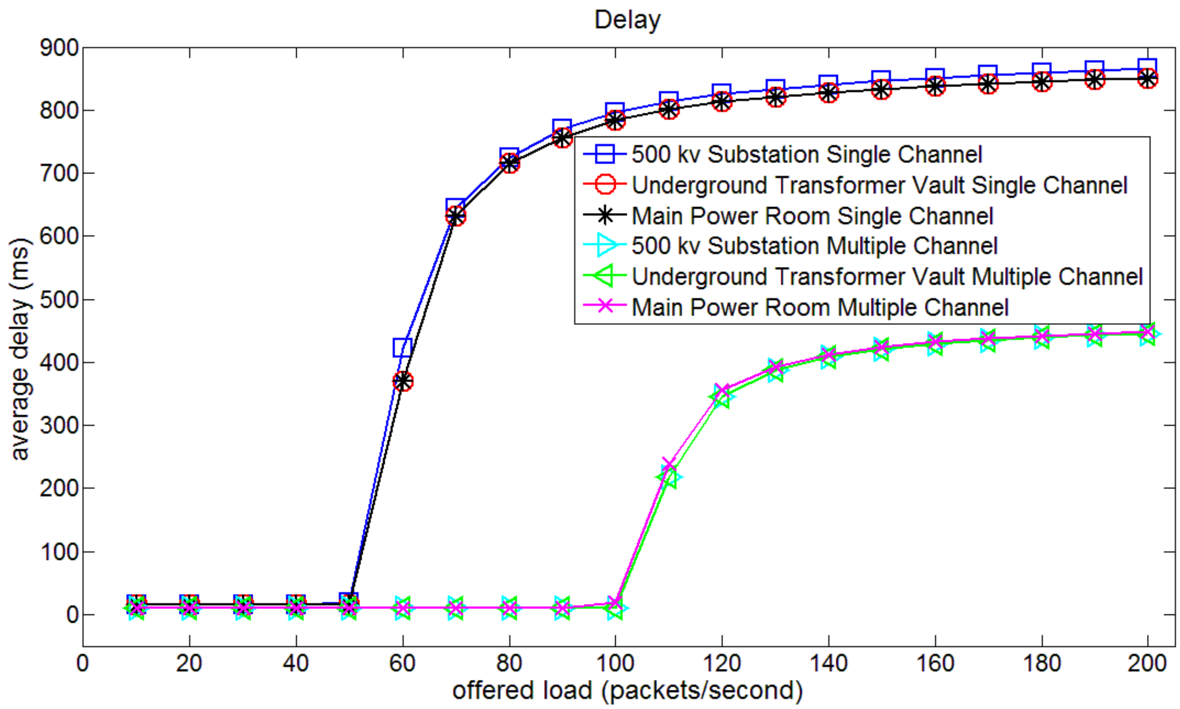

Figure 5.6 : Average delay vs. offered load

6. CONCLUSION AND FUTURE WORKS

Recently, a new approach, called smart grid, has been proposed to overcome the existing problems such as lack of pervasive and effective communications, monitoring, and automation. The collaborative and low-cost nature of WSNs brings several benefits over traditional power monitoring systems. In this regard, WSNs play a vital role in creating a highly reliable and self-healing electric power system that rapidly responds to events with appropriate actions.

In this thesis, firstly, the performance of ZigBee which is based on IEEE 802.15.4 standard and offers an affordable way for communicating energy-related information, such as price, energy consumption, in smart grid environments is investigated for different spectrum environments of smart power grid, e.g., 500kV outdoor substation, main power control room and underground network transformer vaults. Importantly, these performance evaluations are based on a comprehensive set of real-world field tests using IEEE 802.15.4 compliant wireless sensor nodes deployed in different smart grid environments. To the best of our knowledge, this is the first reported study, which evaluates the performance of ZigBee in terms of network throughput, end-to-end delay, delivery ratio, energy consumption specifically for smart grid environments. Overall, the performance evaluations show that high packet errors and variable link capacity in harsh smart grid spectrum environments pose great challenges in the reliability of ZigBee-based wireless communications in smart grid.

Secondly, an Adaptive Forward Error Correction (AFEC) mechanism which tunes redundancy according to network condition or channel status has been developed for smart grid environments to increase the network reliability in WSN-based smart grid systems. To the best of our knowledge, this study is the first reported study, which evaluates the performance of adaptive and static FEC-based error control algorithms for different smart grid environments, including 500 kV outdoor substation and underground transformer vaults. Comparative performance evaluations show that the proposed AFEC mechanism achieves high communications reliability without causing unnecessary network overhead. Future work includes investigating the optimal packet size and the impact of different heterogeneous resources, such as transmission power and network bandwidth, on overall network performance and optimal placement of these resources in the network.

Thirdly, we evaluate the performance of a multi-channel multi interface architecture in terms of network throughput, average delay, packet reception rate and packet loss in different smart grid environment, including an indoor power control room, an outdoor 500 kV substation environment, and an underground network transformer vault environments. Recent field tests show that wireless links in smart grid environments are exposed to spatio-temporally varying spectrum characteristics due to electromagnetic interference, equipment noise, and fading due to obstructions. This makes reliable communication a challenging task for WSN-based smart grid applications. To improve network capacity in smart grid environments, multi-channel WSNs might be a preferred solution, while achieving simultaneous transmissions through multiple channels. To the best of our knowledge this study is the first reported study, which applied in the smart grid environment. Comparative performance evaluations shows that throughput and packet reception rate have increased twice as much, and average delay and packet loss have halved by increasing number of channels. Future work includes investigating optimal packet size and number of channels and the effect of different heterogeneous resources, such as transmission power, on overall network performance in WSN-based smart grid applications.

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