University of Southern Queensland
Faculty of

COMMUNICATIONS FOR SMART GRID SUBSTATION MONITORING USING WIMAX PROTOCOL.

A dissertation submitted by

Sreekanth Anumula

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ABSTRACT

The SMARTGRID is a general term for a series of infrastructural changes applied to the electric transmission and distribution systems. By using the latest communication and computing technology, additional options such as Condition Monitoring can now be implemented to further improve and optimise complex electricity supply grid operation. Lifecycle optimisation of high voltage assets and other system components in the utility provide a case in point. Today Utility experts agree that application of scheduled maintenance is not the effective use of resources. To reduce maintenance expenses and unnecessary outages and repairs of equipment due to scheduled maintenance, utilities are adopting condition based approaches. Real time online monitoring of substation parameters can be achieved by retrofitting the existing substation with SMARTGRID technology. The IEC 61850 is a common protocol meant for Substation Automation Systems, designed for the purpose of establishing interoperability, one that all manufacturers of all different assets must comply with. This thesis advocates the estimation of bandwidth required for monitoring a substation after retrofitting the existing substation with smart communication technologies. This includes establishing a latest wireless communication infrastructure from the substation to the control centre and evaluating the performance modelling and simulating the physical layer of communication technologies such as WIMAX (IEEE802.16) and MICROWAVE point to point using MATLAB SIMULINK and RADIO mobile online simulation software. Also, link budget of the satellite communication for the same application is calculated. Satellite communication in this case is considered as a redundant or back up technology to ensure that the communication between entities is continuous. On performing the simulation on different environments the results prove that the selected protocols are best suited for condition monitoring. The measured Latency could be the best approximated value which complies with the current objective. However the white noise that exists in the substation has significant hazard with respect to the security of the wireless network. To compensate this constraint whole substation is hard wired by means of plastic fibre optics and the data sent to the base station located near the substation.

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Limitations of Use

CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

Student Name
Student Number:

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Signature

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Date

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List of Acronyms

ACSI	Abstract Communication Service Interface
ADC	Analog to Digital Converter
AMI	Advanced Metering Infrastructure
AMR	Automatic Meter Reading
AWGN	Additive white Gaussian noise
BER	Bit Error Rate
CDC	Common Data Class
CID	Configured IED description
CIGRE	Conseil International des Grands Réseaux Électriques
CP	Cyclic Prefix
CT	Current Transducer
DNP3	Distributed Network Protocol
EMC	Electro Magnetic Compatibility
EMI	Electro Magnetic Interference
EMS	Energy Management Systems
FAN	Field Area Network
FFT	Fast Fourier Transform
GOOSE	Generic Substation Object Oriented System Event
GPRS	General Packet Radio Service
GSM	Global System for Mobile
GSSE	Generic Substation status event
HMI	Human Machine Interface
HSR	High-availability Seamless Redundancy
ICD	IED capability Description
IEC	International Electro technical Commission
IED	Intelligent Electronic device
IEEE	Institute of Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
ISI	Inter symbol interference
ISO	International Organization for Standardization
LAN	Local Area Network
LN	Logic Node
LOS	Line of Sight
LTE	Long Term Evaluation
MMS	Manufacturing Messaging Specification
MTBR	Mean Time Between Removals

MTTF	Mean Time To Fail
MTTR	Mean Time to Recovery
NAN	Neighborhood Access Network
NC	Normally Close contact
NCBPS	National conference of black physics students
NLOS	Non Line of Sight
NO	Normally Open contact
OFDM	orthogonal frequency division multiplexing
OSI	Open Systems Interconnection model
PLC	Programmable Logic Controller
PMU	Phasor Measuring Unit
PRP	Parallel Redundancy Protocol
PT	Potential Transformer
QAM	Quadrate Amplitude Modulation
RTT	Round Trip Time
SAS	Substation Automation Systems
SCADA	Supervisory Control and Data Acquisition
SCD	Substation Configuration Description
SCL	Substation Configuration Language
SCSM	Specific Communication Service Mapping
SHF	Super High Frequency
SLD	Single Line Diagram
SMV	Sample Measured Values
SNR	Signal to Noise Ratio
SSD	System Specification Description
TASE2	Tele control Application Service Element
TC57	Technical Committee 57
TCP/IP	Transmission Control Protocol/Internet Protocol
TNC	Trip Neutral Close Switch
UCA	Utility Communications Architecture
UHF	Ultra High Frequency
WAN	Wide Area Network
WiMAX	Worldwide interoperability for microwave access
XML	extensible Markup Language

1. INTRODUCTION

1.1 Background

The fact that electric power is among the most important technologies that has enhanced rapid globalization and industrialization in the twentieth century is undeniable. Electric power grid is the most complex, extensive and largest physical system that is interconnected in the world. As a result of its extensiveness, complexity and size, the electric grid is considered to be an ecosystem by itself. In the whole world, there exist more than 9200 electric power generating stations that can produce approximately 1,000,000 megawatts of electric power. The generating stations are connected to the power consumers though transmission lines that extends all over the globe. Consumers have different power needs and therefore the need for substations is unavoidable. Substations help in the control of power distribution and transmission.

For a long time, there has been hardly any change in the structure of the electrical power grid. But, centrally controlled hierarchical grid of the twentieth century cannot accommodate the elevated needs that have cropped up in the twenty first century. As a result, the new concept of smart grid has emerged to replace the old grid communication and control system. The new grid is considered to be a modern infrastructure in the power transmission and distribution established in order to achieve reliability and higher efficiency by the use of automated control system, modern communication infrastructure, high power converters and energy management techniques that are modern and ensures energy and network availability. The current power system is based on a communication and information system that is solid while the new smart grid operations will be based on a complex and more efficient model of communication.

In the past and even some of the recent substations in the world are designed for four main functions that include monitoring, protection, metering and control (Eftekharnejad). Protective function involves the isolation and recovery and detection of electric faults to caution the equipment from any damage and ensure human safety. Monitoring entails the tracking of the equipment state in the network and within the substation. Control on the other hand is the act of issuing commands either locally or remotely in order to determine the actions of the electric apparatus. Metering entails the use of field devices to measure the analogue signals and transforming them to digital signals by the use of intelligent electronic devices.

The situation situated its phase to business integration from the year 2000 to present, which incorporated retrofitting the substation which characterized the system into automation and other business oriented networks, asset management of the entire system occupied the major part of the budget and involvement of other IT firms. The network architecture joined WAN with private networks and facilitated the customer to be able to use the network and

Internet (Ekanayake.). The typical communication paths are IP radios, wireless Ethernet, LTE cells, and other gigabyte backbones. The communication system development activities for electrical utilities are initially lack standardization during 1985. The system characteristics of this system had single vendor per system and it used to collect only basic data by using single master network architecture. Communication channels were typically power line carrier, RS232,and RS485,Dial up and radio data the typical data rate used to lie less than 1200bps .The communication protocols and standards were typically(Anton, Pöltl & Michael).

The standardization development started during 1985-2000 with multiple vendor systems and exchange of protocols with different network topology. The architecture was with multiple masters and for ensuring the continuity of the data, redundancy was introduced. The communication media was represented by packet radio and other hired lines with the data rate of 9600 to 19200 bps. The communication protocol were DNP3 serial, IEC 60870 standard, TASE2.

WiMAX(worldwide interoperability for microwave access) communication channel is wireless and is was earlier designed to accommodate and provide 30 to 45 Mbps. However the data rate has greatly increased to up to 1gigabits per second. The fact that the channel is wireless, there is minimal input in for of a running cable networks. However, the cost of installation may be high. WiMAX technology can be affected by environmental changes that may make it ineffective. Also, if the channel is not well guarded by use of firewalls and protocols the channel is never secure to transfer confidential data.

IEC (International Electrotechnical commission) an international body has published IEC61850 standard which governs the communication requirements of the entire smart grid . This standard is defined to realize interoperability and also future proof features are embedded to imbibe the new technology.

1.2 Motivation

Currently there are many technologies like Ethernet, Optical fibre, PLC are available for facilitating communication requirements of the smart grid. However to integrate all the elements like generation including distributed generation, transmission and distribution and especially in remote locations wireless technologies offer a cost effective alternative.

Wimax is one of the wireless communication technology is based on IEEE 802.16 standard which was basically designed as an alternative to the wired broad band network. The bandwidth and the latency offered by the Wimax can support the requirement of the smart grid. However as the Wimax was not basically designed for the substation communication a thorough analysis is to be made to study the performance and analyze the suitability of this protocol for substation communication.

This prompted me to take up this as my Master’s thesis to analyze the performance of remote monitoring of substation parameters using this wireless protocol.

1.3 Outline

The rest of the thesis is organized as follows:

In Chapter 2 literature review of substation, condition monitoring of substation, smart grid, smart grid communication requirements and network topologies is presented.

In Chapter 3 a brief overview of IEC 61850 is presented, in Chapter 4 the Methodology used for problem formulation and analysis is discussed.

In Chapter 4 a brief account of methodology used in this thesis is discussed, in chapter 5 the bandwidth estimation and calculation is presented. In chapter 6 the Matlab model of Wimax is discussed, in Chapter 7 Results and analysis are presented and finally in chapter 8 conclusions and future study areas are highlighted.

2. LITERATURE REVIEW

2.1 The smart grid

In conjunction with the increased need for an advanced and smart system in the power and energy industry, the design of the smart grid should fully address the past functionality problems that are prevalent in the present system.

2.1.1Required functional areas

The current concept of the smart grid substation monitoring system as defined by The European Union's Smart Grid whose vision is "Vision and strategy for Europe's Electricity Networks of the future" outline the priority areas that include:

- Demand response and consumer energy awareness: it covers the incentives and mechanisms for business, utilities, residential and industrial customers in order to cut peak demand time energy usage.
- Energy storage: energy is never stored but the new methods of storing electric energy are important in order to caution the consumers in the times when the generating stations may fail. The only technology that stores energy today is the presence of pumped hydroelectric technology of storage.
- Electric transportation: the concept inculcates the integration of plug in electric vehicles.
- Cyber security: cyber security revolves in the trials to achieve maximum levels of confidentiality, availability and integrity of the communication and electric information systems. Maximum security should also be ensured in the control systems that are used in the operation, protection and management of the smart grid's information technology, telecommunication and energy infrastructures.
- Network communications: there exist a variety of both private and public network systems that are either wireless or wired and they can be utilized in the substation monitoring system if they are efficient and meet the desired specifications.
- Advanced metering infrastructure: a metering infrastructure consists of a software and hardware for communication. Also, in the infrastructure are data management software that is used to create a network between the utility business system and the advanced meters for the collection and distribution of customers and control information.
- Distribution grid management: The system mission is to increase the performance of transformers, feeders and any other equipment that is in the network of distribution system and have an interconnection with the customer operations and transmission systems.

2.1.2Characteristics and requirements

Chun-Hao and Asrin Nirwan in 2009 discussed the detailed overview of the smart grid paradigm and incorporation of smart communication and information technologies in the present power grid system. There exist different intelligent and automation technologies that can be used to actualize the idea of the smart grid system for example the SCADA/EMS (supervision Control And Data Acquisition / Energy Management Systems), Automatic Meter Reading/ Advanced Meter Infrastructure (AMR/AMI), Phasor Measuring Units (PMU), Home Area Networks and Field/ Neighboring Area Networks(FAN/NAN).

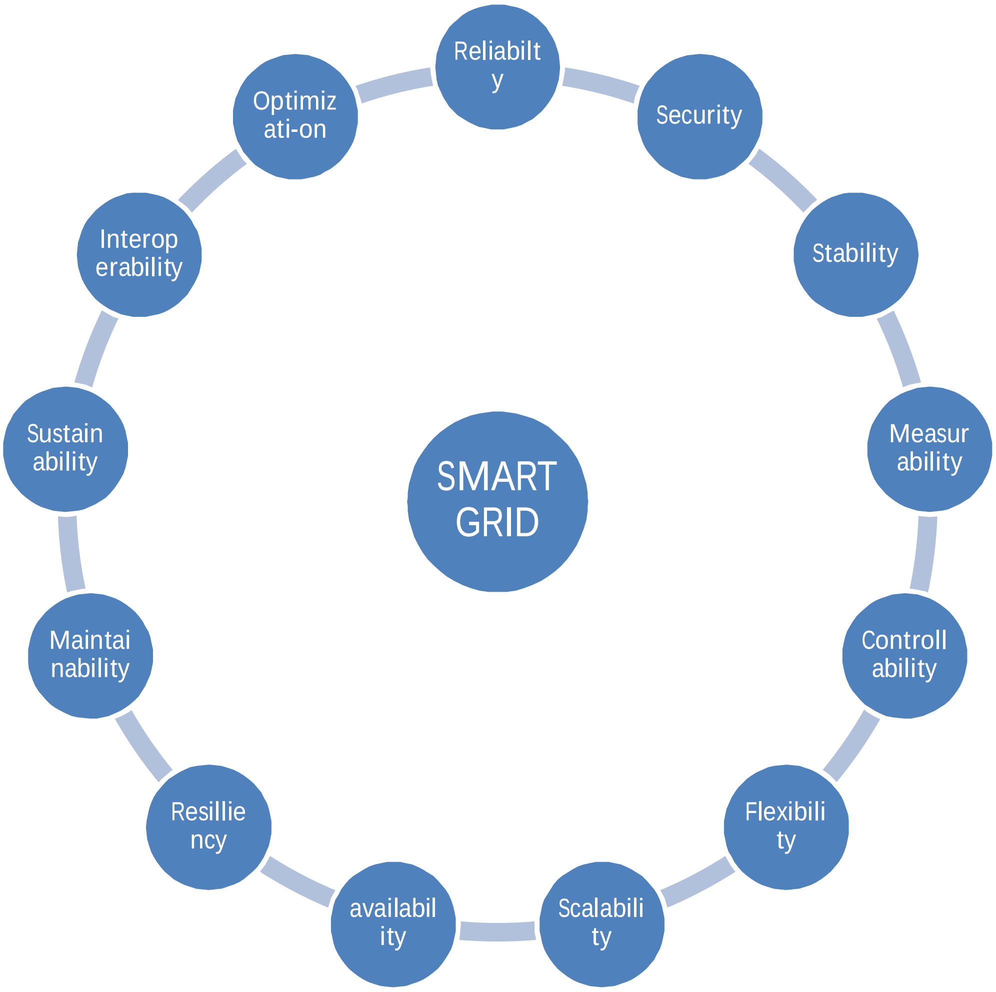


Fig. 2.1 Smart grid requirements.

A smart grid should be comprised of the below characteristics and specifications according to the two authors. The specifications possess a very close interconnection because the causes and the effects are related. If the features in the figure above are met, the smart grid can deliver results that will deal with market and consumer needs, environmental challenges and innovative technologies in communication and infrastructure challenges.

- Reliability and sustainability- guarantee for current and voltage stability must be ensured by the new smart grid system. Load variability and peak demand problems should be eliminated by the integration of the distributed system and wide area energy storage facilities.
- Measurability and controllability- the smart grid should have the capability of eliminating any operation that could be disruptive through an efficient control monitoring, communication and data flow system in the real time.
- Flexibility and scalability- the substation control and monitoring system provides for the decentralization of the grid system to have micro grids that can also be controlled centrally. As a result, a perfect communication and data flow system is inevitable in order to have a streamlined operation and control.
- Availability- communication and power availability is the most essential input to the smart power grid. Information for control and customer needs should be readily available especially when there is an issue of security. Once a substation is in operation, it must run all year round without disruption. If any failures occur in the system (e.g. network primary or secondary equipment) the communication system must return to normal operation in a very short time. Even with system maintenance, some defective components must be reinserted. This requires high levels of availability and reliability, which, network redundancy can enhance. Any delay or failure to properly control the substation may lead to a great loss to the electric utility and even harm the public. As a result, the control system should always be available to update the controllers on all the activities that are taking place in the power lines and substations.
- Resiliency- a smart grid should have the capability of recovering and restoring from any destruction or failures that may occur as a result of natural disasters, malicious activities and deliberate attacks by the use of a robust and fast response process. Consequently, safety and security can be ensured after the incidents have already occurred.
- Maintainability- the communication and monitoring system for the smart grid should be designed in such a way that maintenance is simple and fast. Proper and efficient means of troubleshoot for the malfunctions, inspection, replacement procedures and efficient communication components are key to the systems architecture.
- Sustainability- in order to deal with the environmental concerns effectively, the smart grid should be capable of providing more green energy and ensuring that the energy is utilized well by having a proper and efficient communication system.

- Interoperability- the smart grid technologies and protocols should be interoperable in order to allow interconnection between various communication and power technologies. The system should also support uninterruptible data transport and power transmission throughout.
- Security- safety and security are major concerns in any communication system. In modern substation automation systems, the networks are always connected to the corporate WAN or remote access is allowed. Even a completely isolated substation network is under threat of attack. Network security mechanisms like syslog, security audit trials, user authorization passwords, access control, port security and encryption should be implemented. If proper security is not incorporated into the systems then unscrupulous elements may misuse the system or may collapse the grid, which is highly dangerous.
- The smart grid communications system is supposed to offer maximum confidentiality of customer and controller information. Security breaches and hacking of the communication equipment and channels should be as minimal as possible. The channel that is adopted for data and information transportation between substation and control center must have great capability to avoid security breaches.
- Optimization- in the verge to reduce the capital cost, resource usage and network complexity, the smart grid assets and operations must be optimized at all times.
- Mobility- due to the increased complexity of the grid system in the future, the communication and control system should be situated in such way that it will be a subject to minimal interferences.
- Power level and receiver sensitivity- in relation to the communication channels, if the media is only applicable for the line of sight transmission, the transmitter and receiver power should be effective in order to ensure that information reaches the destination in good time and unaltered.
- Energy consumption- in wireless sensor and communication networks is a top concern for any communication design. Most equipment that is used in wireless communication is repowered. In the smart grid the powering system should be properly and carefully chosen in order to avoid any failure in communication due to low power in the gadgets or power failure.
- Data traffic and classification/prioritization- the smart grid sends and collects data in form of packets when the packet switching system is used. In this system, priority is given to the most urgent packets. In order to reduce any delay in communication, a dedicated path is the most efficient because it ensures that the delay in data transmission and communication are minimal.

2.2 Substation and Condition Monitoring

Currently majority of the electrical power transmitted is AC. From generation, transmission, distribution to consumption the electrical power is supplied at various voltage levels depending on the length and the quantity of power to be transmitted with an objective to minimize losses and economy.

The reason behind is economy, safety and low losses. AC voltage and current can be stepped up and down very conveniently and efficiently

Substation is an important part in this flow of electrical power from generation to utilization .In substation, generally voltage is either stepped up (at generating end) or stepped down (at load end) using transformer. There are substations which are used only for switching purpose or power factor improvement or voltage profile etc.

Substations may be classified on various criteria. Based on the voltage sub stations are classified as Low, Medium, High, Extra High and Ultra High voltage substations; based on location they may be classified as Indoor, outdoor substations, depending on insulation design they are classified as Gas Insulated substation or Air Insulated Substation and likewise there are some other classifications.

Typical transmission voltages worldwide are 132kV, 220kV, 420 kV, 550 kV, 765kV, 1100kV & 1200 kV. Typical distribution voltage levels are 33kV, 11 kV. The voltage at utilization level is 110V, 230 V, 440 V etc.

A substation contains the following important equipment; they may change depending on the substation requirement and purpose.

- Power Transformer
- Circuit Breaker
- Current Transducer
- Voltage Transducer
- Isolators
- Shunt Reactor
- Station Transformer
- Lightning arrestor
- Series Reactor

In addition to these main equipment there will be lot of protective relays like distance protection, over current protection, differential protection; control equipment like Point on wave switching relays, Synchronizing relays and other auxiliary equipment like contactors, sensors, TNC (Trip Neutral Close) switches, various measuring devices which are used for control, protection and monitoring the substation operation.

Traditionally the relays used were of electromechanical relays. As already mentioned the control logic was achieved by hard wired contactors which have NOs and NCs. The sensors and transducers were wired to each and every measuring relay. For example a measuring

CT secondary all the devices are connected in series by a 2.5 sqmm copper cable if they were to have the current inputs. Similarly Voltage parameter is required by Power measurement relay, and also over voltage protection relay. Both these equipment are connected in parallel to the voltage signal by copper wires.

With this conventional equipment substation automation was not possible and also remote monitoring very difficult. Hence these substations were heavily manned to physically monitor and control.

However, with the technological developments slowly numerical electronic relays have replaced the conventional electro-mechanical relays which can be configured with ease. These were operated on built in algorithms which could be altered depending on the requirement. These could be remote monitored with communication protocol like R232, RS485 etc. Slowly substation was automized using SCADA with transducers analog inputs and digital inputs to the SCADA servers. Over the period with the technological advancement in electronics and communication technology powerful electronic devices emerged which are called the IEDs (Intelligent Electronic Devices). These IEDs could be configured to function as relays or be used as Circuit breaker condition monitoring relay or can act as a bay control unit with appropriate hardware design and software configuration. With these intelligent devices and SCADA servers the substation operation and control were automated to some extent. Remote monitoring and control also became a reality.

But still the CT and PT were to be hardwired to each and every IED which want the respective inputs. Loads of data was generated whose management and interpretation for an efficient grid management was required, each IED was having its own protocol interoperability was a problem for which costly and unreliable protocol converters were being used. With the smart grid initiatives non conventional energy sources like solar power plants and non conventional consumers like electric cars are also connected to grid. With such a diversified grid requirement existing communication infrastructure required a major enhancement. To govern this communication requirement of present day grid an International protocol IEC61850 was framed which would solve the myriad of problems mentioned earlier. This protocol is presented in the subsequent chapters.

One of the important smart grid initiatives is Condition Monitoring of important equipment like Transformer and circuit breaker. Condition Monitoring helps in asset management and improves grid reliability by reducing downtime.

Today, many industry experts agree that the application of time-based maintenance programs is not the most effective use of maintenance resources. In an effort to reduce maintenance expenses, many utilities have moved away from the traditional maintenance recommendations, which are principally based on in-service time and number of operations, towards reliability centered maintenance and condition based approaches [18] [19]. Conventional method was to perform time based Maintenance schedules which were less efficient as the condition of the equipment is not known and maintenance is done only to check whether everything is intact. This caused unnecessary outages and on the other hand when the equipment requires some repair due to some malfunction it may not be considered because of the time based strategy, which, may lead to the breaker failures and explosions causing loss both due to asset damage as well as outage.

High-voltage circuit breakers provide a case in point. Not only are high-voltage breakers essential to the protection of other system components under fault conditions, their reliable switching operation is necessary for maintaining optimal system conditions. A breaker's failure to operate as required can result in equipment damage, increased system disturbance, and loss of load. With many years of experience, utilities have established programs for maintaining circuit breakers in good operating order. Because of their sheer numbers, however, breakers represent a significant portion of a utility's power delivery maintenance budget [18]. Due to this importance of circuit breaker in the power system, additional cost of implementing Condition Monitoring to it is often justified.

The circuit breaker monitoring system is a real time supervision system of the circuit breaker main parameters (currents, voltages, pressures, temperatures, contacts etc). This supervision is made through digital; equipments and special sensors that are installed in the circuit breaker. The data are collected in a data acquisition and control unit to thereafter through a communication network, using desirably a protocol standardized internationally, be sent to a central computer located at the control building of the substation and later to the operation centers and so allowing remote supervision. With the special sensors the physical parameters are measured and converted to an electric analog signal usually 4-20 ma or a digital signal. These all are fed to an intelligent electronic device (IED) which is generally a programmable numerical relay.

Each sensor measuring particular parameter is connected to a particular slot of the IED where the parameter is defined in it. Algorithms may be written to enable the IED to collect the data continuously from the sensors at the specified sampling rate. The collected data may then be processed and analyzed by the IED based on the programs written. Then the analyzed information shall be informed to the operator by publishing it to SCADA using RS 485 communication or as is now the international protocol of IEC61850.

This IED may be programmed in such aw way that it will throw up alarm and alert the operator if any abnormality is observed. This will enable the maintenance personnel to attend the problem immediately thus avoiding a future operation failure, thus improving the grid reliability.

Similarly Transformer parameters are also monitored online to predict the health of the equipment.

2.3 Communication technologies for smart grids

The smart grid ensures real time and reliable information to the end users from the generating units and substations. Equipment failure, natural accidents, capacity constraints and other catastrophes that may cause power disturbances and outages can be prevented or avoided if an online power system diagnostic, condition monitoring and protection is put in place. Consequently, an intelligent control and monitoring system that can be embedded in the substations and control centers will be an essential improvement and advancement in the incorporation of the smart grid to the current electric power transmission and distribution system.

It is very crucial for the electric utility managers to clearly define the communication specifications and requirements to incorporate the best communication infrastructure. The communication system should have the capability to handle output data and ensure a cost effective, secure and reliable service in the whole grid system. Most of the electric utilities attempt to incorporate their customers' attention and have to encourage them to participate in order to ensure a vast and efficient electricity usage. Outages and disasters that lead to the interruption of the power infrastructure encourage the need for a perfect relationship between the communication systems and the electric grids. The different communication technologies that can be utilized by the smart grid system are grouped into two main groups: the wireless and the wired communication channels. Both of the media can be utilized to support data transmission from the substations, control centers, smart meters and electric utilities.

Wireless communication media at some instances has some merits over the wired communication technologies. The advantages include having a low cost on infrastructure and easy reach to the remote areas where wired channels cannot reach. However, there exists a lot of attenuation when the wireless communication media is used due to the nature of transmission path. Wired communication media is more efficient in the realization of higher transmission speeds and are not affected by much interference. In addition the operation of the wired channels is usually not dependent on the availability of power from batteries like it is the case with the wireless channels.

Basically, the smart grid system requires two types of infrastructure for enhanced and efficient information flow. The first flow is from the utility data centers to substations and the second between the electrical appliances sensors to the smart meters. Data flow from the sensors to smart meters can be achieved by the use of wireless communication media or the power line communication channel. On the other hand, communication between the substations, smart meters and the control centers can utilize the internet. However, the cost of installation, management, operational costs and technology availability are some of the factors that need to be taken into account when resolving to use the smart meters. In an effort to reduce maintenance expenses, many utilities have moved away from the traditional maintenance recommendations, which are principally based on in-service time and number of operations, towards reliability centered maintenance and condition based approaches. Not only are high-voltage equipment's essential to the protection of other system components under fault conditions, their reliable operation is necessary for maintaining optimal system conditions, the failure of the system components will increase system disturbance, and loss of load. To provide connectivity to these endpoints in a cost-effective manner, high speed wired or wireless broadband access is needed. The system-wide intelligence is acceptable only if the information exchange among the various operational units is expedient, reliable and trustable.

2.4 Smart grid communication requirements

Communication infrastructure between the consumers, transmission channels and generating stations demand for a two way channel. The channel should also be fully reliable, inter-operable and very secure with sufficient bandwidth and low latency. Moreover, security of the system should be fully robust to always prevent cyber-attacks and provide advanced controls for system reliability and stability. Below, some of the major requirements for a smart grid are discussed:

2.4.1 Security

Security is very fundamental in the communication system between the substations and control centers. It ensures that there is utmost privacy during billing and grid control Cyber-attacks should be avoided at all costs.

2.4.2Reliability availability and robustness

System reliability provision is one of the greatest desires and requirements for any power utility. Failures in power transmission usually occur due to diversified causes like poor communication and aging devices. If the power systems utilize more robust and faster control devices, secure and modern protocols in communication and improved communication and information technologies, the consumers will be cautioned against any power failure in advance or even the same could be avoided if proper communication channels were available.

2.4.3Scalability

To facilitate the proper operation of the smart power grid should be scalable enough. Gadgets like smart meters, smart data collectors and sensor nodes are progressively being incorporated in the grid communication network. As a result, advanced web services and reliable protocols should be integrated in the smart grid in order to maintain the security aspects.

Quality of service

Effective communication between the power grid system users is very essential due to the high expectations and delivery specifications. The communication network to be utilized should ensure that there is uninterrupted flow of information and data throughout the grid.

With many years of experience, utilities have established programs for maintaining field equipment's in good operating order. Here for the purpose of retrofitting an existing substation into a smart substation requires condition monitoring of the entire system on a real time basis, for this communication exchange between large endpoints is required in within the utility territory.

To provide connectivity to these endpoints in a cost-effective manner, high speed wired or wireless broadband access is needed. The present communication abilities of the established power systems are limited to small-scale local regions that operationalize fundamental functionalities for system monitoring and control, such as power-line communications and the traditional Supervisory control and data acquisition (SCADA) systems. Only status information is monitored and shared by these conventional methods with very low bandwidth requirement and latency which do not meet the demanding communication requirement of automated and intelligent future generation power system. The communication requirements for the real time monitoring of the circuit breaker requires so Real-time two way communications are the foundations to strengthen the comprehensive power system management operations which, in certain cases, require time-sensitive and data-intensive information exchange. When we retrofit the smart grid into an existing substation it is vital to take advantage of the breakthroughs in communication technologies to enable the automated and intelligent system management.

Although the currently available networking technologies have greatly satisfied our personal communication needs, applying them to power systems and addressing the specific requirements for power communications are challenging by all means. The data generally contains the phasor measurement unit data for the propagation of this data a large bandwidth communication channel is required. Potentially, the substations communicate with the central control centers using point to point telephone or radio data wave known as micro wave links. Thus with no speed network in operation, the sensed digital data from PMUs is only limited inside substations and cannot be effectively utilized by the control centers .This incorporates the need of a high bandwidth wide area network in the smart grid system. Bandwidth requirement has a case in point in the information exchange between entities. In this preliminary report the methodology is depicted for the calculation of the bandwidth required and modeling the communication technologies by using the Matlab/Simulink software.

2.5 Communication networks and protocols

The existing smart substations possess a high-speed local area network that combines the control, protection devices together with high speed system applications. In addition, the substation must have a human machine interface (HMI), an engineering station and servers that uses routers in order to connect to the control center. The communication infrastructure is supposed to possess a certain extent of redundancy so that it can ensure the availability and reliability of protection, monitoring, and substation control.

Communication protocol of a smart grid substation supposed to be standardized and have the capability to allow improvements in terms of interoperability of the networks of communication. Substation Automation Systems (SAS) future aspiration is to adopt the IEC 61850 standard. The standard allows direct and reliable communication not only between the devices but also between the control center and the substation (Usman & Haider).

Once a substation is in operation, it must run all year round without disruption. If any failures occur in the system (e.g. network primary or secondary equipment) the communication system must return to normal operation in a very short time. Even with system maintenance, some defective components must be reinserted. This requires high availability and reliability which network redundancy can enhance. MTTF (Mean Time to fail), MTBR (Mean time between removals) and MTTR (Mean time to recovery) of the communication network must be also considered.

It is possible to divide the substations into three levels depending on their functions; the station level, bus level and the process level and into two groups depending on the communication buses i.e. process bus and station bus. Local substation communication networks have high requirements in terms of security, availability, accuracy, performance, coverage and capacity that can never at any one time be ignored. Besides, scalable, robust, cost effective and highly reliable communication channel must exist between the control center and the substation so that remote control and supervision can be actualized.

This calls for a careful choice in the network topologies for use in the Local Area Network (LAN) because the different topologies have their merits and demerits that are supposed to be evaluated in order to have the best infrastructure of communication. The most common and frequently used topologies are the star topology, ring topology and the bus topology. Hybrid topologies like cascaded-star and star-ring topologies have also emerged. Use of Ethernet communication protocols in the design of the emerging smart grid substations is on the rise due to their effectiveness. Ethernet is very reliable when remote access, monitoring and control of the electric system are desired.

2.6 Communication media

In 2007, Mahmood Qureshi was able to successfully analyze the current state of the communication system and technologies that effected the automation of substations in terms of their performance, capacity, coverage, accuracy, availability and security. Cagri and frank Lambart were also able to outline and discuss the challenges and opportunities of different communication technologies and network architectures that were being used for the automation of power systems applications. Both articles describe the power line, wireless, satellite and optical fiber technologies for communication. They were able to detail the pros and cons of each of the communication channels.

2.6.1 Power line communication

Power line communication is a method that utilizes the existing transmission lines for the transmission of high speed data signals ranging from 2 Mbps to 3 Mbps from one device to the other. The power line communication link can be the first option to the electric power utilities due to the presence of direct links with the meters all over the grid system. In a typical communication system utilizing the power line, the smart meters are all connected to the data center by the use of cellular technology. The greatest advantage of this communication system is the presence of an existing infrastructure that connects the whole electric grid system. There is minimal installation cost. The broadcast nature of data transmission brings out a critical nature of the security status during the communication.

A smart grid has to ensure that the information is secure, confidential, authentication levels are high and user intervention is always maintained and upheld. In urban centers, the power line communication system technology is very effective due to the fact that the infrastructure covers almost the entire geographical location. However, transmission through the power lines is very noisy and harsh. Hence, it is difficult to model the system. Low bandwidth characteristic of this communication channel makes it unreliable and inefficient for application that may have a higher bandwidth requirement. The power line is also very sensitive to disturbances. As a result, it becomes undesirable for data transmissions for large distances.

2.6.2 Cellular network communication

Cellular networks are a good choice for communication within the smart grid. The presence of existing cellular infrastructure from mobile services providers encourages the electric utility providers to utilize the wireless channels. Consequently, they save huge amounts of money that could have been used to put up their own communication infrastructure. The cellular networks accommodate communication over long distances and covering a wide geographical location. Technologies that are incorporated in the wireless group include WIMAX, LTE, 2G, 2.5G and 3G. Depending on the type of switching, the cellular technology can achieve very high transmission speeds, efficiency and reliability.

The cellular networks can also provide a wide bandwidth for applications that demand high large spectrum specifications. Due to the high levels of authentication and security measures, cellular networks are very secure in data transmissions. GSM technology can achieve up to 15Kbps and GPRS can support up to 170 Kbps. Lower cost, fast installation, better coverage and lower maintenance costs highly recommends the cellular networks for use in the smart grid system. However, cellular networks are curbed with congestion due to the diversified services that they offer. Some of the applications that are used in the smart grid system require a dedicated path and reliable channel for utilization, which, the cellular technology may not offer. During harsh weather conditions the cellular networks may not guarantee their services to the electric utilities and this may negatively affect transmission.

2.6.3 Satellite communication

Satellite communication is very viable when data transfer and communication is over very long distance and covering a wide geographical area. The smart substation can utilize the already available satellite communication infrastructure and this would reduce the installation and maintenance costs. However, this channel is bound to cause many unavoidable delays during communication and data exchange. Delays can cause great harm and danger to power systems due to the sensitivity of electricity. Thus, the use of satellites is never a preference (Nigim).

2.6.4 Optical fiber communication.

Optical fiber possesses much significant advantages when compared to the use of copper cables that have been in use traditionally. However, the cost of installation of fiber optic cables is very high. Cases of cable vandalism and theft are also very much prevalent and this may cause unwarranted and predetermined interferences. Optical fiber is used in various applications like telecommunications for transmitting audio signals, Internet and also cable TV. Optical fiber has huge advantages over conventional copper wire like low attenuation and interference which makes it ideal choice for long distance applications. But fiber optics are associated with huge costs hence are preferred only for long distance applications where the advantages offered by optical fiber justify the cost. Despite the risks and high cost of running the cables over long distances, their effectiveness and high performances increases their usage.

The *advantages* are as outlined below:

Band width- fiber optic cables have a very wide bandwidth that allows greater amounts of data to be transmitted through them simultaneously. The large bandwidth is very desirable because it increase the performance of the channel and offers chances for expansion.

Low power loss- for long transmissions, optical fiber is very effective because they have a very low power loss as compared to the copper cables. Copper transmission is never recommended to go beyond100 meters while fiber optic cables can be used for distances of about 2000 kilometers.

Interference - Fiber transmission is very admirable because the data rates are very high and they are rarely affected by electromagnetic interferences and frequency interferences.

Size**-** the size of the fiber optic cable that is needed for transmission is thin and hence the volume is approximately thirty times less than the capacity needed when copper wire is used.

Safety- fiber optic is never a security hazard because it never emits sparks.

Cost- the cost of installation of the fiber optic cables is very high compare with the copper wires.

Fragile**-** it is possible to break the cable by bending. As a result, if the cable is run around sharp corners, there is a probability that the cables will lose continuity and hinder transmission.

Protection- due to high value in for of cash that is attached to the fiber cable, more protection and surveillance on the areas where the cable p[asses is always high to avoid tampering and theft. As a result, more cost may be incurred to hire security personnel.

Copper cables

Copper cables are effective over short distance to transfer data at a considerably high data rates. The channel is always secure and the cables are cheaper to install than the fiber optic cables However, there are a lot of power losses when it is used for transmission over long distances. The data transfer is always affected by electromagnetic radiations that may alter the original; signal that was intended to be transmitted.

2.7 Communication architectures:

The communication architecture gives the details of the system components and the way they interact with all the requirements and principles of the smart grid. Whole grid is supposed to be connected by a communication network and should possess the capability of control and monitoring from a central position. There exist no defined communication architecture that is supposed to be used between the control system and the substation. If a communication architecture can fully accommodate the successful working and running of the substations and control centers, information exchange and coordination, the whole system could easily be automated. Some of the available communication architectures are discussed below:

2.7.1 Direct connect architecture

This architecture is the most basic and it outlines a situation where the smart meters have connection that is dedicated with the substation through a data hub. The architecture utilizes the star topology where the data hub that is located within the substation is connected to a large number of communication links that are dedicated to different devices. The connection links can either be wireless or wired. The direct connect architecture lost publicity due to the increased devices that demanded a dedicated path. However, the architecture can be viable in sparsely populated areas. The main advantage of the direct connect architecture is the reduced cost and effectiveness because the channel is dedicated to the respective intelligent devices (Wang).

2.7.3 Local access aggregators architecture

The main specification of the local access aggregator architecture is the presence of aggregating smart meters data center at a certain locality. The data center is then connected to data hub located at the substation. The architecture was better because the amount of wired cables that could be running to the substation if the direct connection architecture was used were greatly cut down. This model introduced the Neighborhood Access Network (NAN) that ensured that there is communication connection between the data aggregators and the smart meters. The NAN aggregator connects at one end with the Wide Area Network (WAN) while the other side collects data from the customer home network. This architecture possesses an advantage that it cuts down the quantity of the communication links that connect to the data hub in the substation (Desai).

2.7.2 Interconnected local access aggregators architecture

This architecture is framed the same way as the local access aggregator’s architecture but it the NAN networks are interconnected by trucks. The trucks are important as they provide redundancy to the network. This produces more routes that can be used to transmit data from the local communication centers to the data hub in the substation. As a result, resources can be shared effectively with the neighborhood aggregators that are located closely.

2.7.3 Mesh architecture

The architecture allows an added degree of possible connections at the smart meters and the aggregator’s level. As a result of the added communication paths, the smart meters that may not be having a wired connection can use wireless technologies like the wireless radio frequency channels in a certain area.

In addition, the radio frequency contains the ability of establishing communication links between adjacent networks. It is therefore possible to increase the communication range by determining all the links that can reach the destination. However, radio frequency channel cannot be used for communication in the smart grid because it is highly susceptible to attacks that causes interferences and reduce confidentiality. This setback can be mitigated upon by incorporating strong data encryption to ensure security.

2.7.4 Internet cloud architecture

The architecture utilizes the internet to connect to the customers and the control center. This is aided by the fact that most of the households and substations are connected to the internet. However, the rural areas that lack access to the internet are exempted for using this architecture. The fact that the architecture uses the already available internet network makes it cost effective because there are no monthly charges. In addition, the utility companies can easily store the customer’s data in servers that prove to be less costly than the aggregators.

2.7.5 Outside substation

The Tele control Application Service Element (TASE) also known as Inter- control center communication protocol is used for real-time communication and data exchange by utilities between control centers. The inter-control center communication protocol works with a TCP/IP transport layer and is based on a server/client model. It can accommodate the following requests: request for periodic transfer, request for exception and single request.

2.8 Network topologies

An effective communication and control system that connects the entire monitoring, protection and control equipment in a substation determines the performance of a substation automation system. There exist three types of network topologies in for communication; the star, ring and the bus topologies that are mainly implemented when Ethernet switches are used in electric substations. Hybrid topologies are built from the connection of the three main topologies in order to provide better performance at a lower cost.

2.8.1 Star topology

In a star architecture, all the switches are connected to the common central node or the backbone switch in a star connection for the Ethernet network. The configuration introduces the lowest latency than all the other topologies. In addition, the message transmission time delay complies fully with the IEC 61850 standard. However, the reliability of the topology is low because there is no redundancy because all the equipment and devices are terminated to a single switch which is the backbone. The switch is very susceptible to harsh electromagnetic and environmental conditions similar to the electric substation communication networks.

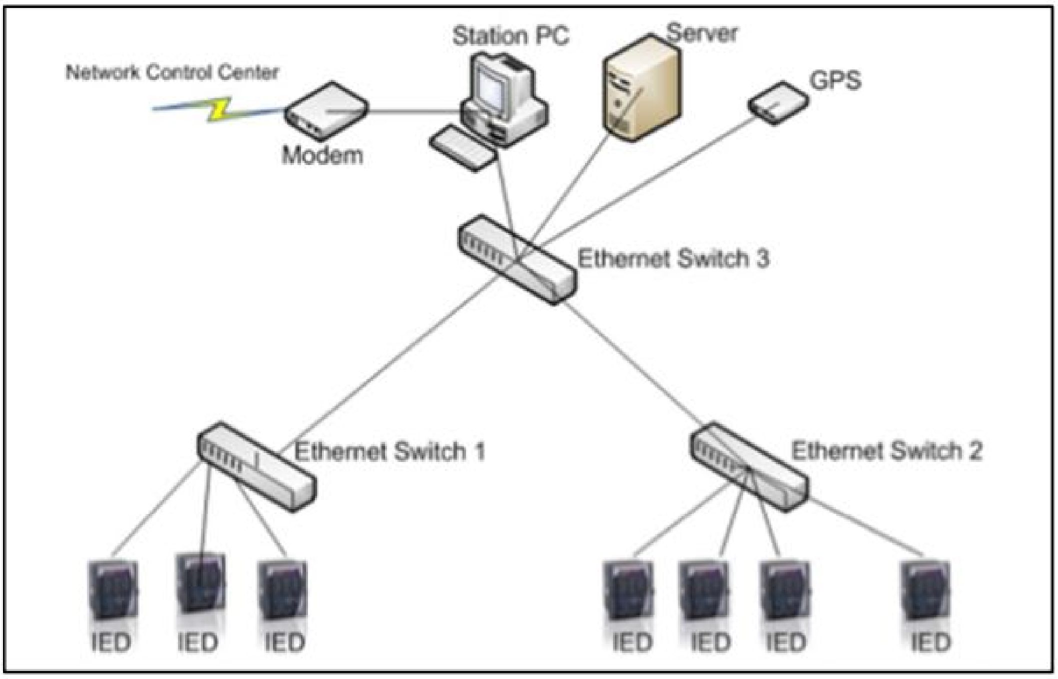


Fig. 2.2. Star Topology

2.8.2 Bus/ cascading topology

The bus architecture comprises of switches that are connected each other in a cascade through one of the switch ports. The cascade ports are able to realize higher transmission speeds than when the ports are terminated in other devices. However, there exists a transmission time delay because each switch takes a certain time to process thus introducing latency. Due to this reason, the maximum tolerable delay that can be accommodated by the system determines the maximum number of switches that a can be connected to form the cascade. Bus topology is capable of providing acceptable time delays that are cost effective, but it never assures a complete reliability because of the redundancy in the system. The architecture is as shown below:

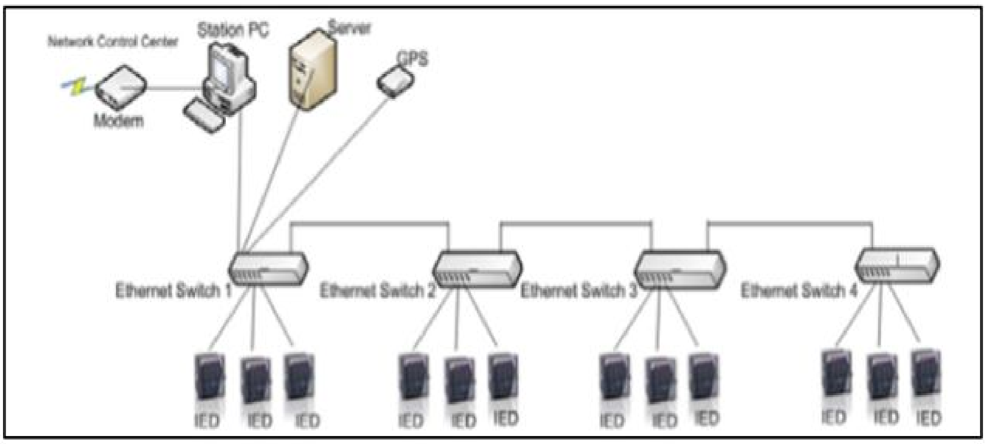


Fig. 2.3 Bus or Cascade Topology

2.8.3 Ring topology

The ring topology is close has a close similarity to the bus or cascading architecture except the fact that the loop connects the first switch to the last switch. This provides a certain level of redundancy in case one of the ring connections fails. In order to prevent the message from making indefinite circulations in the loop, which would result to improper utilization of the bandwidth, the switches should be well managed. The Rapid Spanning Tree Protocol (RSTP) is implemented by the managed switches. The protocol allows the switches to detect when the loops are being made and break them logically. As a result, in the ring architecture the managed switches allow the reconfiguration of the sub second network when a communication faults causing physical redundancy. Ring network topology offers the highest reliability and allowable time delays over the other two topologies. However, this is to the expense of the increased cost and complexity than the other architectures. The architecture is as illustrated below:

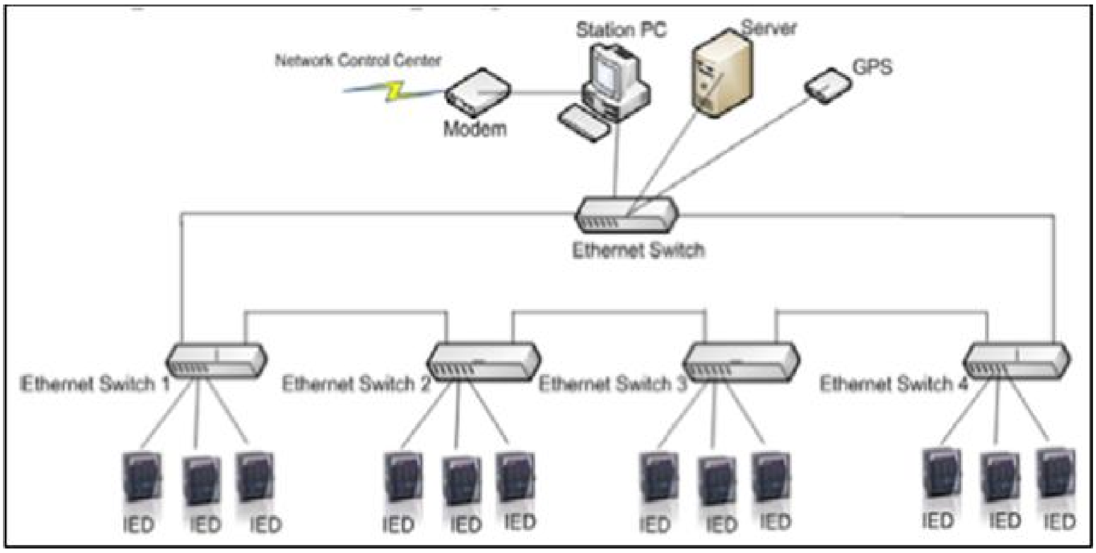


Fig. 2.4 Ring Topology

As defined by the IEC 62439 standard, there are two redundancy protocols that fulfill the industrial communication network reliability. They include the Parallel Redundancy Protocol (PRP) and High-availability Seamless Redundancy (HSR). The mentioned protocols help the network to mitigate any case of mitigation delay when a fault occurs to any of the devices in the network by providing active redundancy same way as in case of a link or switch failure. The parallel redundancy protocol and the high availability seamless redundancy work on the basis of a like active principle of redundancy where the information that is exchanged is also duplicated. However, the two protocols address different network architectures. Due to the fact that these protocols provide seamless redundancy, they are mainly applied to offer protection that is based on the digital communication standards like the IEC 61850. The redundancy is very important in the actualization of substation automation system.

2.8.4 Parallel Redundancy Protocol (PRP)

The parallel redundancy protocol introduces redundancy to the device directly via the double attached nodes. Each of the nodes is terminated to two local area networks that are independent; possess the same like topologies and both have parallel operation. The destination node is able to receive frames from the source node through both networks. As a result, the duplicated frame is discarded by consuming the first frame. However, the two local area networks are supposed to be having the same protocol but the topology and performance may differ in relation to the transmission delays.

2.8.5 High-availability Seamless Redundancy (HSR)

The High-availability Seamless Redundancy protocol operates on the basis of similar operation principles. In case the equipment fails, the protocol has a zero recovery time which applies only with the ring topologies. The sender nodes just like in the parallel redundancy protocol, sends duplicated messages to both the ring directions. The circulation is then interrupted by both frames of the receiver node. However, as opposed to the parallel redundancy protocols the high availability seamless redundancy protocol requires each node to be capable of transmitting in the HSR protocol.

The emerging generations of substation are usually advised to utilize the parallel redundancy protocol for the station bus while the process bus uses the HSR protocol. Communication network that is used between the control and protection devices is actualized by the station bus. Station bus also makes the communication network that joins to the high level systems. The architecture supports connection of devices to two redundant and independent networks that have the capability of handling any communication equipment failure without causing communication interruptions. Process bus on the other hand forms the communication network that is used to join the control and protection devices with other measurement and sensing elements in the field. In the process level, a topology where the HSR ring connects the control and protection devices to the primary equipment in order to acquire data by the use of the merging units. The illustration below depicts the connection of the PRP and the HSR protocols.

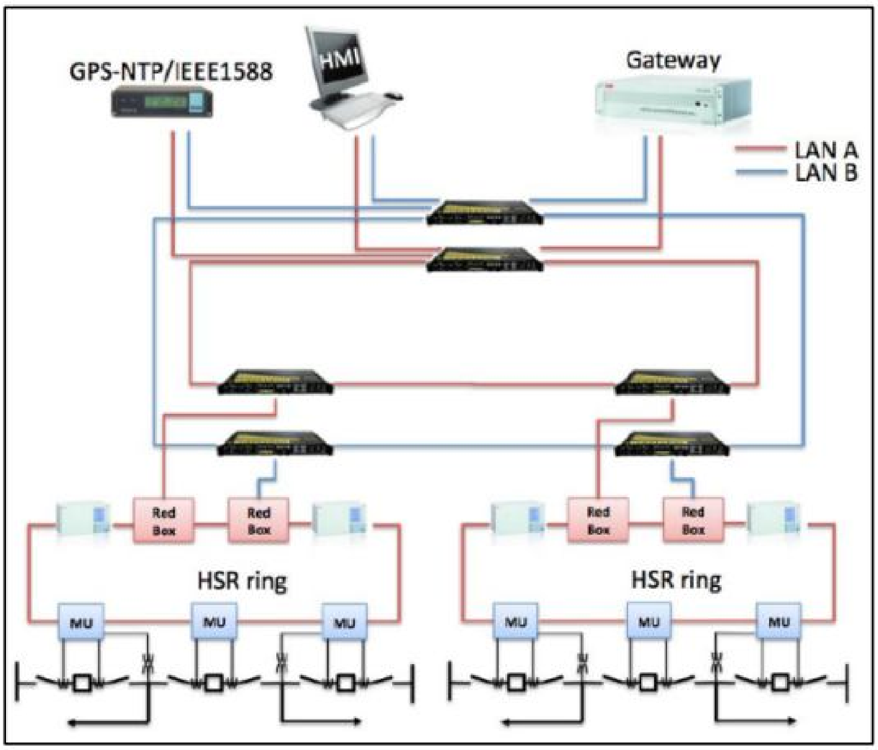


Fig 2.5 High-availability Seamless Redundancy Architecture

2.9 Security in the smart grid substation communication networks

The best communication network to be used to transmit data from the substation to the control center has to very secure. Different parts of the communication system network are exposed to different threats to security. Then communication network is modeled in concurrence with the OSI 7 layers model. The layers that are exposed to security threats are explained below. Knowledge of the network layer threats assists with the choice of the channel that is more secure.

2.9.1 Network physical layer

All the communication networks that can be used to transmit data and information from the smart substation to the control center are modeled as per the OSI model with 7 layers. In the physical layer, bits are converted into signals for out- going messages and signals are converted back into bits for incoming messages. In a wired system, the physical layer is characterized by mainly cables that carry the information, patch channels that form the passive interconnection points, interconnection nodes where the signal is converted either to or from an electrical signal, routing points and switching systems. On the other hand, the wireless networks like the WiMAX is comprised of the base stations that include towers, antennas and radio and interface hardware. The access points to the network may either be stand alone or they can be emended within the communication device. However, for any type of communication network, there are a large number of interconnection points that are used as repeater panels in order to maintain the strength of the channel.

The physical security of the network equipment ranges from cabinet locks, badge systems and video surveillance but they cannot fully prevent the system from cyber security breaches. As a result, it proves to be very difficult to fully secure the interconnection points of networks. When cables are used, either the optical fibers or the copper wires, the security of the signal is ensured if the cables are not tampered because they mainly run underground. However, at the termination points, the cables can be tapped by unauthorized individuals. Wireless transmission is usually deployed on both the unlicensed or licensed spectrum. The licensed spectrum is more secure and there is assurance of availability of the channel. However, due to the increased advancements on the technology, more people can hack on the licensed channels and lead to a security breach.

From the above considerations, it proves that the physical layer architecture and devices alone cannot assure utmost security of the transmission channel. Never the less, the network infrastructure should be protected to avoid scenarios that my compromise the integrity of the signal that is passed to the other layers for transmission.

2.9.2 Link layer

This layer determines the switching method that would be used to transmit the signal. The switching may either be circuit, packet or message switching. Circuit switching is applicable for the wired channels and it is secure if the cables are well-guarded. However, the controller may be able to tap the signal at the terminations. Packet switching is secure due to the fact that the signal is Brocken down to small packets that are sent through the communication media. The channel of communication security determines if the packets can be intercepted before reaching the destination. In wireless channels like WiMAX and microwave, if the signal is not well encrypted, the probability of a security breach is very high.

If there are no dedicated channels in the communication network, the best channel is supposed to support the ability of the network to recognize the critical network from the non-critical traffic. This ensures that the important messages are never delayed. Any channel should possess link layer methods that are capable of differentiating the traffic in terms of the importance and emergency. The switch security is determined by the manufacturer. To increase the security of the switch, some configuration options can be incorporated.

2.9.3 Internet layer

If the channel requires connection to the internet, firewall is the frequently used means to protect the network segments. The network layer achieves the logical traffic separation to ensure security but if the attacker acquires access to the router, the channel can have a permanent security breach. If communication is to use the internet or local area networks, the network administrators should ensure that the network is secure by having perfect encryptions. The wired channels are exempted from the internet attackers because they do not have to use the internet to transmit the data and information.

2.9.4 Transport layer

Transport layer is part of the internet protocol suite that provides the network with different transport protocols that possess different information delivery guarantee. The transport protocols do not promise any guarantee on the confidentiality protection. As a result, the channels that utilize the internet cannot be expected to be secure for use in the smart grid to transmit information from the substation to the control channel.

2.9.5 Application layer

Traffic streams can be protected at this layer by the use of various cryptographic mechanisms that are independent of the network. The communication channel does not have the capability to ensure the security of the signal after it reaches the application layer. However, the substation and the control centers should utilize application devices that can be encrypted to ensure that the confidential information is not accessed by unauthorized personnel

2.10 Selection of Physical Layers for Substation Communication

The physical layer is tasked with the transmission of the signal bits between two devices that are separated by a distance. Different criteria and parameters are used to determine the best channel for the transmission.

2.10.1 Bandwidth

It is the data transfer capacity of a particular communication network. It is represented as bit rates that are quantized in kbps or mbps. Sufficient bandwidth is key to ensuring that substation network performance requirements are met. Additional high bandwidth applications, like video streams, will use the same network infrastructure. In general the network should be designed in such a way, that network load never reaches the capacity limit even in critical situations. If in the future the use of sampled values in process bus applications is planned, it should be taken into account that sampled values need significant bandwidth and may require the use of Gigabit Ethernet networks. The basic methodology on considering the above summary says that all important considerations for instance Bandwidth, delay, signal degradation, signal modeling are considered (Milberg).

For this project when considered safety of communication technology unlike hacking, a wireless technology or a wired technology such as Wimax and copper are more susceptible to electromagnetic inference when considered with power system applications So in this project the entire substation network is interconnected with fiber optic media which is immune to EMI or white Noise, and the network gateway which outcomes from the substation is propagated through many models of media to the supervisory destination. To model significant elements to retrofit the system on considering special issues such as bandwidth for condition monitoring matlab/Simulink software is needed where we obtain simulation results various communication media models that best suits to retrofit the existing substation into smart substation.

The network bandwidth capacity defines the net bit rate or the channel capacity. In other terms, the network bandwidth capacity is used to express the maximum throughput of a physical or logical communication media when the communication system is digital. The Hartley’s laws define this parameter in a communication system. It proves that the maximum data rate is proportional to the channel bandwidth for a physical communication connection.

The network bandwidth consumption is another parameter that may be used to investigate the best communication media to use for data bits transmission from the substation to the control center and vice versa. It is evaluated by having the knowledge of the average successful data rate transfer via a communication link. The channel bandwidth is different from the throughput because a channel with a certain number of bits per second may not transmit the same number of data rate. This is because the encryption, protocols and the lead to addition of a certain amount of overhead. For a communication network to be effective, it has to have a framing protocol, effective throughput and overhead which depend on the implementation.

2.10.2 Gain

The gain of a communication channel defines the capability of the signal to increase or reduce in strength. Some of the channels cause fading of the signal bits such that by the time it reaches the destination, the signal is very weak and sometimes it loses its original message. Wireless channels like the radio waves are more affected by the environmental factors that make it lose a considerable amount of signal power during transmission. The gain of the channel at the receiver tries to rebuild the signal power and strength so that the information is not misinterpreted. Analogue channels are more affected by loss of power and always require large gain factor to ensure that the signal is not misinterpreted. Most of the channels, fiber optic, wimax and copper cables mainly transmit information in form of bits. The problem occurs when if any of the bits is lost because the bit stream gives totally different information at the receiving end. As a result, the channel with a large gain is better than the ones with a very low gain. The gain can be evaluated mathematically or best effectively by the use of Simulink modeling.

2.10.3 The line rate and Throughput

It is the speed with which the bits are transmitted on to the wire. It is a part of physical layer. The direct transfer rate is the transfer rate offered by the physical layer. Throughput is a parameter that defines the rate of production. It is the rate or speed at which something can be produced or processed. In communication networks, network throughput depicts the rate at which the messages are successfully delivered via the communication medium. The physical link acts as the connection through which the messages belong. On the other hand the message can be transmitted through a network node. It is usually expressed in bits per second or data packets per time slots.

Communication network designer’s main interest revolves and is aimed on achieving the maximum performance from the system. The best communication network that will suit the connection of the substation and the control center is the one that will deliver the data in the most effective way at the minimum expenses. As a result the throughput is an important parameter that is always used to choose and put up the communication media that best suits the client. Different ways may be evoked to evaluate other network parameters but their collective results determine the throughput.

Factors affecting the throughput

The highest throughput that can be achieved is always affected by the available bandwidth for the channel together with the signal to noise ratio if the medium is analogue. Due to the fact that all the electric signals that are transmitted through the lines are analogue, the simple digital information cannot be used. When either the wired or the wireless system is used, the limitation of the upper bound of the signal that directly corresponds to the amount of information that can be sent through the channel is inevitable. The Shannon Hartley theorem is the one that is used to predict and calculate the amount of information that can be transmitted. The bandwidth of the wired is always considerably limited than that of the wireless channels. If the digital systems are used, the knee frequency or the time taken for any digital voltage to exponentially rise from 10% which is the value of the nominal digital

‘0’ to achieve nominal digital ‘1’. The required bandwidth of the channel has a direct relation with the knee frequency.

RC losses are also a setback to achieving the maximum throughput. Wires are always susceptible to cause power losses due to their resistances and capacitance with respect to the ground. As the frequency of a channel increases, the electric charges are forced to move to the edges of the cables or the wire. As a result, the cross section that is required and available for the current transmission reduces and the resistance of the wire increase in a situation known as the skin effect. The signal to noise ratio thus reduces. Another limitation to the throughput emanates from ringing and termination. The wired channels must always me modeled in such way that they suit the communication task. If the cables are not well modeled, the reflected signals would result to interferences to the incoming data. The wireless channels limiting effects and interferences result to the reduction of signal to noise ratio and consequently the maximum number of bits that can be transmitted reduces.

2.10.4 Latency

Latency is the time that is used between the input of a signal and its output. It is the time difference between when stimulation took place and the time the response was received. The major cause of latency is limited speeds of the signals as they propagate through the medium. The speed of a signal is always a bit lower than the speed of light. In theory, the speed of transmission is always provide to be equal to the speed of light but due to the media limitations, the speed is less than the speed of light. The nature of stimulation is the one that precisely defines the latency of the channel. When the communication network is two way, the maximum rate of transmission of the information is limited by the latency.

Network latency is prevalent in the packet switched network. In this switching mechanism, the communication network latency is evaluated either by the use of the one way transmission time or in a round trip. One way mode means takes the time that elapses from when the source sends the packet to when the packet is received at the destination while a round trip delay time is determined from the addition of one-way latency from the sender to the receiver and the one way latency from the recover to the transmitter. When the round trip is adopted, the signal processing time at the destination is usually excluded. To determine the latency, software like the ping may be used. The communication channels that possess the minimum latency should be taken to be the best because it means that there is a very minimal delay in the signal transmission. However, delays may be caused by the queuing at the destination due to high traffic flowing through the channel. The latency is usually at the minimum when fiber optic cables are used because the signal travels at the speed of light. Satellites possess the grates latency as a result of the large distances between the transmitter and the receiver.

2.10.5 Jitter

Jitter refers to the deviation that may occur to make the signal move from its true period if the signal is periodic. The parameter is evaluated by having a fixed clock source to act as the reference. Jitter is characterized by changes in the signal period, successive pulses frequency and the amplitude or phase of the signal that must be periodic. As a result of its destructive effects to the desired signal, jitter is always detrimental to most of the communication media that transmit analogue signals that are periodic in nature. The peak to peak displacement and the root mean square value of the signal are used to quantify jitter of a communication channel. For time varying signals, the spectral density or the frequency content is utilized to express the jitter.

Jitter can be expressed by the jitter period that is quantified as the time interval that may exist between times of maximum or minimum effect of a periodic signal that has a regular variation with time. If the jitter frequency is below 10Hz it's termed as a wander but when the jitter frequency gets above 10Hz it is a jitter. A jitter may occur due presence electromagnetic interference together with cross talk with other signal carriers. Results of a jitter include flicking of the display monitor, reduced performance of computers and processors, presence of clicks or unwanted sound signals and probable loss of data between the source and the destination.

During conversion of signal from digital to analog and from analog to digital, the sampled signal is always assumed to possess a fixed period. In case a the clock signal that connects to the digital to analog a converter or the analog to digital converter has a jitter, the signal error at definite instances varies with time. The error is the absolute value from the clock error while it is the slew rate of the signal that was desired.

2.10.6 Bit rate error

The bit rate error or the bit error rate is the quotient of quantity of the bit errors with the total bits that are transferred in the time interval under study and consideration. The bit error probability is expressed to represent the expectation of the bit error ratio. Packet error rate is used in packet switched networks to portray the data packets that have been received incorrectly divided by the whole quantity of the packets that were received. If any bit in a packet does not tally with the sent signal, the packet is considered to erroneous.

2.10.7 Factors affecting the bit error rate

In a communication system, the bit error rate on the receivers end may be influenced by the parameters that are defined by the different transmission channels. The factors include bit synchronization, wireless multipath fading, noise, distortion and interference. If a strong signal strength is adopted the bit error rate can be improved. Also, the modulation scheme to be used in the channel should be robust and slow.

In the methodology all the parameters, theoretical or mathematical in nature are supposed to help in the choice of the best communication channel from the substation to the control center.

3. IEC 61850 - OVERVIEW

3.1 Introduction

IEC 61850 is the new international standard of communications for substations. It enables integration of all protection, control, measurement and monitoring functions within a substation and provides the means for high-speed substation protection applications, interlocking and inter-tripping [20]. The IEC 61850 standard has been defined in cooperation with manufacturers and users to create a uniform, future-proof basis for the protection, communication and control of substations [21].

One of the key components of a communication system for present day substation is the ability to describe themselves from both a data and services (communication functions that an IED performs) perspective. Other “key” requirements include:

- High-speed IED to IED communication
- Networkable throughout the utility enterprise
- High-availability
- Guaranteed delivery times
- Standards based
- Multi-vendor interoperability
- Support for Voltage and Current samples data
- Support for File Transfer
- Auto-configurable / configuration support
- Support for security [22]

IEC 61850 is designed precisely to meet the aforesaid requirements of the substation automation, which, otherwise was operated by a plethora of proprietary protocols which made interoperability cumbersome, costly and inefficient. Also expansion of the substation was a problem.

Broad Design Objectives of IEC 61850

- Address data management cost drivers through modern communication techniques
- Achieve high degree of application interoperability using standardized object models.
- Simplify sub-station engineering using common configuration language
- Online validation of sub-station communications using meta-data and self description.[23]

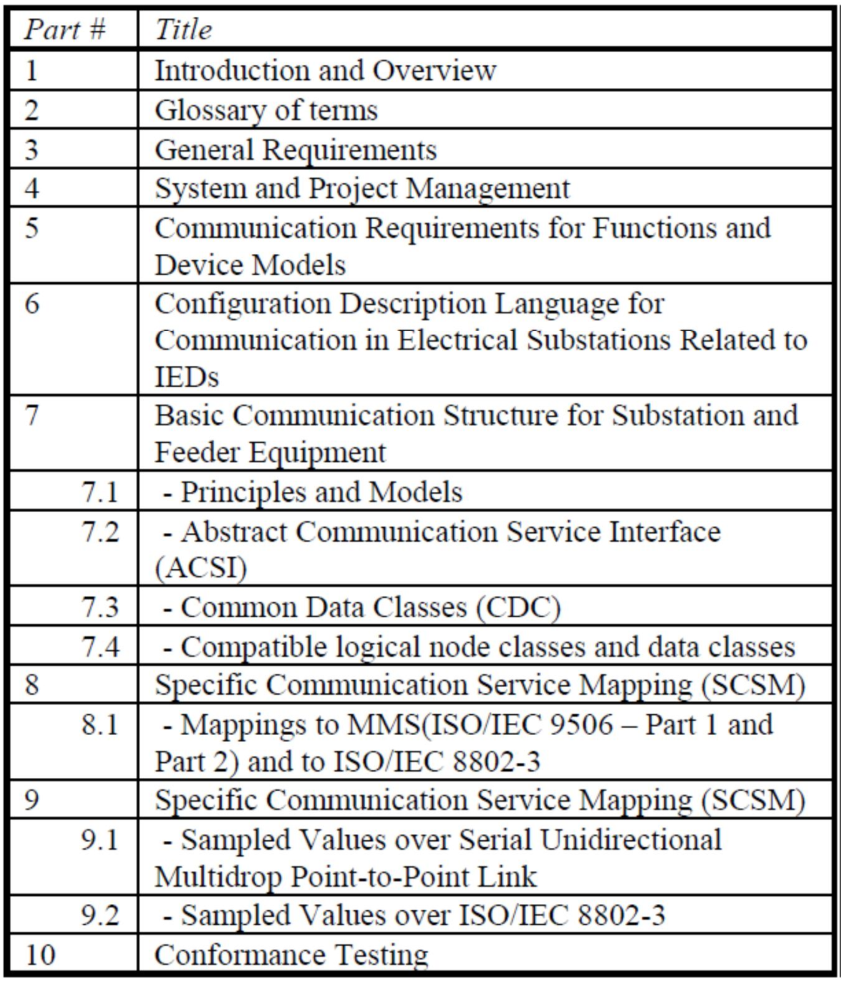
3.2 Background

IEC 61850 was jointly developed by 3 working groups (10, 11 & 12) within TC57.The work was derived from combining CIGRE and UCA submissions. This protocol is mostly backward compatible with UCA [23].

3.3 Scope and Structure

The scope of IEC 61850 is much broader than anything that has been attempted before for sub-station automation. It spans all areas of the substation includes multiple protocols for various special purposes. It has a large and extensible object models including standardized naming and standard data types. It also has for the first time standardized configuration language that can be used for all the devices in the sub-station [23].

The standard is organized into 10 parts as shown in the table which covers all the areas of the sub-station.



Part #	*Title*
1	Introduction and Overview
2	Glossary of terms
3	General Requirements
4	System and Project Management
5	Communication Requirements for Functions and Device Models
6	Configuration Description Language for Communication in Electrical Substations Related to IEDs
7	Basic Communication Structure for Substation and Feeder Equipment
7.1	- Principles and Models
7.2	- Abstract Communication Service Interface (ACSI)
7.3	- Common Data Classes (CDC)
7.4	- Compatible logical node classes and data classes
8	Specific Communication Service Mapping (SCSM)
8.1	- Mappings to MMS(ISO/IEC 9506 – Part 1 and Part 2) and to ISO/IEC 8802-3
9	Specific Communication Service Mapping (SCSM)
9.1	- Sampled Values over Serial Unidirectional Multidrop Point-to-Point Link
9.2	- Sampled Values over ISO/IEC 8802-3
10	Conformance Testing

Table 3.1 IEC 61850 Parts [15]

Parts 3, 4, and 5 of the standard start by identifying the general and specific functional requirements for communications in a substation (key requirements stated above). These requirements are then used as forcing functions to aid in the identification of the services and data models needed, application protocol required, and the underlying transport, network, data link, and physical layers that will meet the overall requirements[24]. Part 3 talks about quality requirements like EMC compliance, reliance, maintenance, environmental conditions for the communication equipment; Auxiliary services other standards and specifications. Part 4 describes about the engineering requirements like tools, parameters and Quality assurances aspects which include type test, field test etc. Part 5 talks about the Logical nodes, logical devices logical communication links and their advantages.

Part 6 to 10 are considered primary parts of this standard. Part 6 describes about Sub-station configuration Language. It is a XML based language through which any third party tool can be used to configure the parameters of various IEDs, Communication devices and also the relationship between different IEDs can be defined.

Part 7-1 describes communication principles and models; Part 7-2 of the document abstract communication service interface defines the services and their parameters. It defines how logical devices and nodes shall be built and it defines about the organization of the data objects derived from the logical nodes. The abstract models for all the different equipments like server logical devices and nodes are defined in this part. Substitution and sampled values the abstract services, which again are common across a wide range of applications within the utility, are also defined in this part.

The major architectural construct that 61850 adopts is that of “abstracting” the definition of the data items and the services, that is, creating data items/objects and services that are independent of any underlying protocols. The abstract definitions then allow “mapping” of the data objects and services to any other protocol that can meet the data and service requirements. In part 7.2 of this standard the abstract services are defined and in 7.4 the data objects abstraction (logic nodes) is defined. In this a new concept of CDC common data class is defined in part 7.3. These classes encapsulate common pieces like status, control, measurement etc. These common building blocks create larger data objects. [24]

Section 8.1 defines the mapping of the abstract data object and services onto the Manufacturing Messaging Specification-MMS and Part 9.1 and 9.2 deals with defining the Sample Measured Values(unidirectional point to point and bi-directional multipoint accordingly) onto an Ethernet data frame. Part 9.2 defines Process bus [24].

In a substation there is a great deal of configuration is required to feed in the control and other parameters in various IEDs or Numerical relays. Parts 6 of this standard define an XML based language called Substation configuration Language which makes configuring easy and error free. The relation between the substation automation system and the substation (switchyard) are clearly defined. At the application level, the switchyard topology itself and the relation of the switchyard structure to the SAS functions (logical nodes) configured on the IEDs can be described. Each device must provide an SCL file that describes the configuration of itself. [24]

At the beginning the scope of 61850 was confined to the substation only. However as already mentioned earlier this protocol scope is expanded beyond substation and now parts related to wind power generation, Substation to substation communication are also incorporated [24].

Finally, part 10 of the document defines a testing methodology in order to determine “conformance” with the numerous protocol definitions and constraints defined in the document. [24]

3.4 Communication Architecture:

The IEC 61850 standard based substation automation system is organized into three levels as illustrated in the figure below

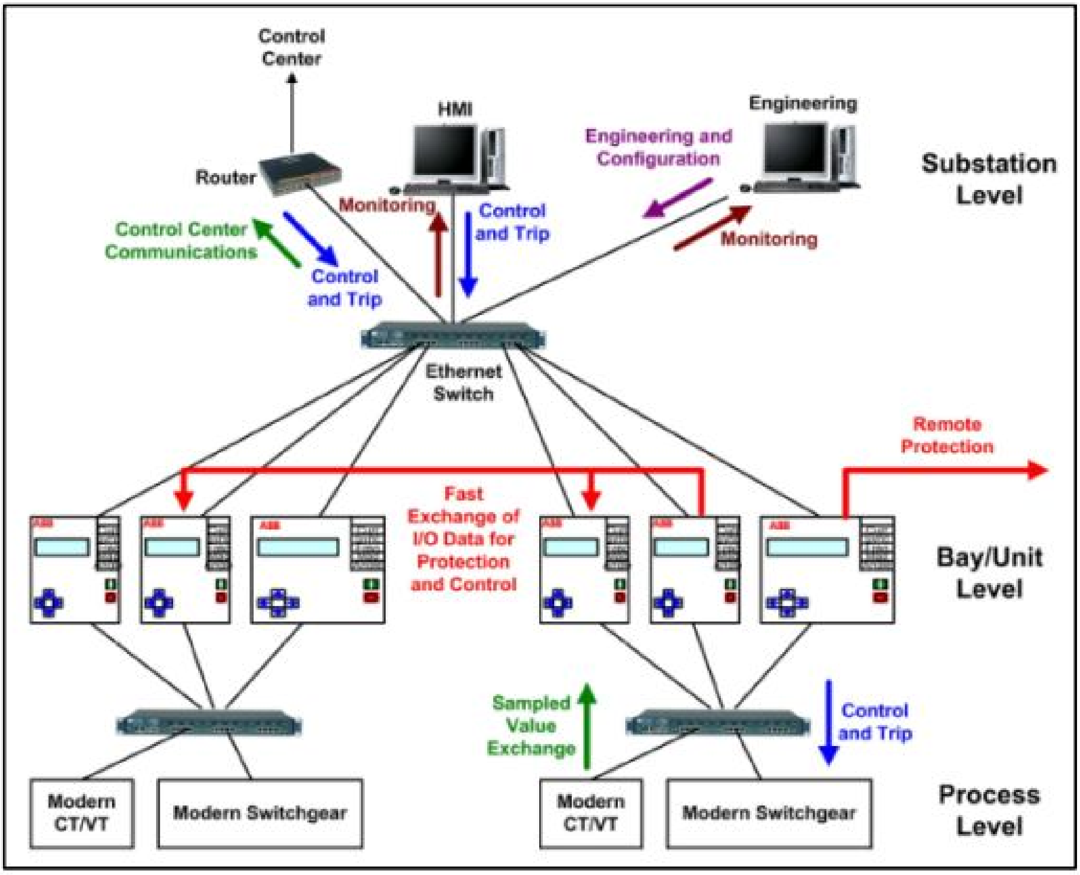


Fig 3.1 Three level communication architecture of IEC 61850

Substation level

The substation level is characterized by gateways and a Human Machine Interface (HMI) that are used to facilitate communication between the remote control center and the intelligent electronic devices from the bay level to the substation level. Control commands implementations related functions are also performed at the station level for the process equipment after data analysis has been completed at the bay level.

Bay level

The bay level implements the protection, monitoring, recording and control functions and the intelligent electronic devices connect the process level equipment and the station bus.

Process level

The process level is characterized by sensors, actuators and the switchyard equipments. Potential and current transformers are found at the process level. Their role is to collect data and transmit it to the bay level devices for protection and automatic control operations that are achieved through the remote operated switches and the circuit breakers.

3.5 Data Modeling Approach

The IEC 61850 standard environment is based on an object oriented model that breaks down the control and protection functions to far smaller units known as the Logical Nodes (LN). The logical nodes correspond to the various control, monitoring, metering and protection functions together with the physical components like circuit breakers and instrument transformers. The individual logical nodes contain data objects within it. The data objects contain data attributes. Logical nodes are however grouped into logical devices that are defined depending on the physical device that must contain a logical device as illustrated in the figure:

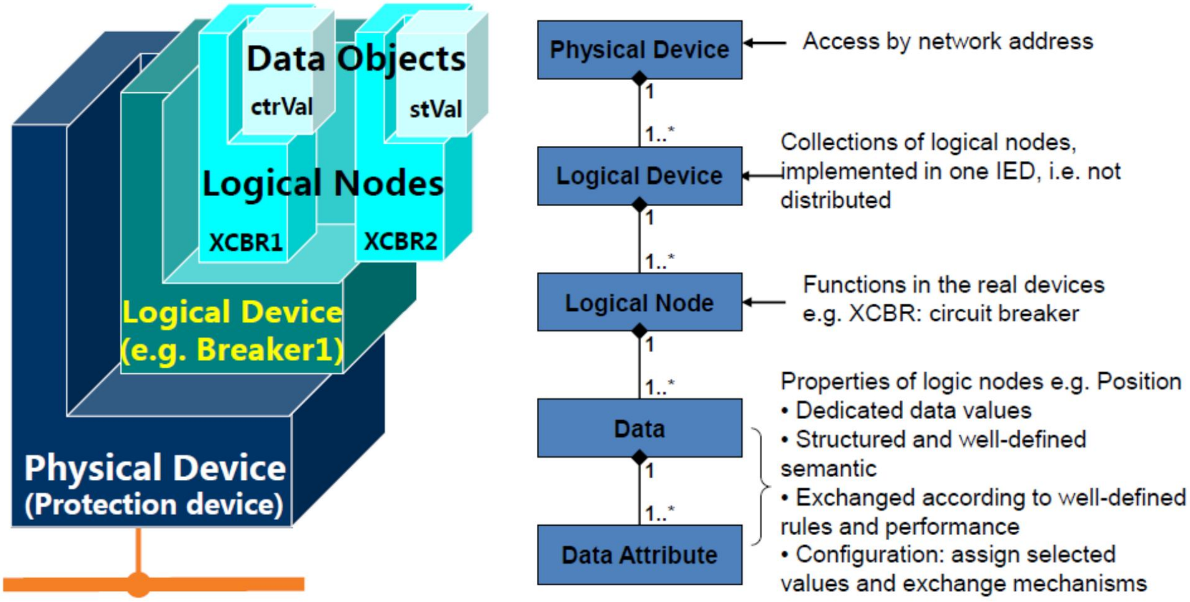


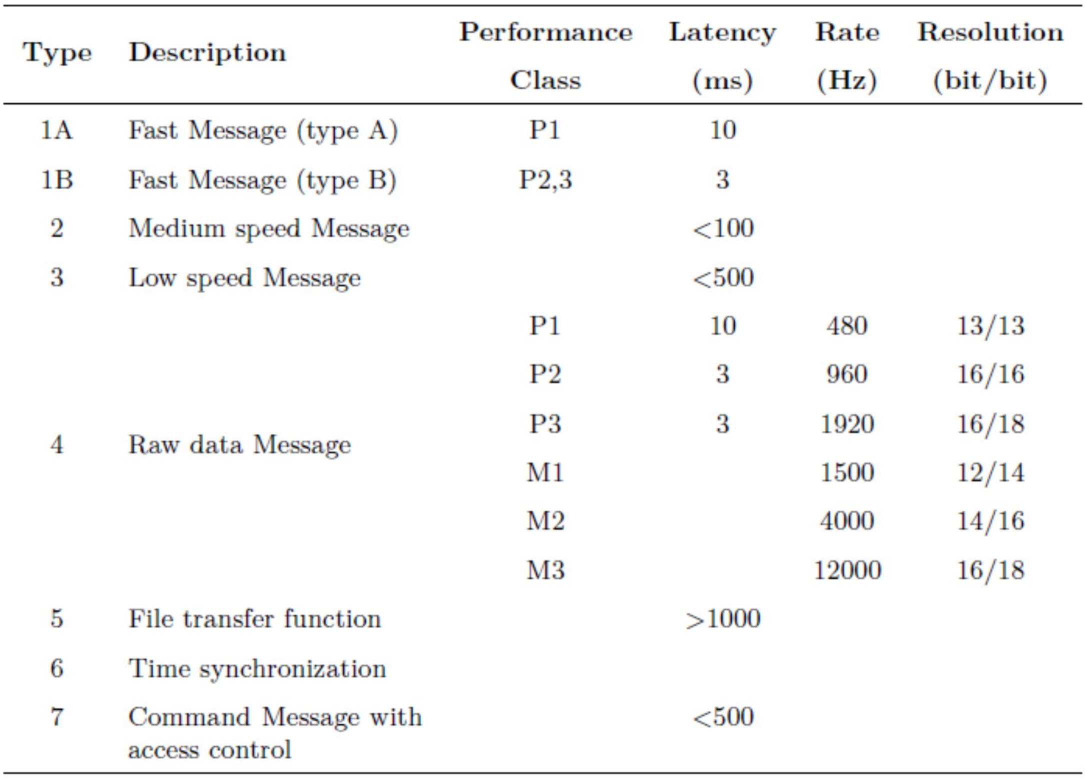
Fig. 3.2 IEC 61850 Data Model Anatomy[27]

Station bus

It is located in the substation level and its main role involves the communication between the intelligent electric devices that are located in the bay level and the substation level. In order to improve the performance and reliability of the various control functions and protection capabilities that are carried out by the intelligent electric devices at the substation level, several redundancy aspects are utilized to select the desired station bus.

Process bus

*A*s already mentioned earlier the process layer of the substation collects all the process information like voltage, current, temperature, status information from the substation equipment like circuit breaker, transducers etc. IEC 61850 defines how this data shall be collected. In 9.1 it defines about Unidirectional Multi-drop Point-to-Point fixed link carrying a fixed dataset and Part 9.2 which defines a “configurable” dataset that can be transmitted on a multi-cast basis from one publisher to multiple subscribers [22].



Type	Description	Performance Class	Latency (ms)	Rate (Hz)	Resolution (bit/bit)
1A	Fast Message (type A)	P1	10		
1B	Fast Message (type B)	P2,3	3		
2	Medium speed Message		<100		
3	Low speed Message		<500		
4	Raw data Message	P1	10	480	13/13
		P2	3	960	16/16
		P3	3	1920	16/18
		M1		1500	12/14
		M2		4000	14/16
		M3		12000	16/18
5	File transfer function		>1000		
6	Time synchronization				
7	Command Message with access control		<500		

Table 3.2. Messages defined by IEC for a distribution Substation [15]

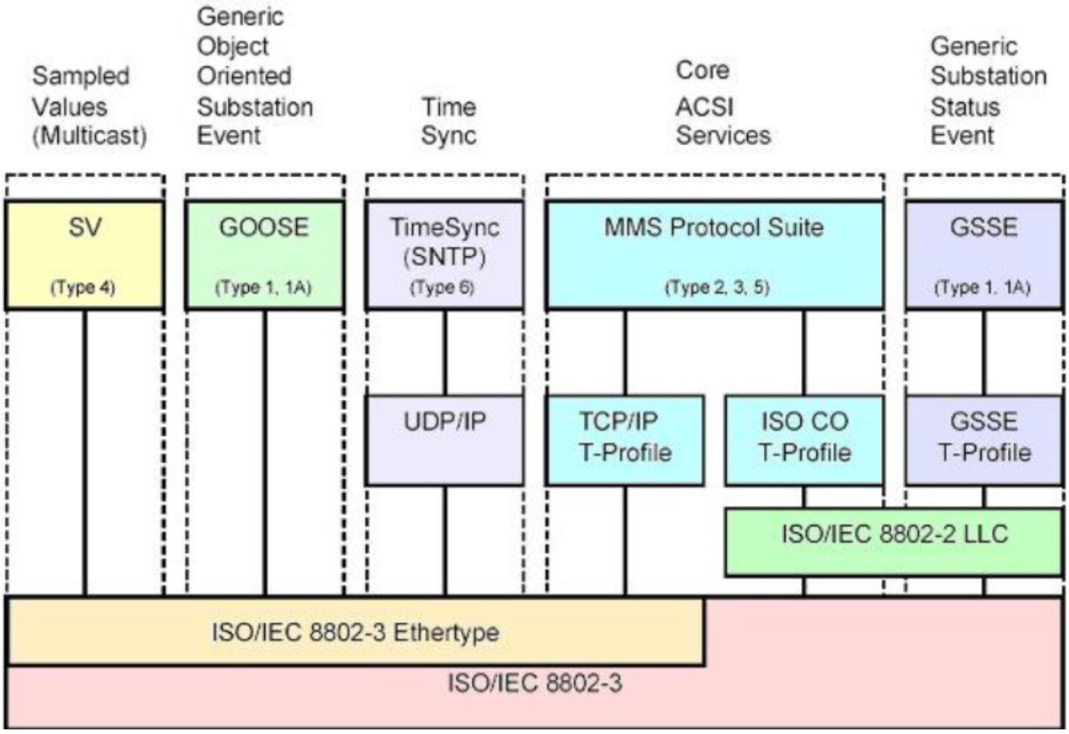


Fig 3.3 Profile Mapping in IEC61850 [26]

In the above figure and table we can see that various messages of the substation are classified on priority wise for example trip block or close block messages are type 1 GOOSE time critical messages and these are mapped directly on to the Ethernet layer whereas other non-critical messages like status information etc are mapped through all the seven layers of client server model.

3.6 Substation Configuration Language (SCL).

IEC 61850-6-1 specifies a Substation Configuration Language (SCL) that is based on the eXtensible Markup Language (XML) to describe the configuration of IEC 61850 based systems. SCL specifies a hierarchy of configuration files that enable multiple levels of the system to be described in unambiguous and standardized XML files that means starting from the substation topology to individual IEDs configuration details are defined. Different types of SCL files include system specification description (SSD), IED capability description (ICD), substation configuration description (SCD), and configured IED description (CID) files. These files are all constructed using the same methods; however the scope varies from application to application.[22]

SCL files can be created by vendor according to IEC 61850-6-1 or there he can use the third party which would generate the required SCL file.

With SCL based approach of configuring considerable amount of time and money can be saved and also the configuration will be uniform without any human error.

3.7 Advantages of the IEC 61850 over legacy protocol

The list below outlines the major advantages that are realized when the IEC 61850 standard is used in place of the legacy protocol such as DNP3 and the Modbus:

- IEC 61850 standard is easily expandable than the legacy protocol.
- It provides approximately 100 logical node classes that have more than 2000 data attributes or objects.
- IEC 61850 standard uses hierarchical names in place of indexed addressing that are used in the legacy protocols.
- It supports time stamps, cause of transmission and quality attributes.
- The IEC 61850standard is more flexible to allow parameter setting control so that the user can be able to change, edit and define the parameters at any instance of time.
- It offers support to the vendor independent engineering equipment for development due to the capability of interoperability.

In addition to above IEC 61850 addresses wide range of issued not presented here which make not only substation automation easier but also is helpful in realizing smart grid potential and reap its benefits.

4. METHODOLOGY

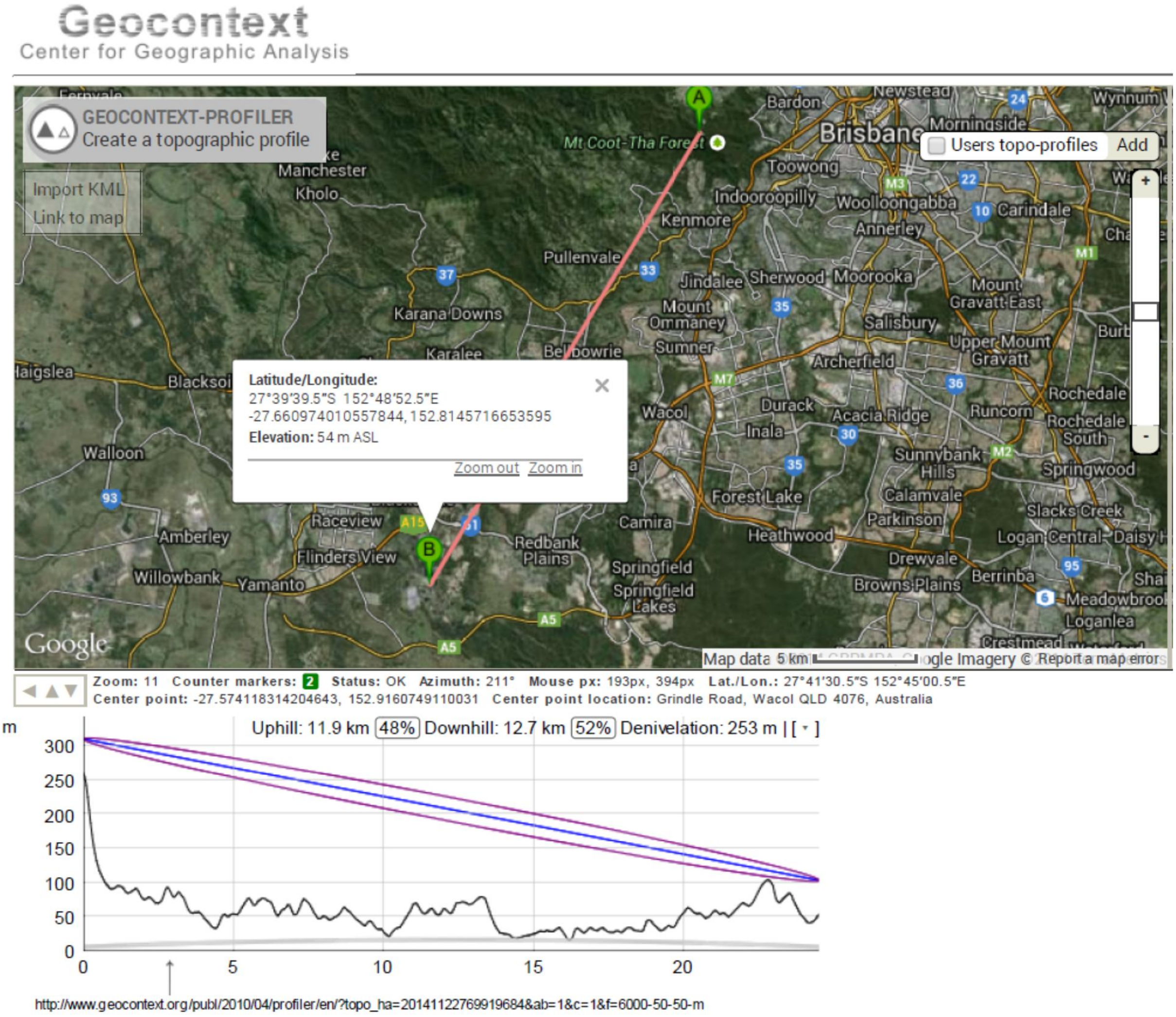
4.1 Introduction

As the electric substation is retrofitted in to a smart substation it is important that the assets in substation should be compatible with the existing as well as retrofitted smart applications over an integrated communication infrastructure. In respect with the above arguments broad -band networks with high speed data transfer rate are significantly considered. The methodology of this thesis involves the selection of locations of substation and control centre then estimating the bandwidth for the assumed number of equipment present in the utility. The estimation is done considering the normal operations and backup operations during critical grid incidents such as an outage. After estimating the required data rate, planning a wireless communication network between the two points is done. This planning is carried out by following certain technical specifications such as latency required, throughput etc, these, are the communication parameters whose optimum approximations best suits the condition monitoring purpose. Then designing a plan for building the communication link between the two entities is done. As the estimated bandwidth covers all situations, therefore on simulating the performance of the selected wireless technologies in different environments and by contrasting the obtained results we can show that the selected technology meets all the required objectives for performing the condition monitoring. The simulations are done by using the simulation software such as MATLAB and SIMULINK for performance modelling of physical layer of WIMAX and Radio mobile online for checking the radio coverage and link budget calculations are also made. The satellite communication is used as backup technology which is not simulated but the link budget calculations are performed in a spread sheet for obtaining the fade margin and other overall budget. The communication technologies chosen in this thesis for analysis are WIMAX IEEE802.16, Microwave point to point and Satellite

The location for substation is considered as Swanbank power station and the control centre is at MT Coot-Tha.

4.2 Locations

The location of the substation is chosen as the swan bank thermal (coal) power station area of the greater Brisbane area. The control centre area is located near the MT Coot-Tha. If possible of getting licence it shall be considered that a tower is installed on channel 9 tower of Mount Coot-Tha. The link distance between both the locations is 24.6km. After an extensive research these locations are finalized as the line of sight conditions were perfect. By means of Geo context analysis we can find LOS and NLOS matching conditions for any topography. The following figure explains link connecting between two point A and B. Here A is the control room and B is the substation which is Swan Bank Power station. There is a plot shown which explains LOS conditions between the two locations. The blue line in the plot shows the actual node connecting the two locations there is a Fresnel zone shown between the two locations.



Latitude/Longitude:
27°39'39.5"S 152°48'52.5"E
-27.660974010557844, 152.8145716653595
Elevation: 54 m ASL

Zoom: 11 Counter markers: 2 Status: OK Azimuth: 211° Mouse px: 193px, 394px Lat./Lon.: 27°41'30.5"S 152°45'00.5"E
Center point: -27.574118314204643, 152.9160749110031 Center point location: Grindle Road, Wacol QLD 4076, Australia

Uphill: 11.9 km 48% Downhill: 12.7 km 52% Denivelation: 253 m | [▾]

http://www.geocontext.org/publ/2010/04/profiler/en/?topo_ha=20141122769919684&ab=1&c=1&f=6000-50-50-m

Figure 4.1 The Geocontext topographic line of sight analysis with frenel zone

Locations	Latitude	Longitude	Elevation	Polarization
A) Mt Coot-Tha	-27°28′16.9″S,	152°56′31.4″E-	24m ASL	0.92°
B) Swank Bank Power station	-27°39′39.5″S -	152°48′52.5″E	54m ASL	0.92°

Table 4.1 The geographical angular positions with directions of the two points

The substation consists of two distribution transformers and two circuit breakers with other measuring instrument transformers which are of huge importance in estimating bandwidth. The electric substation chosen

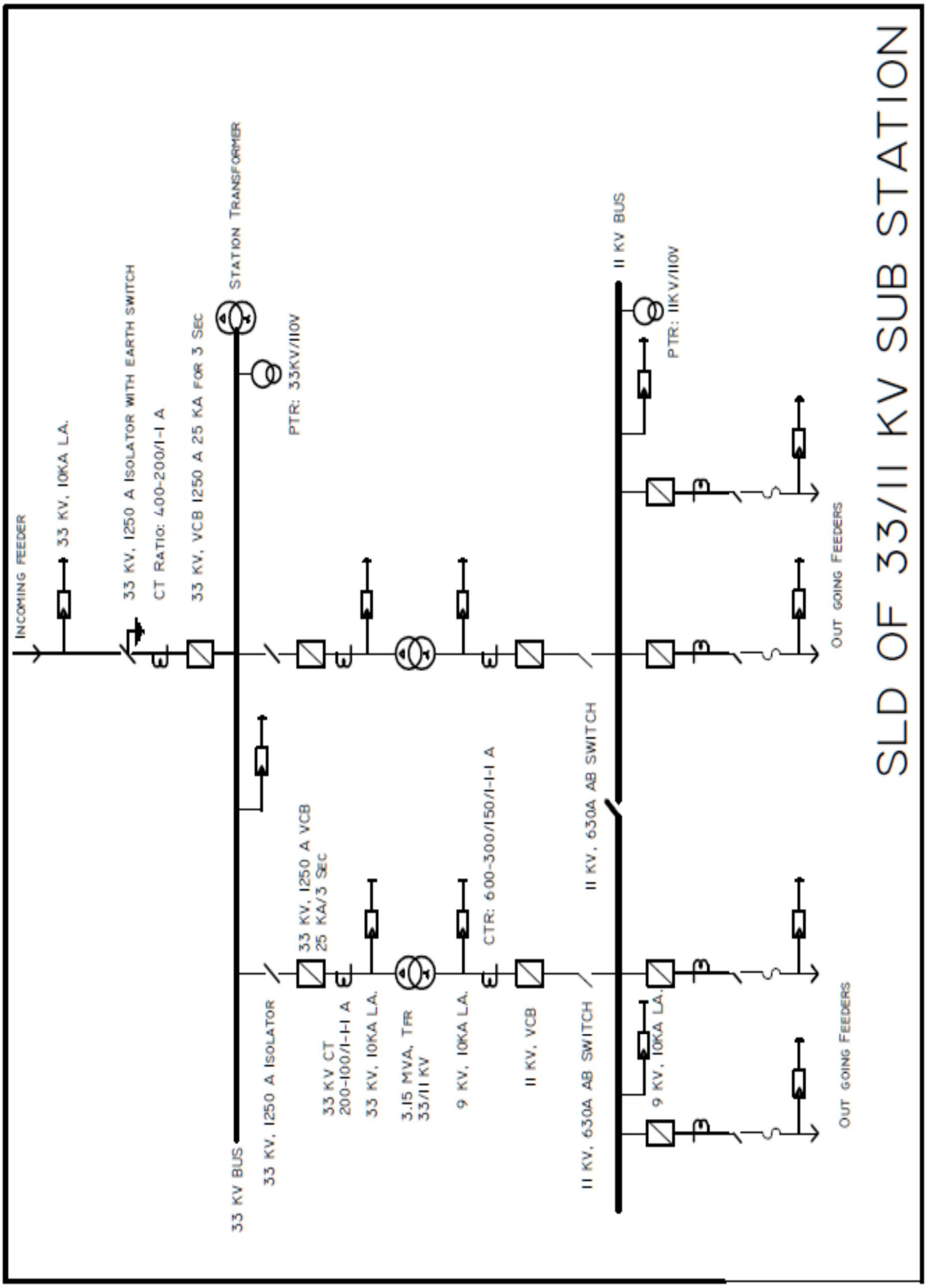


Figure 4.2 The SLD of 33/11 kV substation at swan bank power station

The table 4.2 shows the number of equipment's considered

S/NO	Equipment	Number
1	Current Transformer	27
2	Potential Transformer	6
3	CCTV(MPEG-4)	5
4	Vibration Monitor	2
5	Remote Control State monitor	1

Table 4.2Devices of the 33/11 kV Substation to be monitored

4.3 Bandwidth computation methodology

The bandwidth is computed by analytically exercising the above estimation methodology. The total no of bits that has to be transmitted per signal is estimated by number of samples multiplied by the bit converter and the total divided by the supply frequency.

The formulation is given by

$$Data\ rate = \frac{\{Xbit\ ADC\ converter\} * (no\ of\ smaples\ per\ half\ cycle)}{(0.01 seconds)}$$

4.4 Communication networks

Based on the obtained data rate, the communication networks are planned. Irrespective of the bandwidth considerations, in the view of network safety and security against the substation impairments the entire sub equipment's are hardwired by means of fibre optics which is an insulator and there is no chance of communication failures. All the data collected is fed to data integrator provided within the substation. Here the data management plays a big role by transmitting the useful data such as data that represents the condition of the equipment. The data such as CCTV footage is stored in the records available within the substation as it occupies a huge bandwidth.

The communication networks chosen here are wireless broadband networks such as WIMAX (IEEE802.16) standard and MICROWAVE peer to peer and satellite technology as a backup redundant technology, due to high latency satellite communication may be used sometimes as SCADA communication network and other auxiliary network. On performing the simulation of physical layer of WIMAX 802.16 we can obtain the estimated channel frequency response, BER curve at various SNR values and Scatter plots at the reception side, which, best explains the behaviour of the technology under various environments. Finally, the desired parameters like Latency throughput can be found. For condition monitoring purpose the latency desired is 10 ms which explains that in case of spikes the undesired portion should be tripped within 10 ms such that there will not be any undesired outage of the equipment. Here the Round trip time should be of high speed such that the command will be given to the substation by means of an automated setup within the substation or from the central station.

The microwave link will be designed with respect to the selected locations. This is done by using Radio mobile online software simulating the link configuration by entering all the link budget values. After obtaining the radio link the coverage is simulated by choosing the different antenna specifications.

The satellite network is chosen as the backup technology and the GEO stationary satellite coverage within the two points is searched for. Leasing the bandwidth from the available commercial satellites will be a better idea for cutting the cost. On performing the link budget calculations analysis of overall budget and parameters like fade margin is performed.

5 BANDWIDTH ESTIMATION AND MANAGEMENT

5.1 Estimation of Bandwidth

The traditional SCADA system will only have critical incident data and commands such as intrusion, outage, where, the response commands are only trip commands. This involves much less bandwidth in terms of kbps. Even Bluetooth Zig-Bee can cater to the needs of this kind of system. When substation is retrofitted into smart substation, the bandwidth requirement is high which can give the information of all the power system signals. These signals are very useful in checking the health of the machines which avoids time based maintenance and helps to do condition based maintenance of the equipment. Bandwidth of a signal is defined as measure of highest frequency component occupied by the signal. The substation busbars are of high tension and carries large values of currents which are impossible to measure therefore instrument transformers and transducers and thermal cameras are used to measure. The analog data is then converted into the digital form by means of a 5 bit ADC generally an 8 bit converter for large substations. The general estimation is made of calculating the samples of signal for a half or a full cycle with which are generally 20 electrical degrees that is 9 samples per half cycle and equivalent to 18 samples per full cycles. The no of samples are multiplied by the BIT converter then divided by time period 20mseconds or the supply frequency 50Hz.

5.2 Bandwidth computation

The bandwidth is computed by analytically exercising the above estimation methodology. The total no of bits that has to be transmitted per signal is estimated by number of samples multiplied by the bit converter and the total divided by the supply frequency.

The formulation is given by

$$Data\ rate = \frac{\{Xbit\ ADC\ converter\} * (no\ of\ smaples\ per\ half\ cycle)}{(0.01 seconds)}$$

From the above formula we can state that the data rate is directly proportional to the ADC converter. Here X is taken as 5 bit converter and no of samples per half cycle is assumed as 20 electrical degrees which is equivalent to 9 samples per half cycle. The consideration of half cycle has a significance as the measured value that is the resolution is divided into levels and during critical conditions there will be huge spike in the signal of the voltage and current that should be sustained within the half cycle for safety of machines that is tripping or the isolating the equipment or restoration should be done within the 10ms of the signal. Here the data is sent to the control centre and the command from the control centre or from the internal substation should be received within the 10ms .That is the latency of the communication network used should satisfy this condition i.e., less than or equal to 10ms.

S/NO	Equipment	Number	Estimate bandwidth for Each Equipment(kbps)	Total estimated bandwidth (kbps)
1	Current Transformer	27	4.5	121.5
2	Potential Transformer	6	4.5	27
3	CCTV(MPEG4)	5	512	2560
4	Vibration Monitor	2	230.4	460.8
5	Remote control state monitor including Time stamp	1	128	128
Total estimated Bandwidth including Timestamp				3297.3

Table 5.1 Total estimated bandwidth of the entire substation equipment

The calculated data rate is approximately equal to 3.3mbps .The data rate mainly depends upon factors like bandwidth available and signal levels. Increasing the signal levels of a signal may reduce the reliability of the system.

5.3 Bandwidth Management

For substation parameters monitoring like current, voltage, vibration, etc. a constant bandwidth is necessary. Utilization and implementation of such kind of technology, where the data can be easily transmitted from substation to the control centre with less response time is desired. For sending remote switching commands, and reception of signals like intrusion detection, a packet switched network would be more suitable as this sort of I information is only of low bandwidth and is sent in frequently.
For the CCTV monitoring, most of the time, the cameras will send the same static image, because nothing is happening. In CCTV If you record at the substation, we shall send video to the control room only when you want to display it to the operator. There will be a huge wastage of Bandwidth because of huge record of unwanted data sent to the control center during healthy operation of the utilities. The video footage of the substation is necessary in some underdeveloped nations specifically in some African nations where conductor theft may take place. Bandwidth is of significant importance which determines the network performance. Establishing a communication infrastructure between substation and control center is decided by means of Bandwidth .In this thesis it is clearly mentioned that the substation wide internal area is hardwired with plastic fibre for technology security

purpose. In case of white noise no wireless technology or wired copper cable is capable of sustaining the situation. Wireless broadband technologies are capable of transmission of the data and are capable of huge data rates .Latency issue is important and should be in an order of less than 10ms to perform the necessary action .Many 3G and 4G technologies are considered but they have their own limitations with the bandwidth capability, distance of transmission, LOS and NLOS conditions and cost involved and the delay that is the response time .In this thesis

If the control room is in LOS with the substation then it can be connected to any substation. By means of repeaters WiMAX is useful were you have LOS (or NLOS) between sub stations (and or radio repeaters) when considered shorter distances less than 50km in a higher frequency spectrum considerations. In the greater Brisbane area, we might get a lease to put a WiMAX repeater on say the Channel 9 tower on Mt. Coot-Tha, and any substation in the greater Brisbane area that can see (or almost see) the Channel 9 tower on Mt Coot-Tha can be linked via WiMAX. The below figure shows the channel 9 of the Mt Coot-Tha.

Fig. 5.1 The channel tower of Mt coot-tha

The link from the channel 9 tower on Mt Coot-Tha to the Swanbank thermal (coal) power station. The following assumptions are made WiMAX antenna height above ground on channel 9 TV tower = 50m WiMAX antenna height above ground on Swanbank boiler chimney = 50m frequency of operation = 6 GHz.

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6. Performance modelling of wireless communication systems

6.1 Introduction

To establish a Communication network the designer's main task is to achieve the best networking performance from the system. With the revolution of latest communication technologies the transmission of large data rates by satisfying all the communication requirements is possible .The best communication network is that one which is cost effective and delivers better network performance. The most important parameter to be considered with the performance modelling is the throughput. The increased use of digital networks led to the evolution of new communication technologies with extended capacity and features. The connectivity has an exponential rise with the advent of internet and other new developed standards which eventually resulted in the evolution of wireless broadband tele- communications. Wireless broadband technologies are highly reliable and bring connectivity amongst all the users around the world. The expansion of the technology over several decades and the rate expansion lead to an impeccable growth .The increased rate and the exponential growth of the internet by means of WLAN resulted in providing the extended amount of service with increased capacity wirelessly. WIMAX (wireless interoperability for microwave access).

6.2Modelling WiMAX(IEEE 802.16) physical area

WiMAX is a wireless networking standard which is designed for providing interoperability from IEEE802.16 standard WMAN (wireless metropolitan area networking). WiMAX is capable of providing high data rate throughput from peer to peer or point to multipoint with LOS and NLOS conditions. WiMAX can provide NLOS transmission up to 20 to 30 miles. The IEEE 802.16a was introduced by the forum which incorporates the NLOS conditions in frequency range of 2GHz to-11GHz with OFDM as the physical layer. Further research resulted in 2004 which was 802.16 which superseded all the previous versions which has evolved as the fundamental basis solution for the WiMAX. This is fixed technology; with a further progress 802.16e has evolved as the mobile WiMAX in 2005. Currently this technology is superseded by 802.16m which is the latest version of WiMAX mobile. The standard is incorporated with OFDM based technology which has the capability against the multipath fading and other linear equalization schemes. For avoiding ISI and securing orthogonally among the sub carriers, a cyclic prefix (CP) is assembled as an alternative for guard interval.

6.2.1 WiMAX transmission model

6.2.1 Source

The sources generate and read the data, also import the files to the processes. The processes receives the input from the source and outputs the processed value to sinks finally the sink block functions like displaying the results and also plots the outputs and scopes the output graphically and finally sends the data to the destination.

The source used here in our case is a Bernoulli binary generator as stated in the standard, bits must be random missed to minimise the transmission of un modulated sub carriers. As the process of randomisation is a cumbersome process, we use a Bernoulli binary distribution which generates random sequences of bits. The generated bits should be fed out as frame based and are evaluated according to the size of the packet which in turn depends on the no of OFDM symbols and the rate of coding the output data type will be an integer. For instance to calculate the no of OFDM symbols there will be training symbols generated also called as preamble when subtracted with the transmitted signal ,OFDM symbols can be calculated with respect to that frame. The OFDM symbols are used to know the number of bits that are sent by the source.

The packets sent by the source can be calculated as number of OFDM symbols calculated multiplied by the rate of coding and modulation symbol. The Simulink implementation of the source is as shown in figure

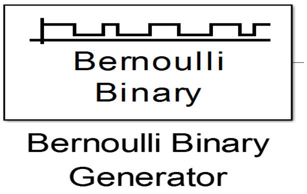


Fig 6.1 Bernoulin Binary Generator

6.2.2Encoder

The purpose of the encoding is to debug the errors that are detection and correction of the errors by means of some redundant information. The encoder is explained as initially a code rate with numerator as data rate and denominator as redundant data is decided which should be less than one. Then the data rate is passed through an encoder which has the decided code rate. The output from the encoder that is the encoded data should be less than one and eventually should be less than the data rate .Therefore total number of errors is defined as the bits in error divided by the total number of bits .The data rate in relation to the channel capacity explains as the data rate will always be less than the channel capacity The encoder is expressed as the concatenation of RS encoding Cs encoding and block interleaver. The Simulink implementation of the encoder and the sub block are ass shown below

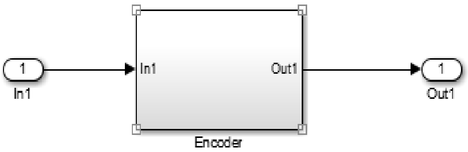


Fig 6.2 Encoder

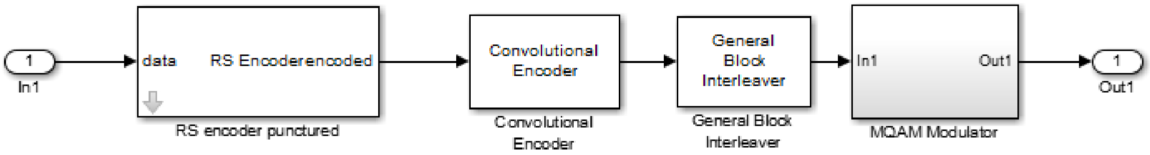


Fig 6.3 Encoder model

6.2.3Reed Solomon coding

Block coding can be explained as it encodes k block of data symbols into n blocks of encoded symbols. The raw data that is k symbols are fed into encoder (n,k,t).where n is the coded symbol and k which should be less than n are un coded symbols and t is the errors corrected. This type of encoding is advantageous when burst of error correction is required at a relatively high SNR.

In the current case (255,239,8)239 symbols are fed to RS encoder in which 255 are termed as symbols and 239 are actual symbols and 16 are parity symbols. Any series of uncoded block when fed into the RS coder will give a coded block.

6.2.4 Coder shortening and puncturing (Code shortening)

The code shortening is explained as the code generated by shortening of the code by adding null symbols. For instance RS (n=255,k=239,t=8) by shortening of k data bytes is done by adding 239-k null symbols, at the output we eliminate the null symbols. All the codes are corrected up to 8 errors (bytes). By puncturing we eliminate parity bytes to obtain the error corrected codes. Puncturing is explained as the puncturing the balloon and passing it into no of blocks. If the balloon has to pass through the number of blocks then it should be punctured and passed to each of the blocks. The Simulink implementation can be performed by converting the raw bits into integer and then to zero pad to code word size where the parameters for this block will be a pad signal at beginning then encoded by means of RS encoder. Here the code word length is specified and the k the length of the message is specified. Then next comes selector where the type of the input is chosen and array element arrays are specified. Finally integer is converted into bits. The RS decoder is exactly the opposite of the encoder except the puncture is replaced by inserting zero blocks where zero vectors are inserted. The un-coded data are specified ASK and PRS is known as punctured RS.

6.2.5 Convolutional encoders

The convolutional encoder is explained as encoding the data which is pre specified and then observing the coded data. Initially a rate is decided as k/n when convolution ally encoded the n>k. that is the un-coded symbols are always less than the coded symbols. The generic example can be given as 2/3 code rating. Originally it has ½ rate. When it is implemented in Simulink, pollystotrellis function is used in order to realize the coding rate. It is also punctured to determine the different coding rates.

6.2.6 General block interleave

The encoded data bits are interleaved in this block. The block size corresponds to the number of bits in a single OFDM symbol, NCBPS. The interleaver is defined by a two steps permutation. This block performs a two-step permutation .The first permutation shows the mapping of adjacent coded bits onto non adjacent subcarriers. The second permutation ensures alternate coding by means of least and most significant bits through constellation, which ensures the removal of burst of low bits on a continuous stream.

6.2.7 OFDM modulation

OFDM is abbreviated as orthogonal frequency division multiplexing. OFDM is a frequency division multiplexing phenomenon. It has a special property by which it maintains orthogonally amongst the carriers. It can be distinguished from frequency division multiplexing by many ways. FDM has a mandatory guard bands for avoiding ISI when compared with OFDM it allows the carriers to overlap such that the spectrum load is reduced and they are still orthogonal even though they overlap.

The data in uplink and downlink is allowed to be sub channelized by means of OFDM. OFDM carriers are divided into subcarriers which can be used as a continuous or random based. The advantageous aspect is the best use of sub carriers when they are evenly distributed and partial usage of the subcarriers when allocated randomly within clusters. OFDM symbol can be explained as addition of guard interval and data interval. The ratio of guard interval to the data interval is explained as cyclic prefix. Cyclic prefix can be represented in dB which has a variable length and represents a loss. OFDM can be constructed by means of data carriers, pilot carriers and null carriers. The pilot carriers are used for synchronization and estimation. The null carriers are for guard frequency bands and DC when modulating a carrier.

In this case WiMAX uses 192 data, then pilot then null 8 pilots and 56 nulls are the three inputs concatenated by means of matrix concatenation. The concatenated output is fed into a selector between these two blocks a serial to parallel conversion takes place. Here for obtaining the data in time domain from sample form it is fed into IFFT block the output of the IFFT is in time domain. Next comes the insertion of cyclic prefix,

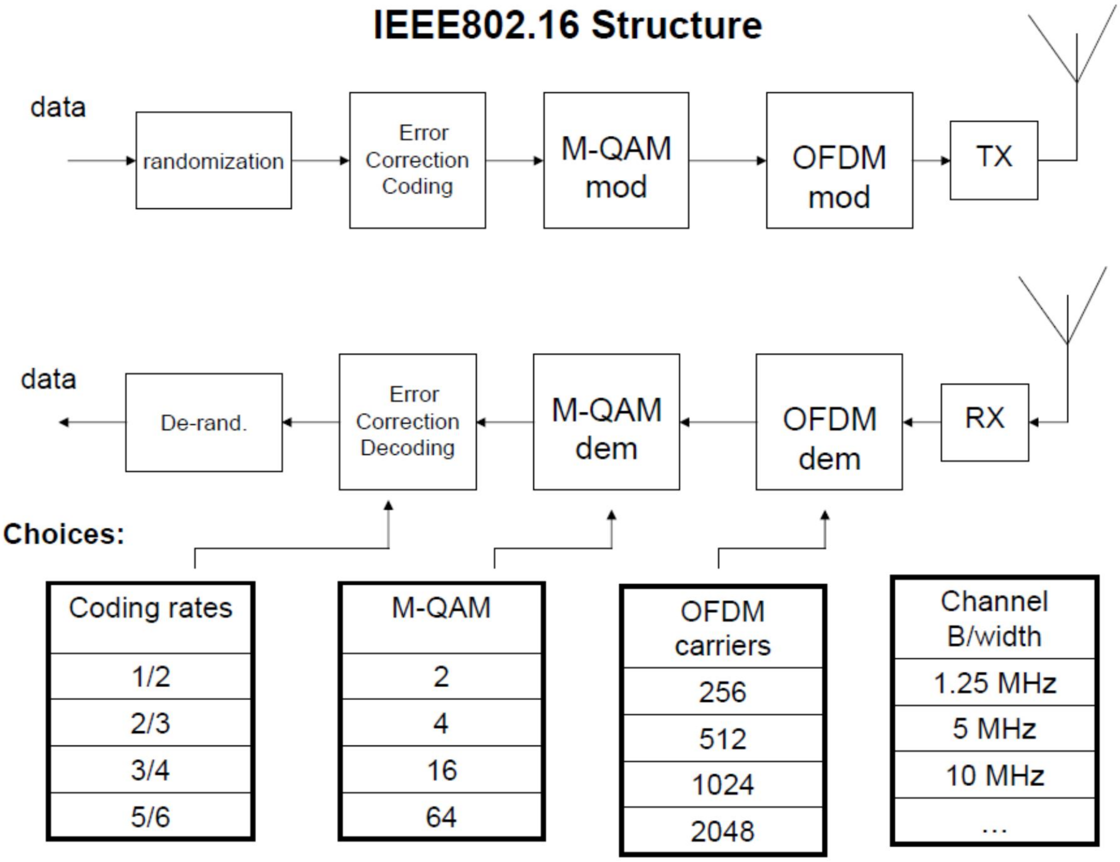


Fig 6.4 IEEE 802.16 Structure

The figure 6.4 shows the basic IEEE 802.16 structure from the source to the sink. The bottom tabular columns show the coding rates, many number and OFDM subcarriers with different channel bandwidths. OFDM transmitter use IFFT and receiver use FFT respectively. For the sake of elimination of ISI guard intervals are also used in between OFDM symbols. The guard interval should be bigger than the estimated multipath delay in order to eliminate the ISI. On adding the guard interval results in power wastage and reduction in the bandwidth. The magnitude of the symbol duration determines the bandwidth efficiency .The magnitude of the FFT in designing OFDM is selected carefully as means of protection against Doppler shift, Multi path and the expense complexity. The symbol time increases and subcarrier spacing reduces if the FFT is selected of large magnitude at a particular bandwidth. This makes it easier to protect against multipath delay spread. Inter carrier interference may occur if there is any reduction in subcarrier spacing which results in a Doppler spread in mobile carriers. The competing influences of delay and Doppler spread in an OFDM design requires careful balancing.

The Simulink implementation of the OFDM block is as shown in the figure

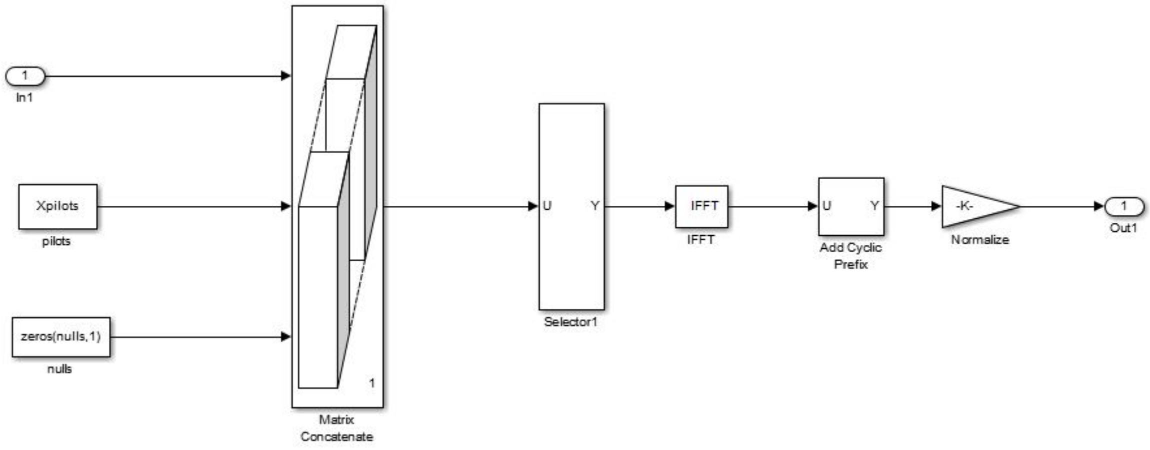


Fig. 6.5 OFDM Block

6.2.8 Channel modelling

In this thesis we have used a multipath fading channel model and simulated and tested for wireless communication system

The transmitted signal when received degrades due to three effects:

- Large scale fading
- Medium scale fading
- Small scale fading

The wireless broad band channel operates in UHF at signal frequencies of interest up to (0.3GHz -3GHz) and in SHF bands .The signal is affected by means of several ways. The path is lost due to energy dissipation which is a function of distance. Due to obstacles, buildings, trees, walls, shadowing is caused which will results in absorption, scattering and reflection. If the path is multipath then a self-interference will be caused. The frequencies in SHF band are termed as LOS frequencies and with UHF are known as NLOS frequencies. Path loss due to free space when consider under large scale propagation. For isotropic antennas path loss in dB is given by the formula:

$$L=10\log(Pt/pr)=20\log(F(MHz))+20\log(d(km))+32.45$$

The free space attenuation is measured as by means of plotting the free space loss versus distance in dB. This condition is valid for satellite communications, point to point LOS microwave. The multipath models are often two ray reflection typically of open environments. The received power of two ray model is assumed with the reflective surface a pure dielectric.

6.2.9Fading channel models

The statistical models of fading channels are explained as the transmitted signal which will undergo several reflections before reaching the destination. Each reflector has several paths all with different time delays and Doppler shifts. For multipath channel NLOS conditions, the parameters are time delays, power attenuation, and Doppler shift. For small scale fading different lengths will assign different paths .For instance if a signal is transmitted with the initial delay the received signal will have coefficient multiplied with the sent signal as the delay is directly proportional to the path difference, the more the path difference the more is the delay.

In a wireless channel models when there is NLOS conditions between the repeaters Rayleigh fading is one of the best approximations even in mobile situations. This model gives a realistic channel conditions performance

The mathematical representation of the Rayleigh fading channel is shown as $y(t) = h(t)\cdot x(t)+ n(t)$, where $y(t)$ is the received signal and $n(t)$ is the noise and $x(t)$ is the transmitted signal.

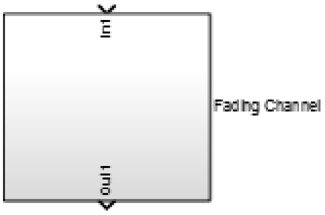
The multi path fading is due to the instability of the wireless environment and rapid fluctuations of the phase and amplitude of the signal. The wireless environment is highly unstable and fading is due to multipath propagation. Multipath propagation leads to rapid fluctuations of the phase and Amplitude of the signal.

6.2.10 AWGN channel

AWGN is abbreviated as additive white Gaussian noise. AWGN is a noise that will affect the signal when it is passed through that channel .the frequency spectrum of this channel is defined as continuous over a particular band. The mathematical representation of this model can be represented as $Y(t)=x(t)+n(t)$ where $Y(t)$ is termed as received signal and $n(t)$ is the additive white Gaussian noise and $x(t)$ is termed as transmitted signal.

In the Simulink implementation of the model there is multipath Rayleigh fading channel which is serially connected to the AWGN channel. A switch is provided which will switch between a two channel blocks and the bypass from the AWGN channel to the output port. Here the channel spreads in time due to multipath. For a frequency selective fading there will be distortion. In this thesis these channel models have great significance on the frequency response of the channel and also on the BER performance. The received signal constellation diagram shows a difference when the switch condition is used.

When the signal is passed through serially form Rayleigh model as well as AWGN channel initially significant amount of inter-symbol interference is seen when there is no channel estimation and synchronization used .When we use channel estimation, from the estimated data, we can see there is no ISI. The Simulink implementation of the channel model is shown below



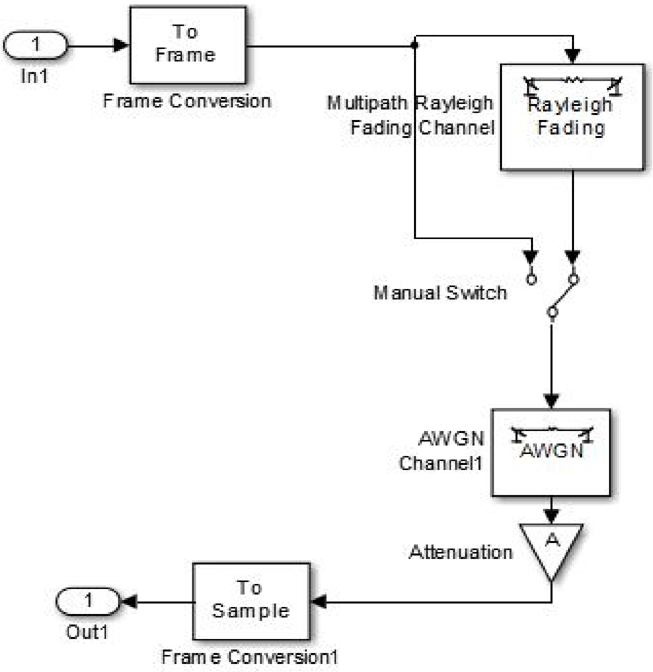


Fig. 6.6 Channel Model

6.2.11 Channel estimation and equlaization

In a basic transceiver system the data is fed into the modulator and is passed through the channel at the receiver. To know the behaviour of the signal we need to know the frequency response of the signal at variable SNR values. The frequency response of the signal at various data points will actually shows the channel behaviour when estimated with the input and output data. The mathematical expression, the information sent by the Transmitter will be changing when it is passed by through the channel. Noise is added to the channel, and hence as the received signal is radio signal i.e., a wireless signal, it will affected by path reflections and also several no of path transmissions.

The receiver should detect the signal which is transmitted, that is, the information sent. The receiver should be intelligent enough to know about the channel response both in time domain and frequency domain. Channel estimation is the phenomenon which provides the desired algorithm which provides the channel estimation based on the available bits which are independent at the transmitter and are usually repeatable and the estimation is performed at every burst.
In this thesis we have estimated the impulse response in each block. This can also be performed by using cross correlation function. The received signal is fed into WiMAX time synchronization and buffer delay. The two output ports are again fed to channel estimation block to the selector. The FFT created that is the preamble value in the code and the FFT frame value are multiplied and sent to estimate channel impulse response block. Here the block is again converted to sample based by using FFT conversion. This data is fed to the estimate channel response block.

6.2.12 WiMAX receiver model

If all the functions of the transmitter model are inversed then a WIMAX receiver model can be obtained .The basic parameters which has their impact on the receiving side are channel estimation synchronization and carrier detecting .the inversion of the fundamental blocks blocks can be explained ae OFDM demodulator,viterbi decoder, RS decoder etc. The figure e – show the initial receiver model simulation performed using multifading Rayleigh channel and awgn channel. The channel estimation and equalization has done by pilot based mechanism. Here with the following model there are different basic input data coded for the purpose of simulating the entire system.

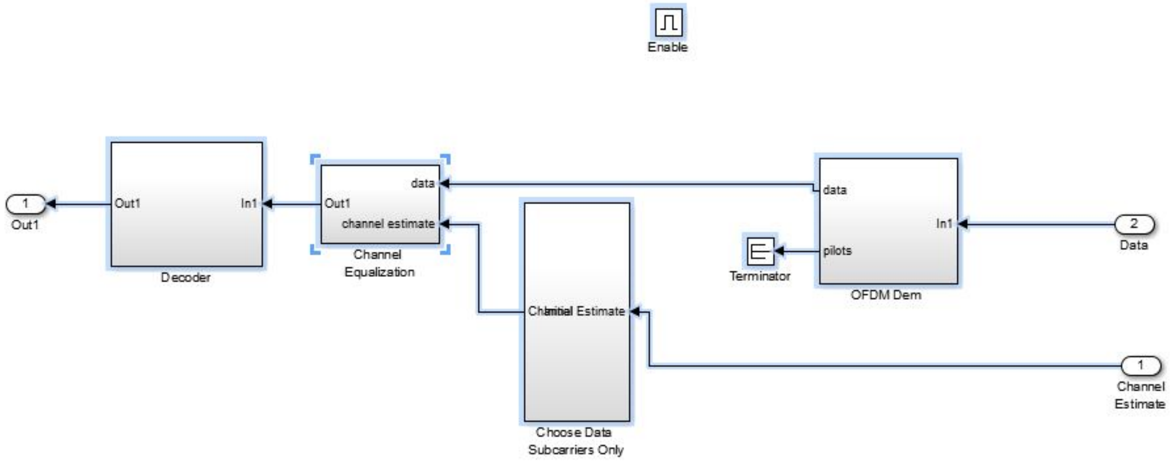


Fig. 6.7 Wimax Reciever Model

6.2.13 WIMAX Simulink transceiver system implementation in Simulink

The codes and the block diagrams of the above system are placed in annexure. The basic input data is coded for several parameterizations of functions. After loading the input data then run the Wimax_transmitter. Then there will be frequency response of the channel estimate is seen with the transmitted and received spectrum. Then start simulating wimax_reciever after running it for 3.8*e0-4 seconds we can see a constellation diagram plotted and the received spectrum. for obtain frequency response of the estimated channel response run the matlab script main.m then there will be flow of frequency response plots at various SNR l values ranging from 0 to 35 finally a BER curve is seen, plotted against various SNR values.

6.3 Micro wave and Satellite link budget calculations

If there is perfect commercial radio coverage then satellite is chosen as the best redundant technology. We can share the bandwidth with the available satellite network. On researching on the network coverage we can see that there is a surplus coverage of the signal around the proposed location. Satellite is considered as the redundant wireless technology or as the backup technology. When checked with the coverage Optus satellite C1 is the selected satellite whose technical specifications are compatible with the considered locations.

The link between the two locations and the radio signal coverage between the two locations can be simulated by using Radio Mobile online software by giving following specifications which are shown in the tabular column.

Radio link study			
Mt Coot-Tha		Swan Bank power station Site B	
Latitude	-27.475153 °	Latitude	-27.658885 °
Longitude	152.950014 °	Longitude	152.814556 °
Ground elevation	222.0 m	Ground elevation	44.3 M
Antenna height	50.0 m	Antenna height	50.0 M
Azimuth	213.14 TN | 202.02 MG °	Azimuth	33.20 TN | 22.07 MG °
Tilt	-0.53 °	Tilt	0.31 °
Radio system		Propagation	
TX power	23.01 dBm	Free space loss	80.15 dB
TX line loss	3.00 dB	Obstruction loss	12.59 dB
TX antenna gain	6.00 dBi	Forest loss	1.00 dB
RX antenna gain	2.00 dBi	Urban loss	1.00 dB
RX line loss	0.50 dB	Statistical loss	11.93 dB
RX sensitivity	-113.02 dBm	Total path loss	106.67 dB
Performance			

Distance	24.406	km
Precision	12.2	m
Frequency	10.000	MHz
Equivalent Isotropic ally Radiated Power	0.399	W
System gain	140.53	dB
Required reliability	90.000	%
Received Signal	-79.16	dBm
Received Signal	24.67	µV
Fade Margin	33.86	dB

Table 6.1 The radio link study of microwave point to point

OPTUS SATELITE C1 LINK BUDEGET CALUCLATIONS			
	Transmit Site	**Satellite**	**Receive Site**
LOCATION	**MT COOTHA**		**SWANBANK**
LONGT	152.94		**152.81**
LATITUDE (+)N (-)S_DECIMAL_DEG	**-27.0**		**-27.0**
AZIMUTH (DEG)	186.72		187.00
ELEVATION(DEG)	261.00		54.00
POLARIZATION (VERT)(DEG)	-5.98		-6.23
SATELITE			
LONGTITUDE(DEG)		**156.00**	
Range_km	36605.23		36596.89
TRANSPONDER			
SATURATED EIRP_dBW			**42.00**
SFD_dBW/m^2	**-90.00**		
G/T_dB/K	**-4.00**		
TRANSPONDER BANDWIDTH__KHz		**36000.00**	
OUTPUT BACKOFF_dB		**3.00**	
INPUT BACKOFF_dB		**6.00**	
SATELLITE GAIN __dB			179.53

MODULATION			
INFORMATION RATE_______kbits/s	**5000.00**		**5000.00**
MODULATION : (BPSK) OR (QPSK)	**QAM**		**QAM**
FEC RATE: (0.5) OR (0.75)	**0.75**		**0.75**
CARRIER SPACING___(1.4 Nominal)	**1.40**		1.40
SIGNAL BANDWIDTH_________kHz	5000.00		5000.00
PROPAGATION			
UPLINK FREQUENCY_________GHz	**14.2500**		
DOWNLINK FREQUENCY_____GHz			**12000.0000**
CLEAR SKY UPLINK LOSS______dB	206.75		
UPLINK RAIN ATTENUATION___dB	**1.00**		
CLEAR SKY DOWNLINK LOSS__dB			265.25
DOWNLINK RAIN DEGRAD_____dB			**2.00**
DOWNLINK NOISE DUE TO RAIN K			100
EARTH STATION:			
TRANSMIT:			
ANTENNA SIZE_m	**7.00**		
ANTENNA EFFICIENCY _%	**70.00**		
TRANSMIT GAIN_dB	58.83		
TX POINTING ERROR_dB	**0.00**		
EARTH STATION POWER_W	**3.00**		
TRANSMIT BACK-OFF_dB	0.00		
EARTH STATION POWER____dBW	4.77		
EARTH STATION EIRP(dBW)	63.60		
FLUX DENSITY_dBW/m^2	-98.66		
RECEIVE			
ANTENNA SIZE			**7.00**
ANTENNA EFFICIENCY (%)			**70.00**
ANTENNA NOISE TEMP.(deg. K)			**179.64**
RECEIVE ANTENNA GAIN(dB)			117.34
POINTING ERROR(dB)			**0.00**
FEEDER/DIPLEXER LOSS(dB)			0.30
LOW NOISE AMP. TEMP(K)			**100**
SYSTEM NOISE TEMP(K)			287.01
RECEIVE G/T RATIO(DB/K)			92.46

TRANSPONDED SIGNAL:			
UPLINK FLUX REL REF.PT.(dB)	2.66		
EIRP (DOWNLINK)(dBW)			36.34
OVERALL LINK BUDGET:			
UPLINK C/No (dB)Hz	78.65		
DOWNLINK C/No (dBHz)			*90.14*
OVER ALL C/No(dBHz)			78.36
INFORMATION RATE(kbits/s)			**5000.00**
OVER ALL Eb/No(dB)			11.37
Eb/No REQUIRED(dB)			**10.0**
MARGIN(dB)			1.37
	Margin	**1.37**	**dB**

Table 6.2 Link budget calculations

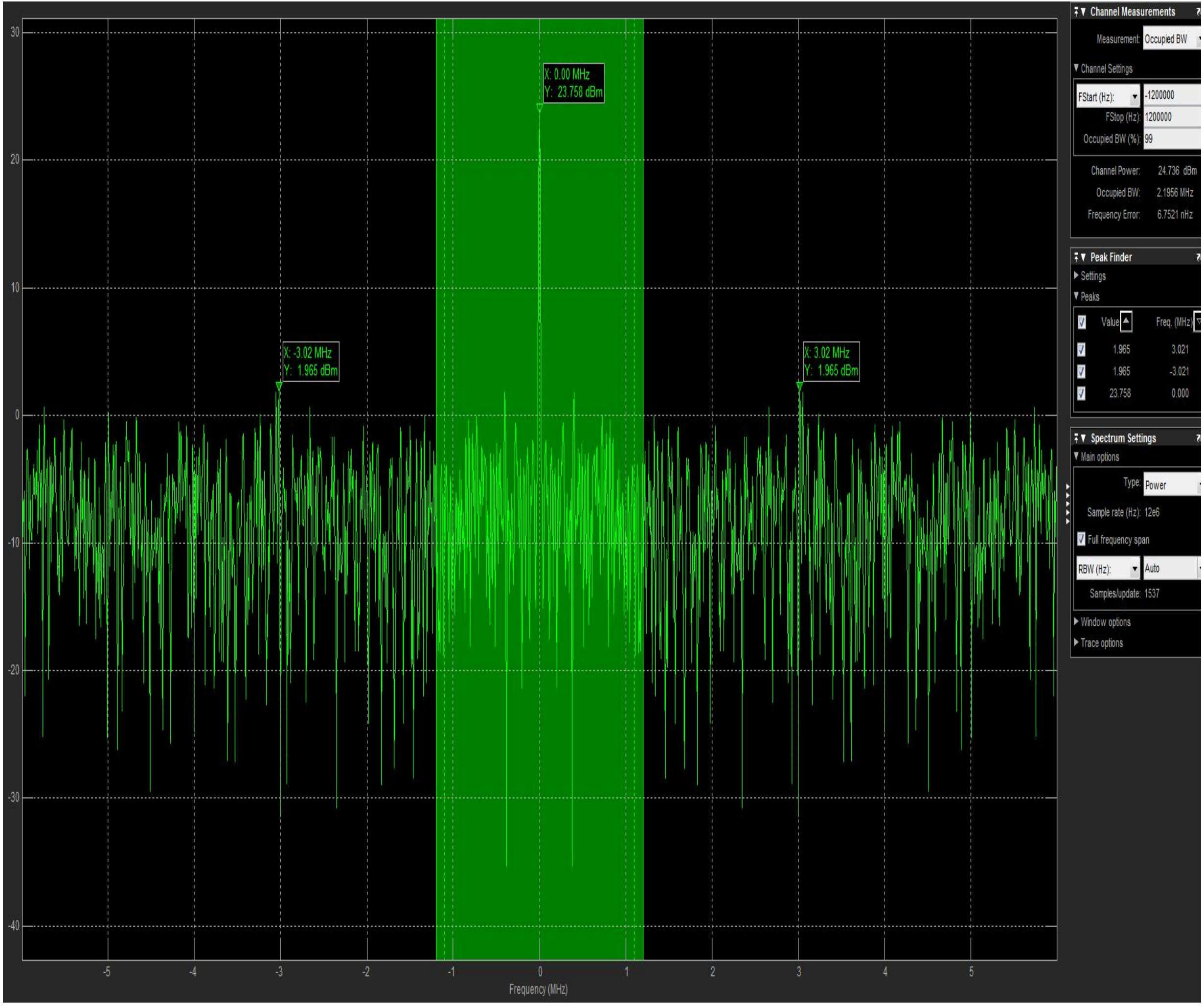
7 SIMULATION RESULTS AND ANALYSIS

7.1 Introduction

The objective behind simulating the physical layer in Simulink is to study the BER performance and to observe the scatter plots with varible signal to noise ratios .We use multipath Rayliegh fading and AWGN channel as transmission path for our transiever system and 16 QAM as the modulator with OFDM system. We have used wimax Time synchronization as well in order to sycnhronize the out put with input and obtained error rate curve as well as sfrequency response of the channel estimation. The frequency response is obtained by by estimating the input and out put data.The BER obtained was with high presision as in the order or 10e-11.

7.2 Performance of OFDM based Wimax physical layer using 16QAM modulation technique

7.2.1Transmitted signal spectrum analyzer



Measurement: Occupied BW

FStart (Hz): -1200000
FStop (Hz): 1200000
Occupied BW (%): 99

Channel Power: 24.736 dBm
Occupied BW: 2.1956 MHz
Frequency Error: 6.7521 nHz

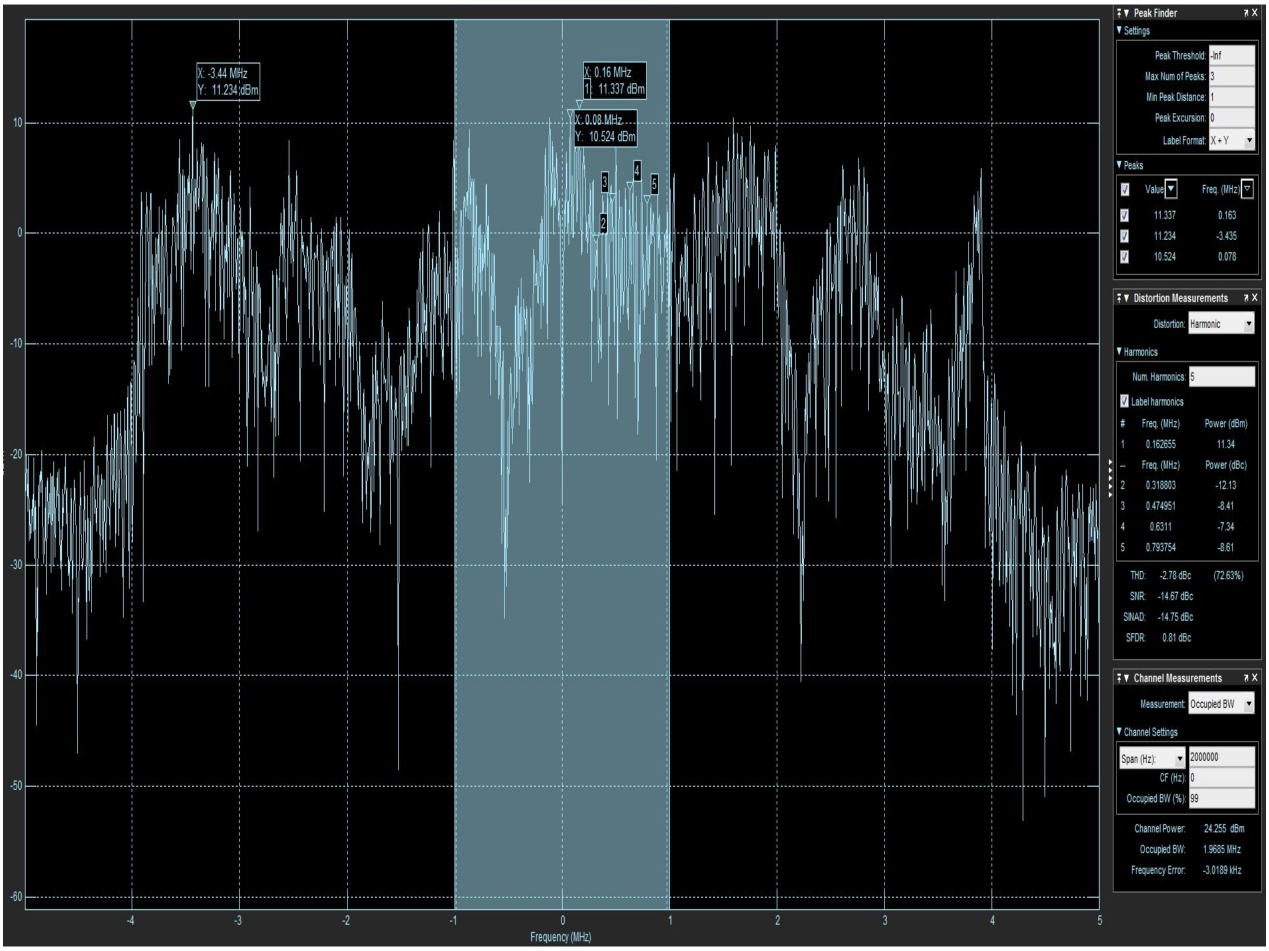
☑	Value	Freq. (MHz)
☑	1.965	3.021
☑	1.965	-3.021
☑	23.758	0.000

Type: Power
Sample rate (Hz): 12e6
☑ Full frequency span
RBW (Hz): Auto
Samples/update: 1537

Fig.7.1 Transmitted signal spectrum analyzer

The spectrum analyzer is used for measuring the magnitude of an input signal versus frequency. Initially it is used to measure the power of the spectrum of all the signals received spectrum when passsed through Rayliegh multipath fading channel and AWGN channel.The transmited signal sample frequency is 12MHz that is the sample rate is (8.33e-08)seconds and the transmitted channel power is 24.736dBm.The total bandwidth of the signal is 6 MHz the spectrum shows the occupied bandwidth is 2.19 MHz this shows that the instantaneous frequency of the signal during Transmission, it takes 1537 samples for updating the spectrum.

7.2.2Spectrum analyzer affected with channel



Peak Threshold: -Inf
Max Num of Peaks: 3
Min Peak Distance: 1
Peak Excursion: 0
Label Format: X + Y

☑	Value	Freq. (MHz)
☑	11.337	0.163
☑	11.234	-3.435
☑	10.524	0.078

Distortion: Harmonic
Num. Harmonics: 5
☑ Label harmonics

#	Freq. (MHz)	Power (dBm)
1	0.162655	11.34
--	Freq. (MHz)	Power (dBc)
2	0.318803	-12.13
3	0.474951	-8.41
4	0.6311	-7.34
5	0.793754	-8.61

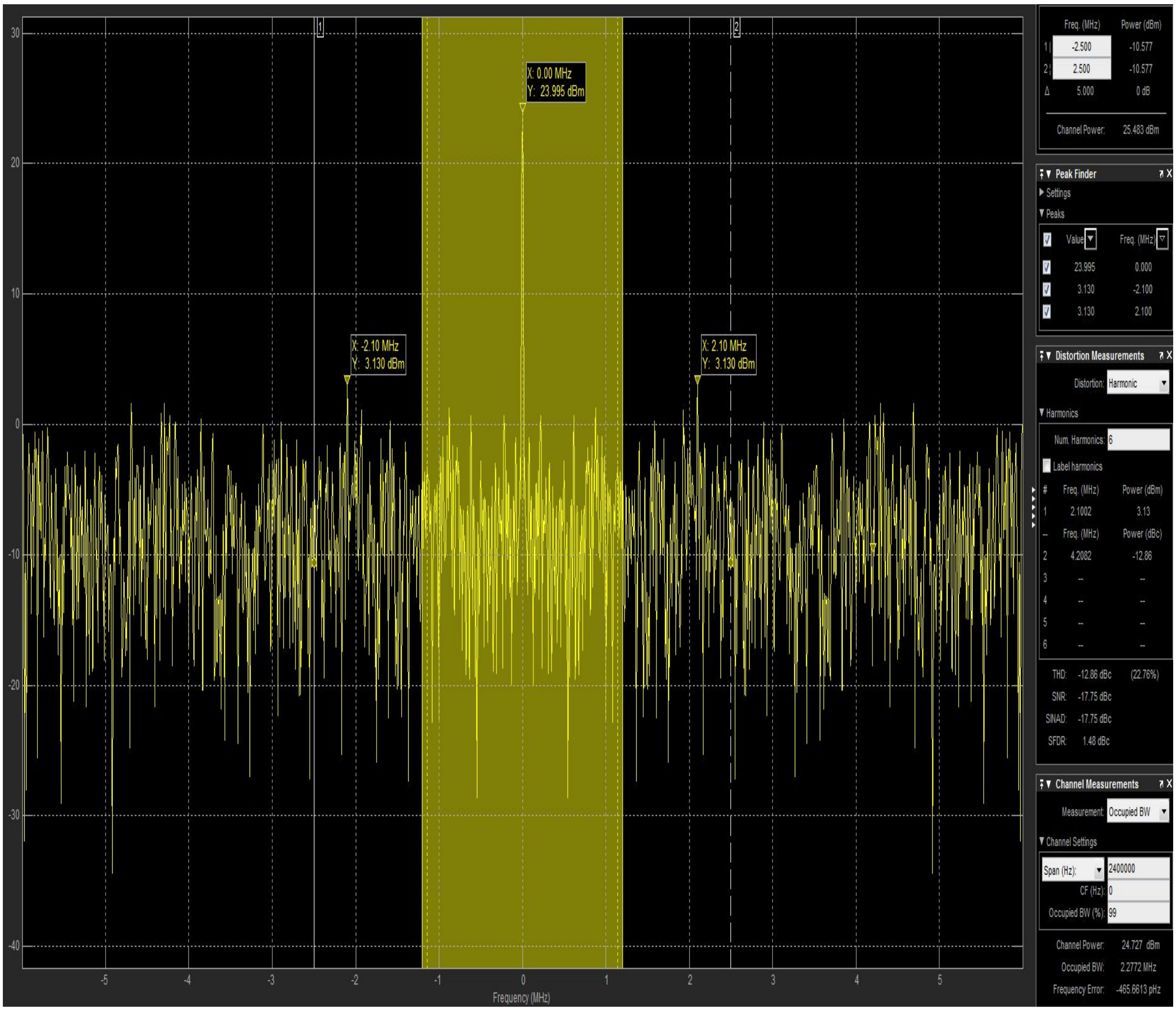
THD: -2.78 dBc (72.63%)
SNR: -14.67 dBc
SINAD: -14.75 dBc
SFDR: 0.81 dBc

Measurement: Occupied BW
Span (Hz): 2000000
CF (Hz): 0
Occupied BW (%): 99
Channel Power: 24.255 dBm
Occupied BW: 1.9685 MHz
Frequency Error: -3.0189 kHz

Fig 7.2 Spectrum analyzer affected with channel

The received spectrum which is channel affected when the signal is passed through the multipath rayliegh fading channel and AWGN channel.intentionally the signal bandwidthis reduced to 5 MHz to observe the channel affect more acurately.from the spetcrum analyzer it is cleraly seen that there are three peaks obsreved.There is a reduction in the channel power reduced to 24.255 dBm. As well as reduction in the sample span rate to 20Mhz that which ultimately reduced the occupied bandwidth with significant frequency error that is -3.0189kHz due to THD(total harmonic distortion).

7.2.3 Demodulated spectrum at the reciever.



	Freq. (MHz)	Power (dBm)
1	-2.500	-10.577
2	2.500	-10.577
Δ	5.000	0 dB

Channel Power: 25.483 dBm

☑	Value	Freq. (MHz)
☑	23.995	0.000
☑	3.130	-2.100
☑	3.130	2.100

Distortion: Harmonic

Num. Harmonics: 6

☐ Label harmonics

#	Freq. (MHz)	Power (dBm)
1	2.1002	3.13
--	Freq. (MHz)	Power (dBc)
2	4.2082	-12.86
3	--	--
4	--	--
5	--	--
6	--	--

THD: -12.86 dBc (22.76%)
SNR: -17.75 dBc
SINAD: -17.75 dBc
SFDR: 1.48 dBc

Measurement: Occupied BW

Span (Hz): 2400000
CF (Hz): 0
Occupied BW (%): 99

Channel Power: 24.727 dBm
Occupied BW: 2.2772 MHz
Frequency Error: -465.6613 pHz

Fig. 7.3 Demodulated spectrum at the reciver

The demodulated spectrum analyzer is shown after estimating the channel and synchronization of the data . The behavious is exactly same as the transmitted spetcrum with a recoverd span of the smaple frequency and channel power the bandwidth occupied that is the realtime bandwidth is shown as 2.277MHz which is the actual bandwidth of the signal at instant of receiving .The frequency error is shown as very mild in the order of the pico Hz.the actual channel power is seen as 24.727dBm at 6MHZ Bandwidth and 25.483dBm at at 5 MHz

7.3 Frequency Response plots

The multi path leads to time domain and frequency domain representations in digital communication systems, where impulse and frequency response will determine the system behaviour. The above plots show the estimated frequency response at various signal to noise ratio (SNR) ranging from (0-35dB).The input given to the channel estimation is of port size NFFT. The initial estimate given was 256 subcarriers only fed into the selector, then after performing maths operations the output of the estimate was 192 data carriers with 8 pilots and 56 nulls. The effect of signal to noise ratio is clearly seen in the above figures.

In the figure 1 both the axis represents the OFDM data carriers and the error vector magnitude of actual symbols to the equalised channel symbols. One at zero SNR there is a sawtooth seen here where the highest peak seen near the 150 subcarriers from the beginning there is a loss of sub carriers seen here. There is an oscillation seen in here between OFDM symbols 0 to 100. It can be clearly seen that the response occupied by the subcarriers is of very little, in fact large number of spikes shown here are with big loss of the subcarriers. Hence, an unreliable estimation at zero signal to noise ration with error rate one out of 10 bits at low SNR more number of pilots are added to improve the performance.

Form the second figure 2 there is a relative variations at the SNR =5,at initial point between 0 to 50 OFDM symbols there is a damping seen for the small increase of average overall carriers . Two big peaks are seen between 100 and 150 OFDM symbols. Here the carrier loss seen is relatively. There is no stability and completely a nonlinear response. Because the pilots are available, system is estimating a channel response even at a small SNR values.

From this figure 3 at SNR value equal to 10, it is clearly seen that the estimated channel frequency response occupied I s never zero with respect to the overall average carriers until 1.2. There is a continuous Swing seen between the OFDM symbols, with a reduction in loss of carriers, the respect of the increased SNR values is clearly seen. Impairments effect is also seen.

From the figure 4 at SNR value equals to 15, there is an improvement shown in the performance. With respect to average carriers up to 2 there is a zero OFDM symbols shown, the effect of the SNR is clearly seen. There is a large portion occupied by the OFDM symbols.

From the figure 5 at SNR equal to 20, the trend completely changed when compared with figure 5 here there is big spike near 100 with error average magnitude almost equal to 6and there is a linear decrease in the spikes. The channel impairment effect is clearly seen.

From the figure 6 at SNR value equal to 25. A large portion of the OFDM symbols are occupied, therefore, the loss of the symbols is reduced relatively in contrast with the previous responses. By inspecting figures 6,7,8 at an increased SNR values it can be seen there is marginal increase in the overall average carriers with respect to the data carriers , sometimes they maintain the stability between two distinct OFDM Symbols. By examining all the figures it can be concluded that at higher SNR values there is low loss of the data carriers with respect to overall average carriers. With lower SNR values we need to compensate the issue by inserting more number of pilots. Generally in digital communication systems filters will compensate such kind of issues.

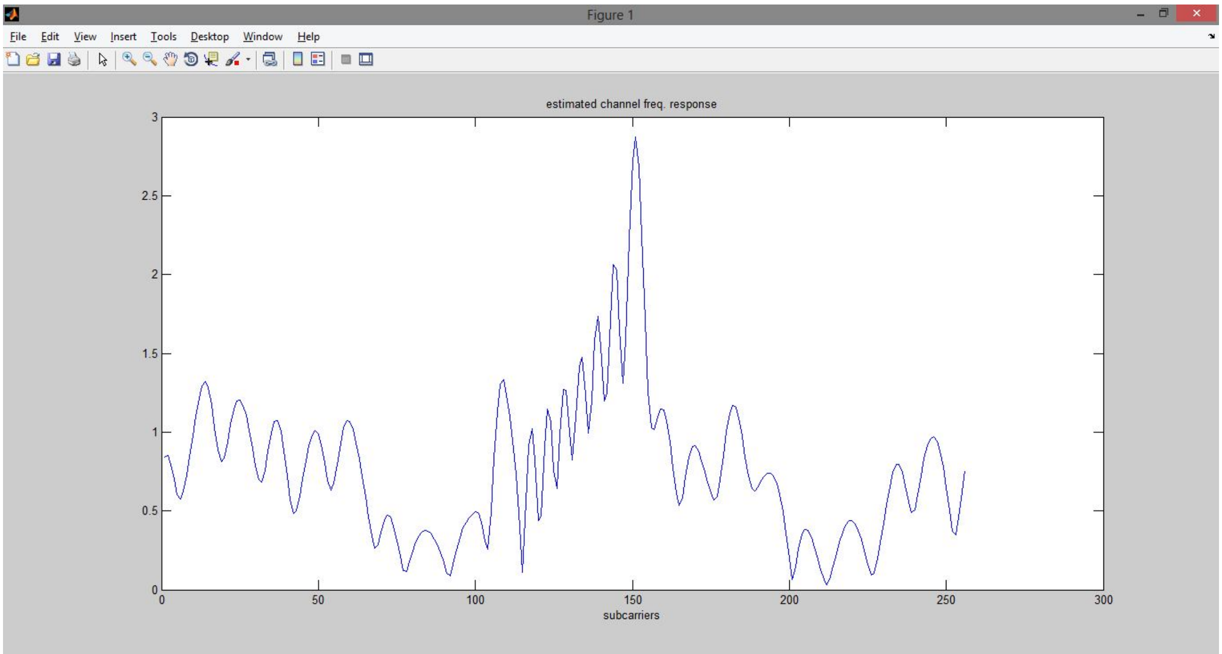


Fig. 7.4 Frequency Response @ SNR = 0

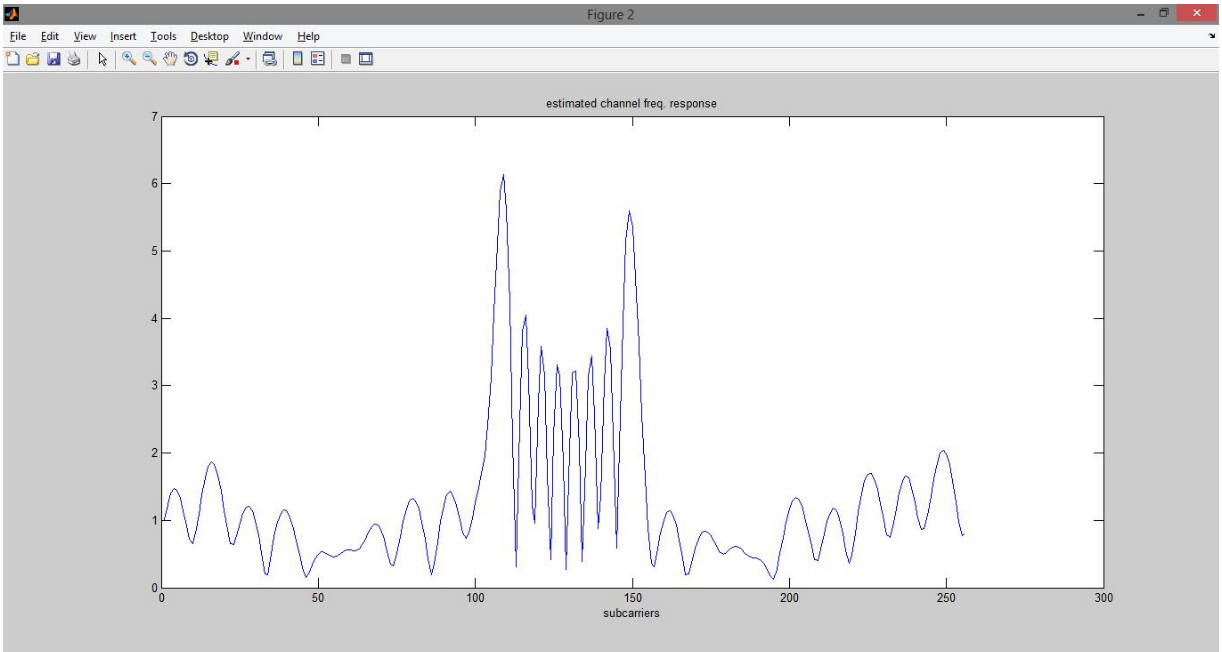


Fig. 7.5 Frequencyresponse@SNR=5

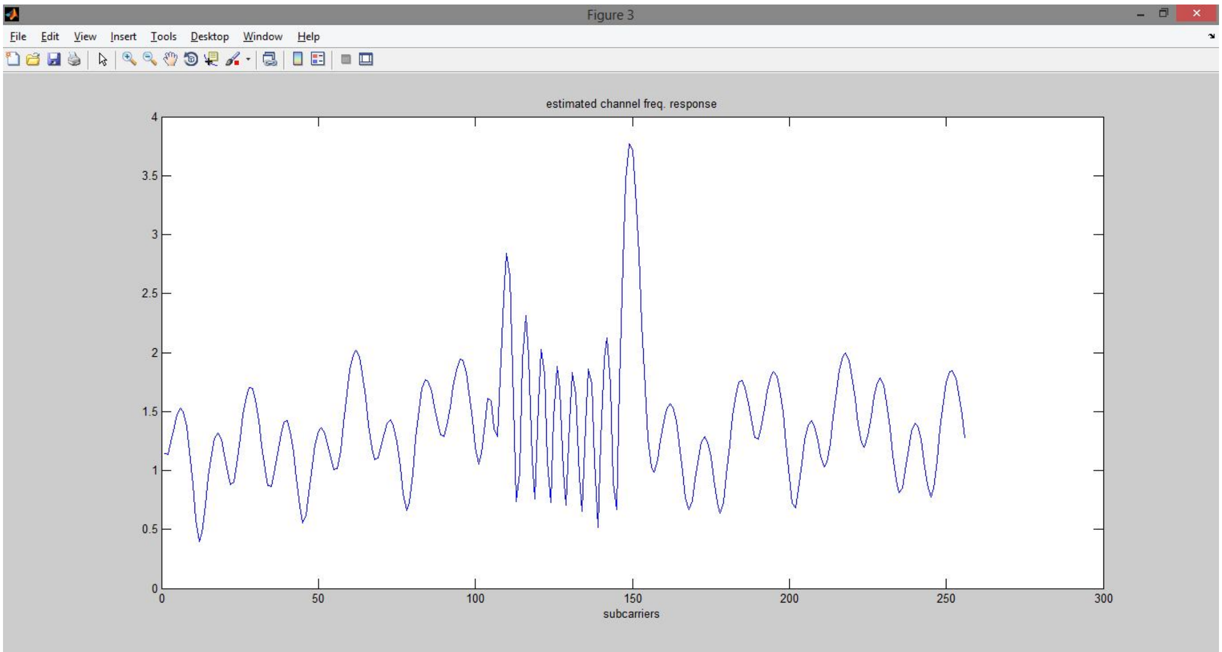


Fig. 7.6 Frequency response SNR =10

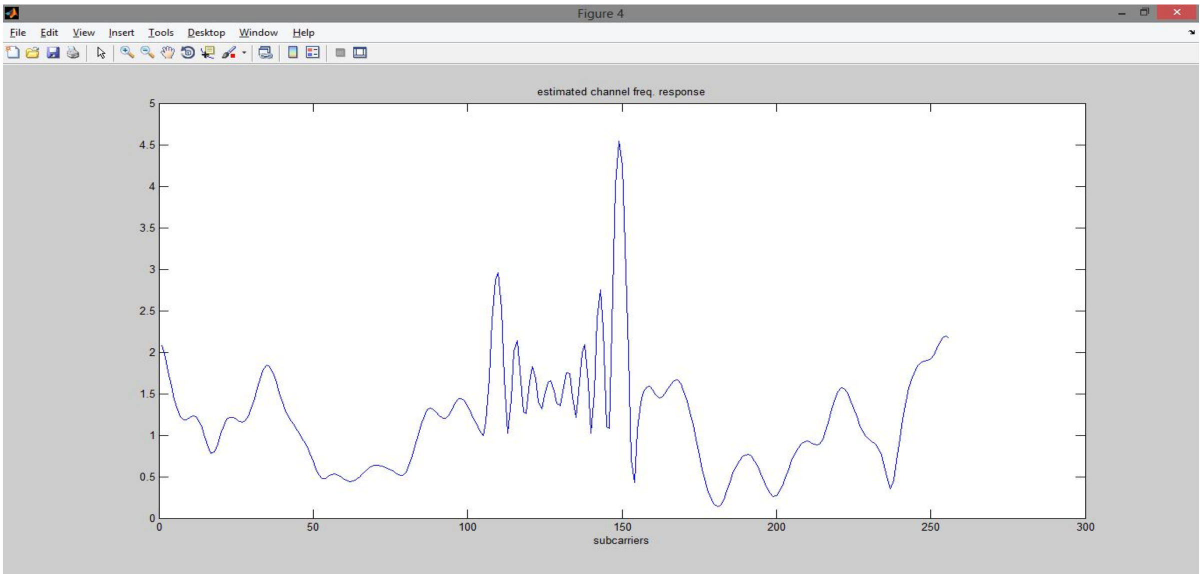


Fig. 7.7 Frequency response @ SNR=15

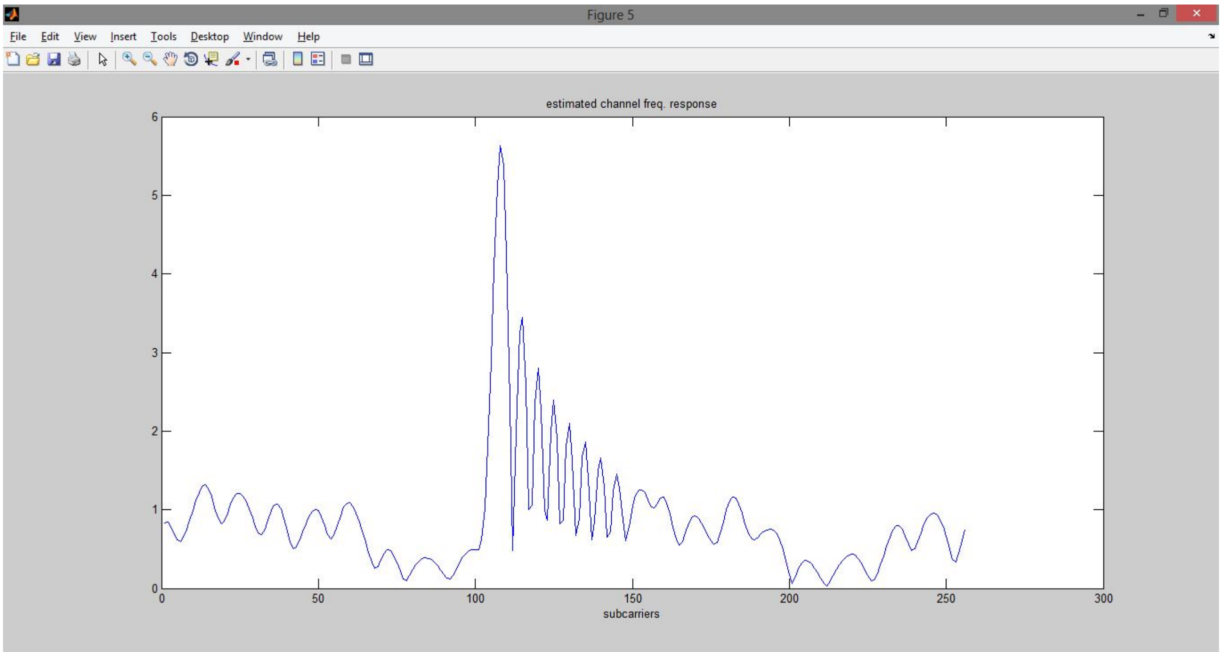


Fig. 7.8 Frequency response @ SNR=20

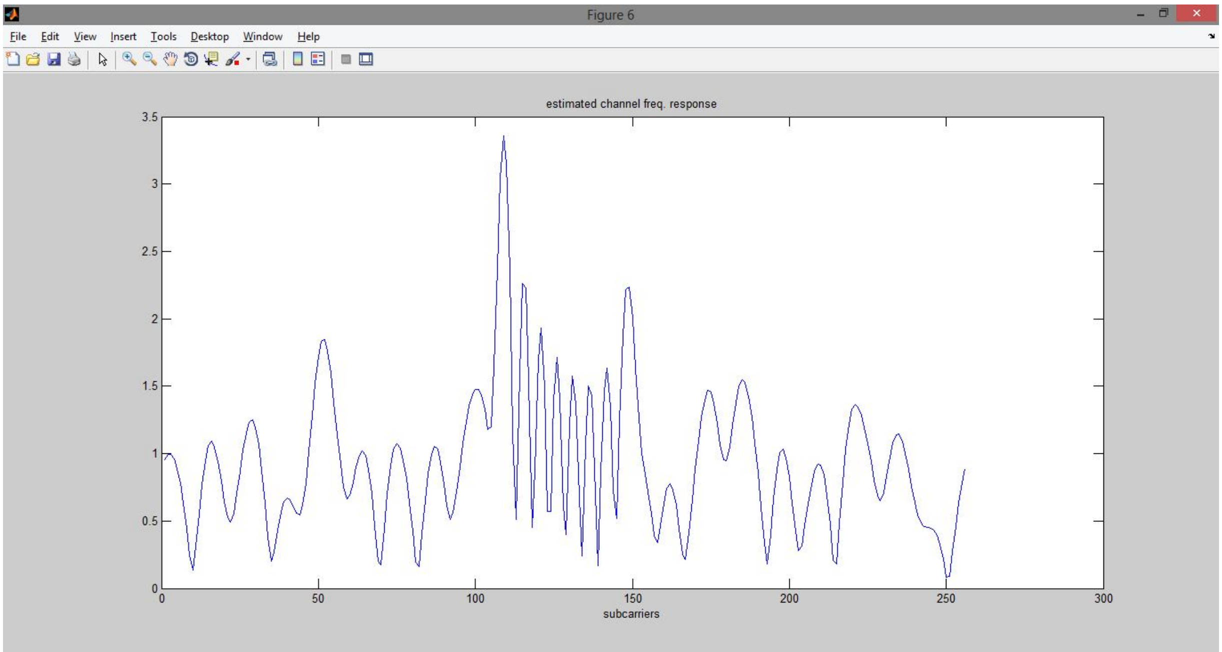


Fig. 7.9 Frequency response @SNR=25

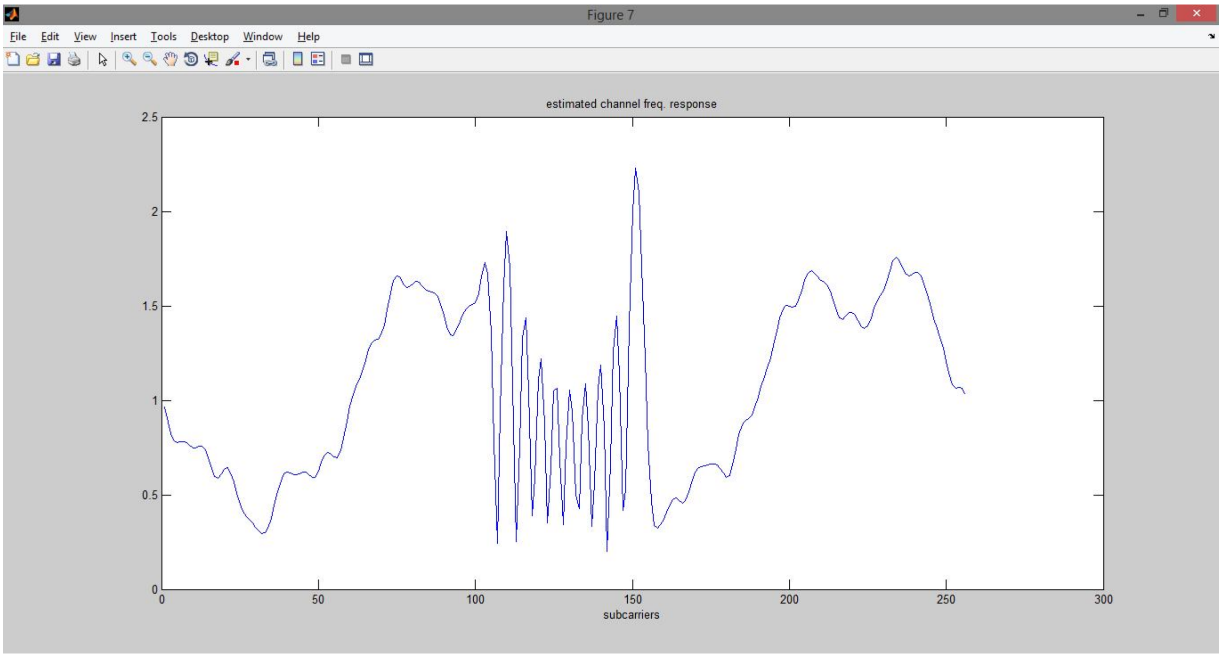


Fig 7.10 Frequency response @ SNR=30

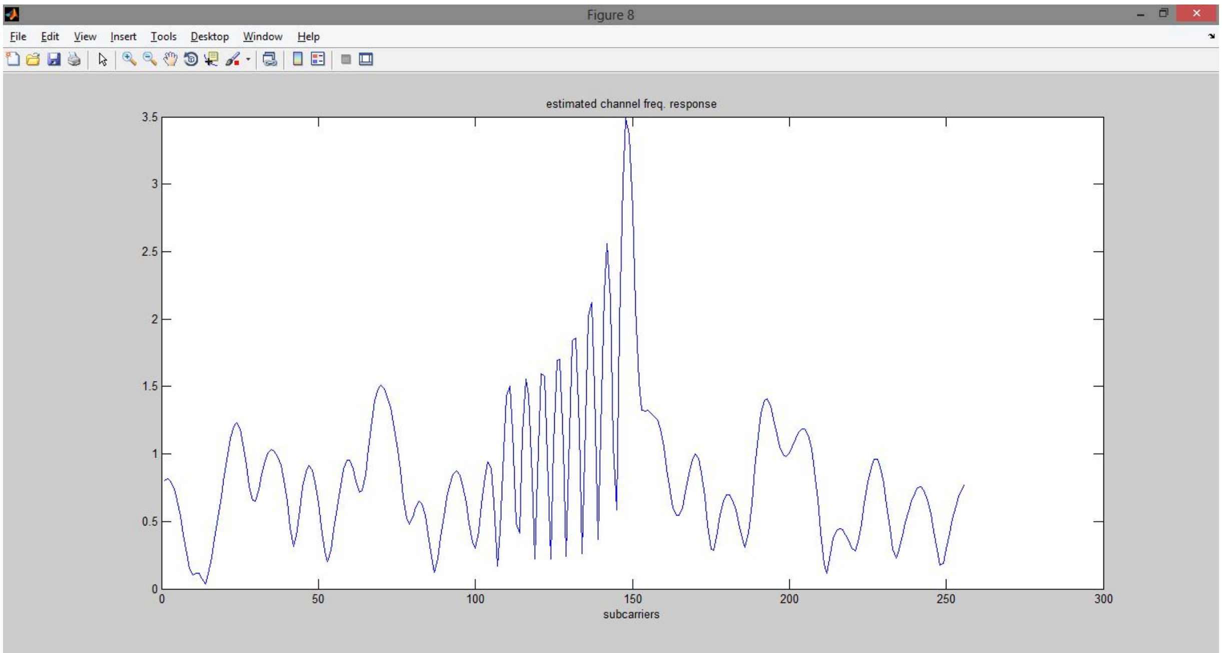


Fig. 7.11 Frequency response @SNR=35

7.4 Constellation Plots:

The figure 7.12 shows the received constellation when passed through the rayliegh multifading and AWGn channel . The affect of SNR values and channel Impairements on the recieved scatter plot diagram shall be discussed.

Constellation Plot is plotted while varying SNR Fig to 7.12 to 7.19 is the constellation plots for the received data for different SNR values varying from 0 to 35 dB.

For 16-QAM Modulation, we can see the 16 different variations in the constellation at every SNR. The effect of channel impairment is clearly seen for every scatter plot. As the simulation run time is set very low the changes in the parameters can show the actual scatter plot at the reception side. Throughout the plots there is no fair ISI seen, at higher SNR values it can be clearly seen that the performance is improved and there is no loss of the symbols.

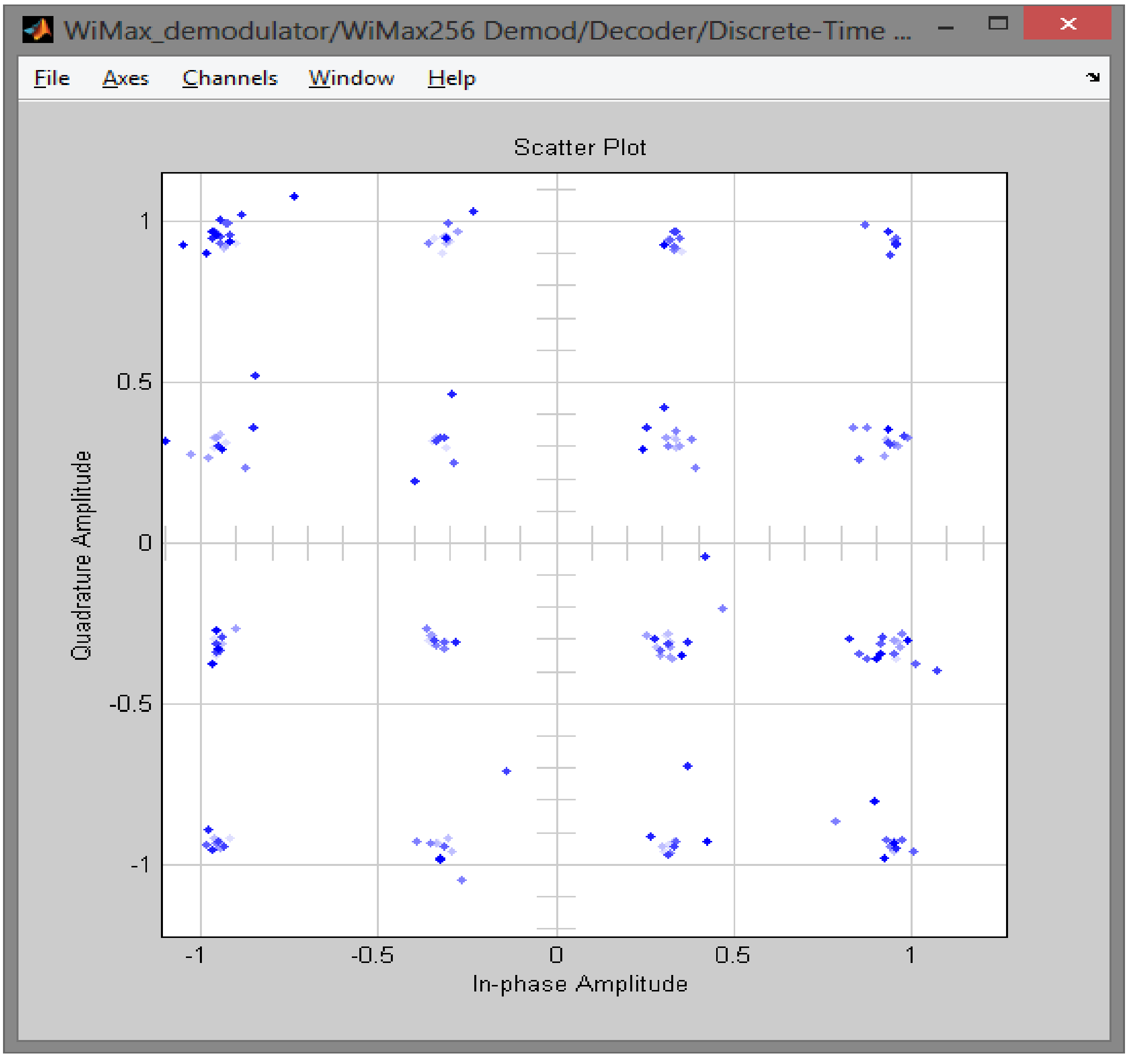


Fig. 7.12 Scatter Plot at SNR= 0

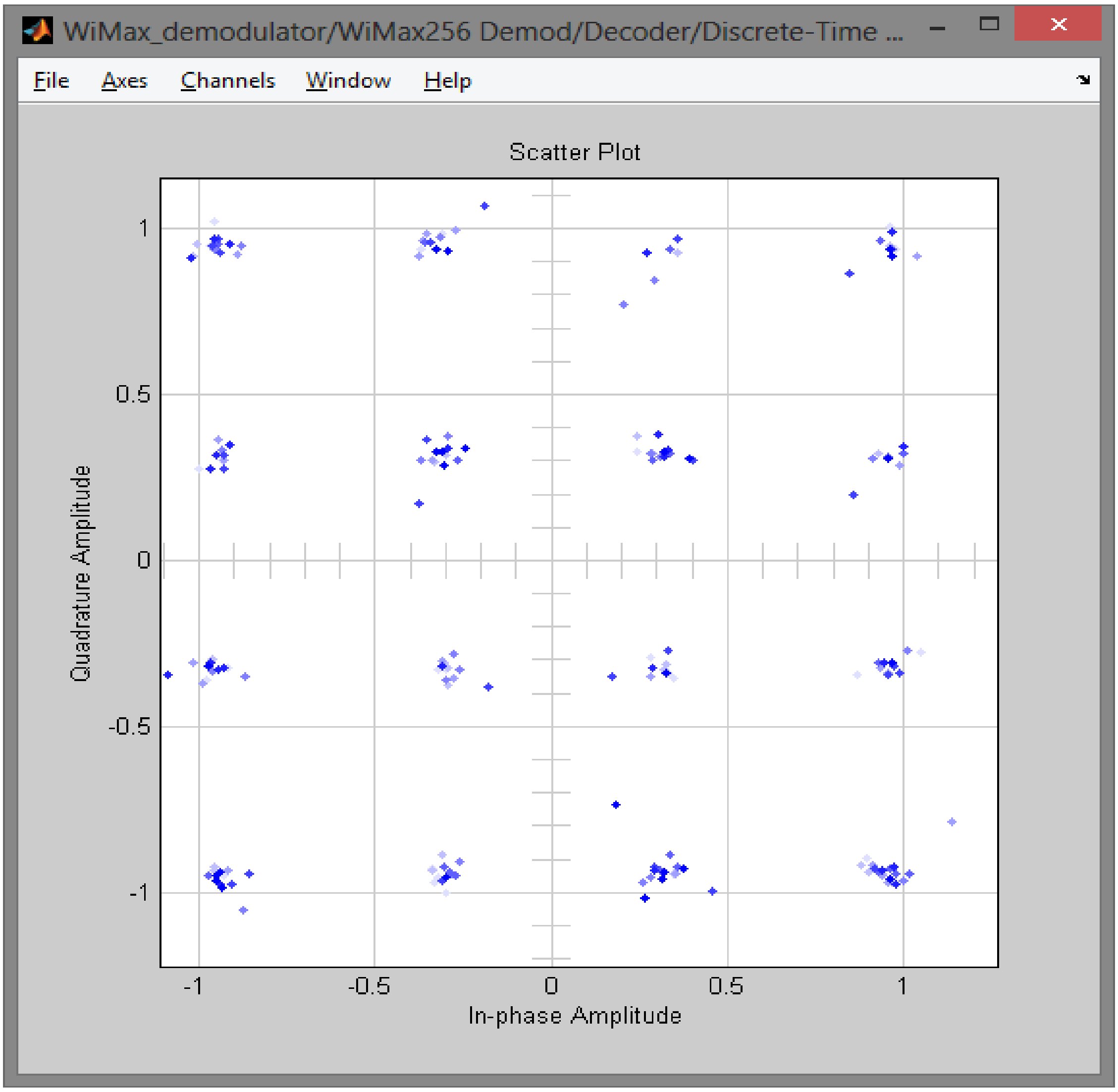


Fig. 7.13 Scatter Plot @SNR=5

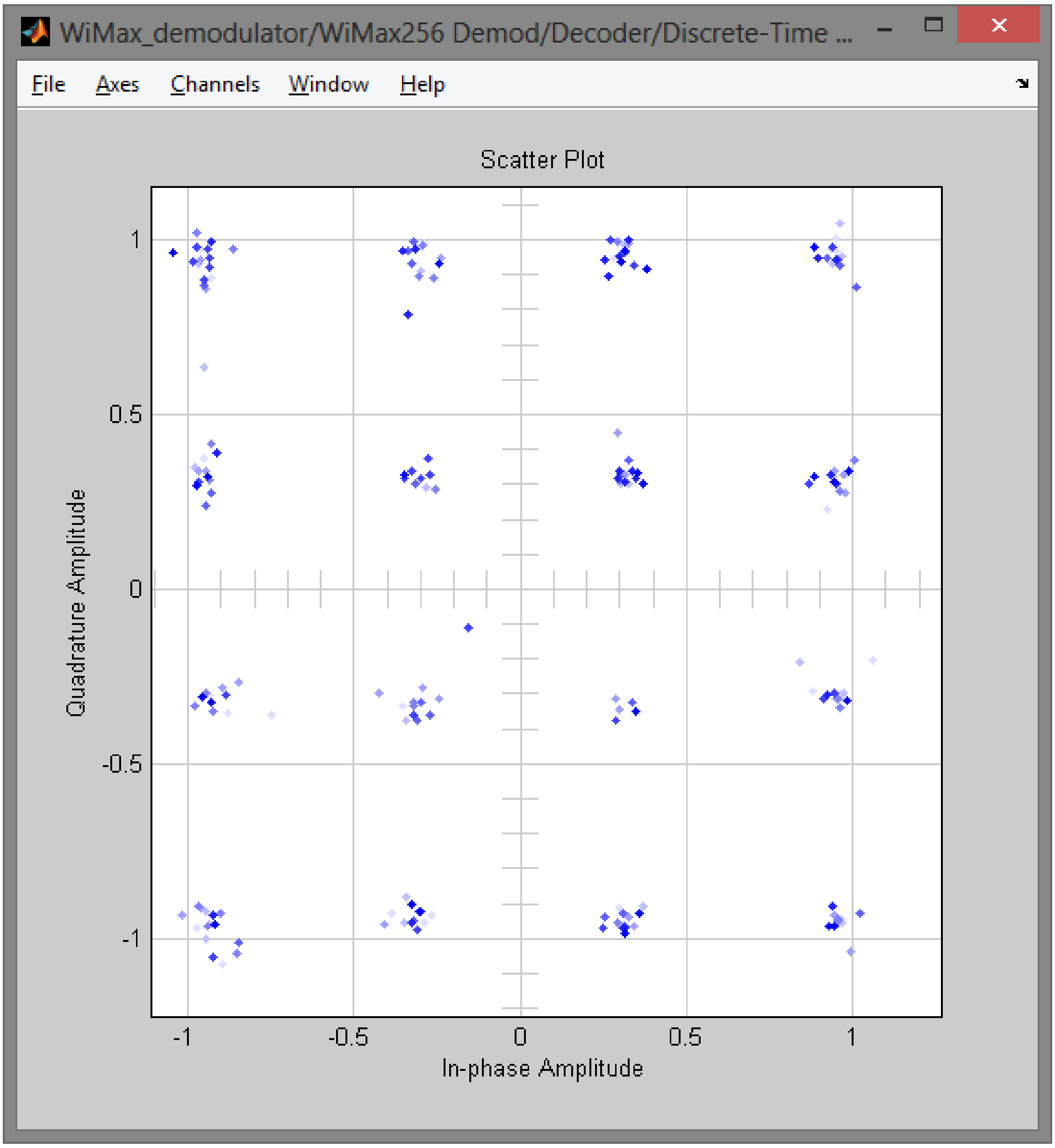


Fig. 7.14 Scatter plot @SNR=10

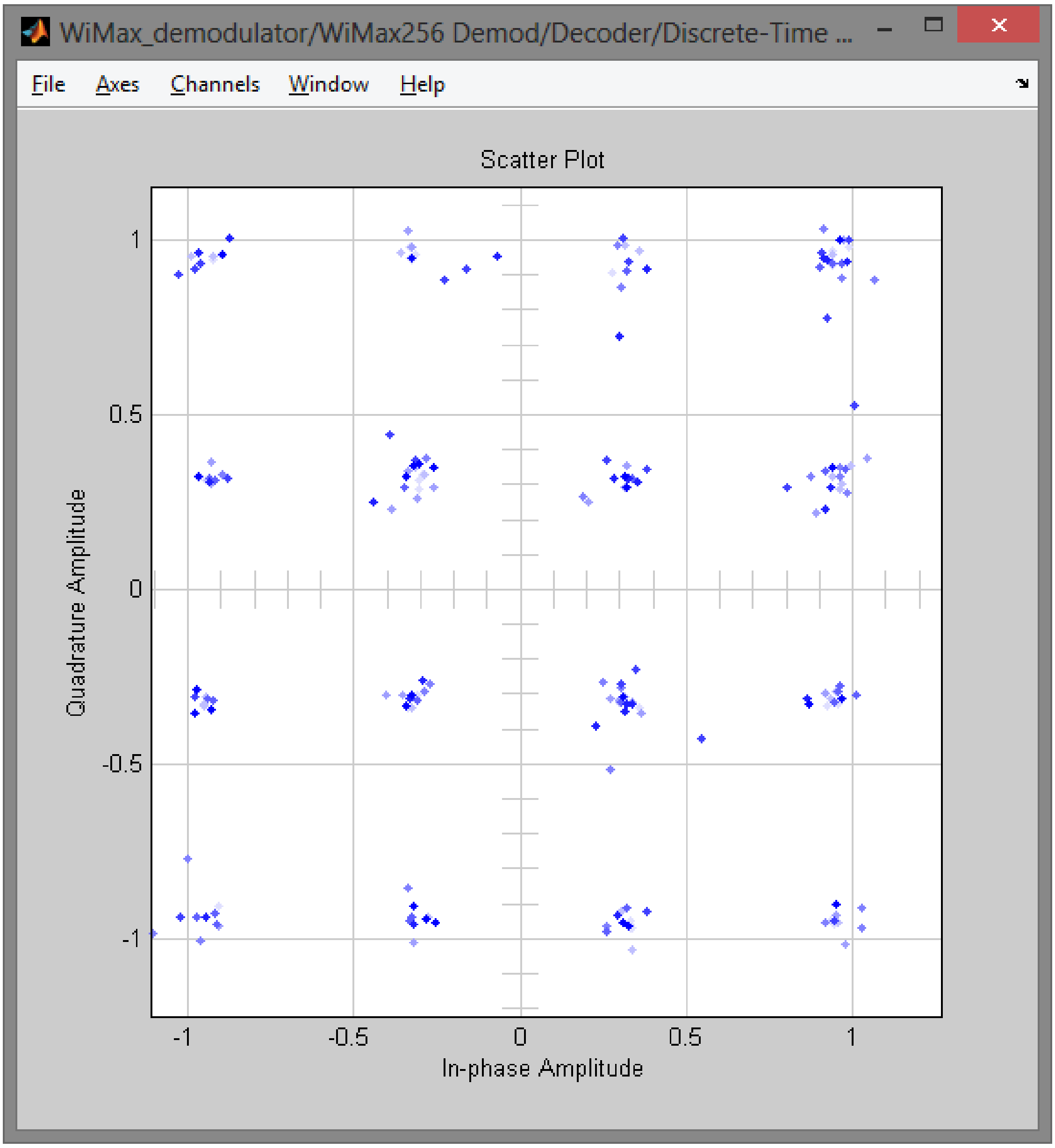


Fig. 7.15 Scatter plot @SNR=15

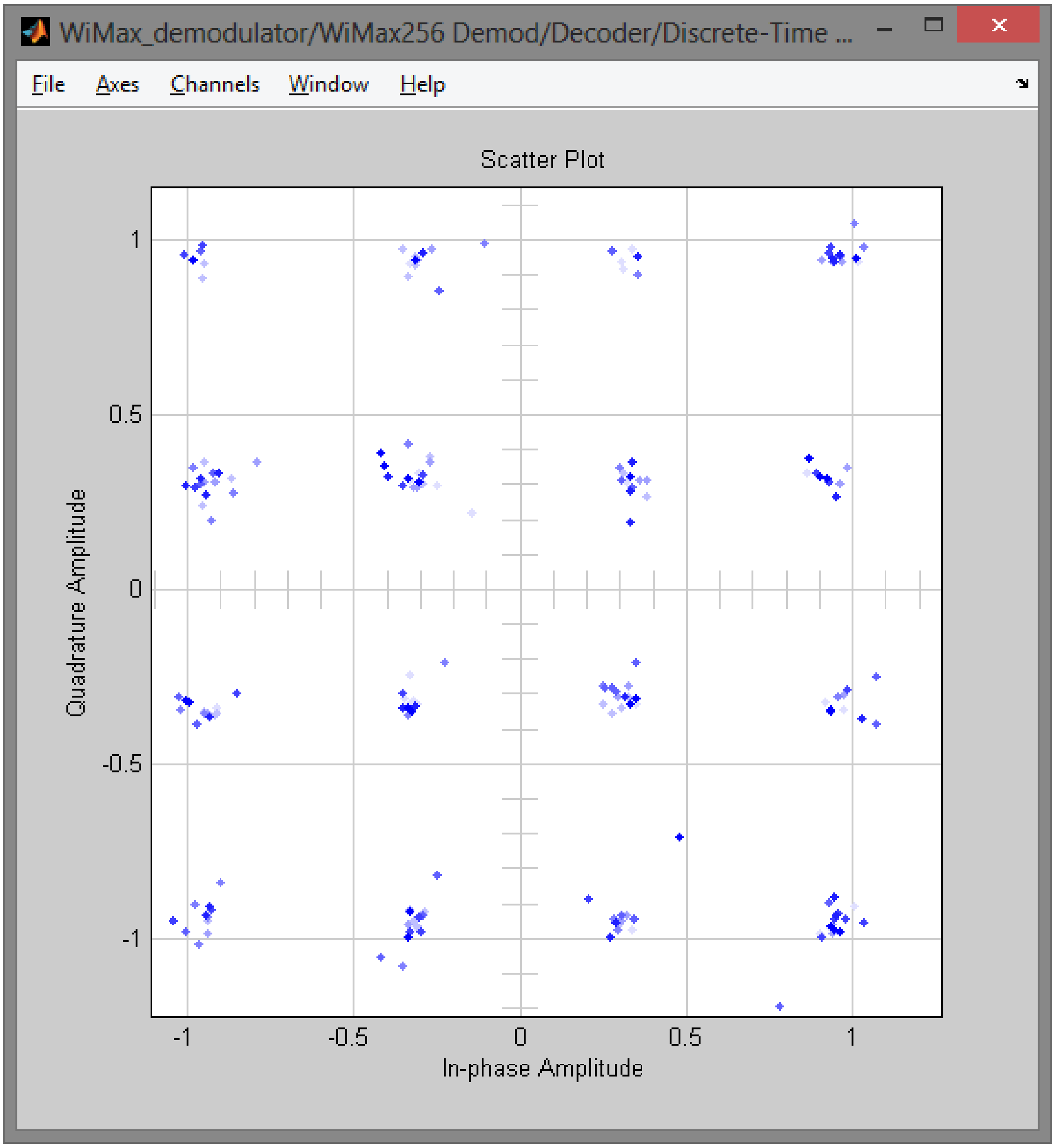


Fig. 7.16 Scatter plot @SNR=20

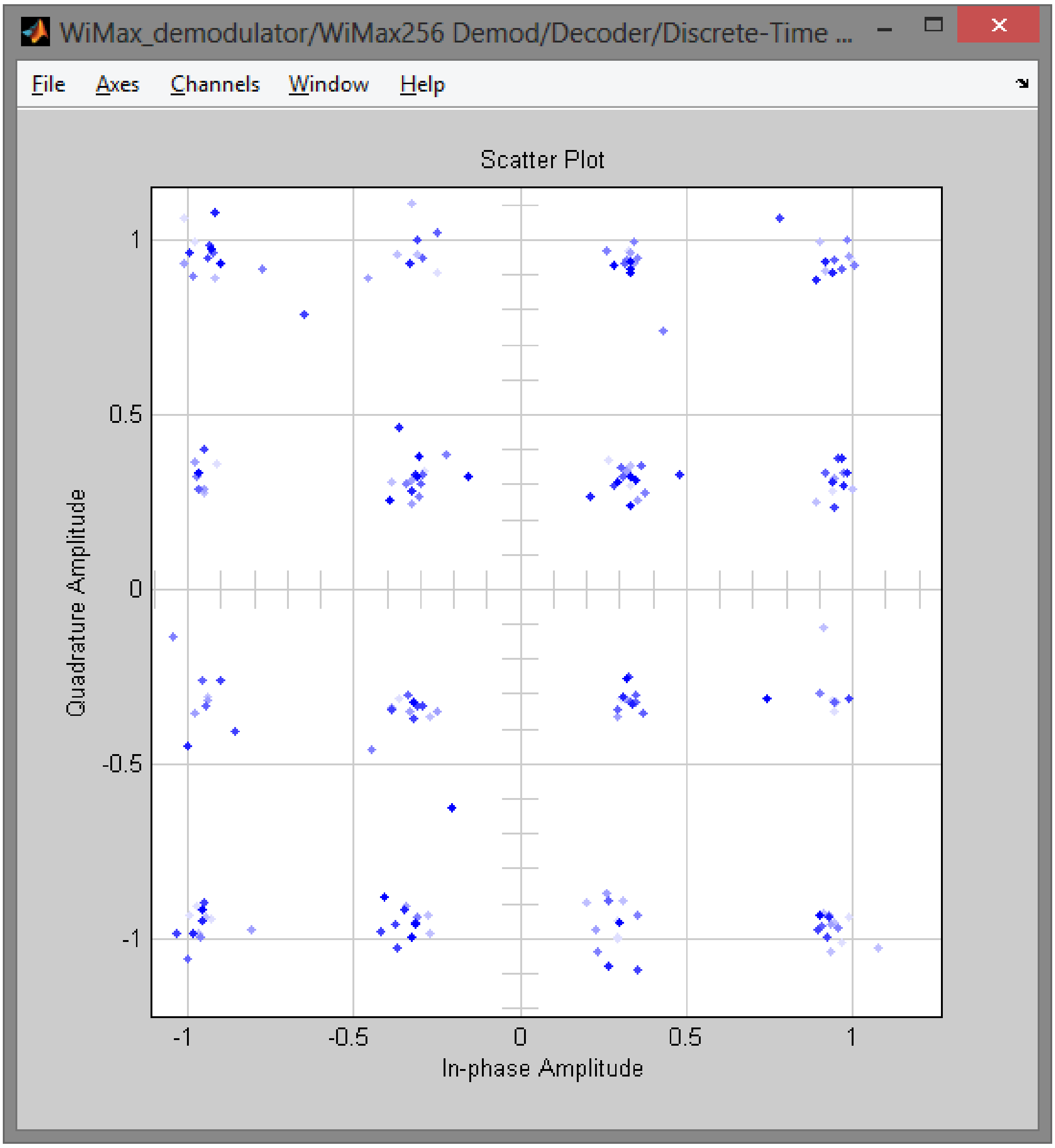


Fig. 7.17 Scatter plot @SNR=25

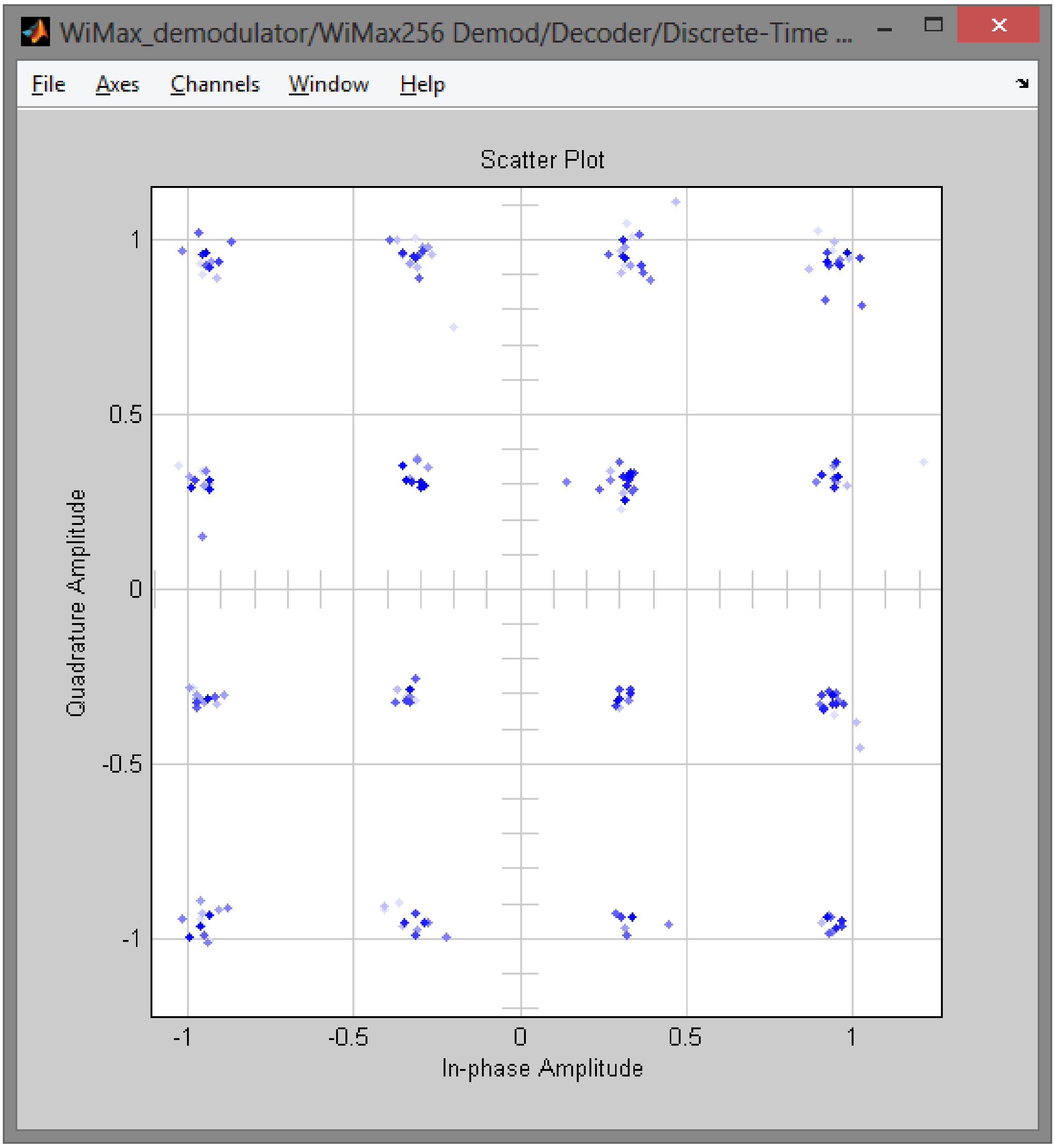


Fig. 7.18 Scatter plot @SNR=30

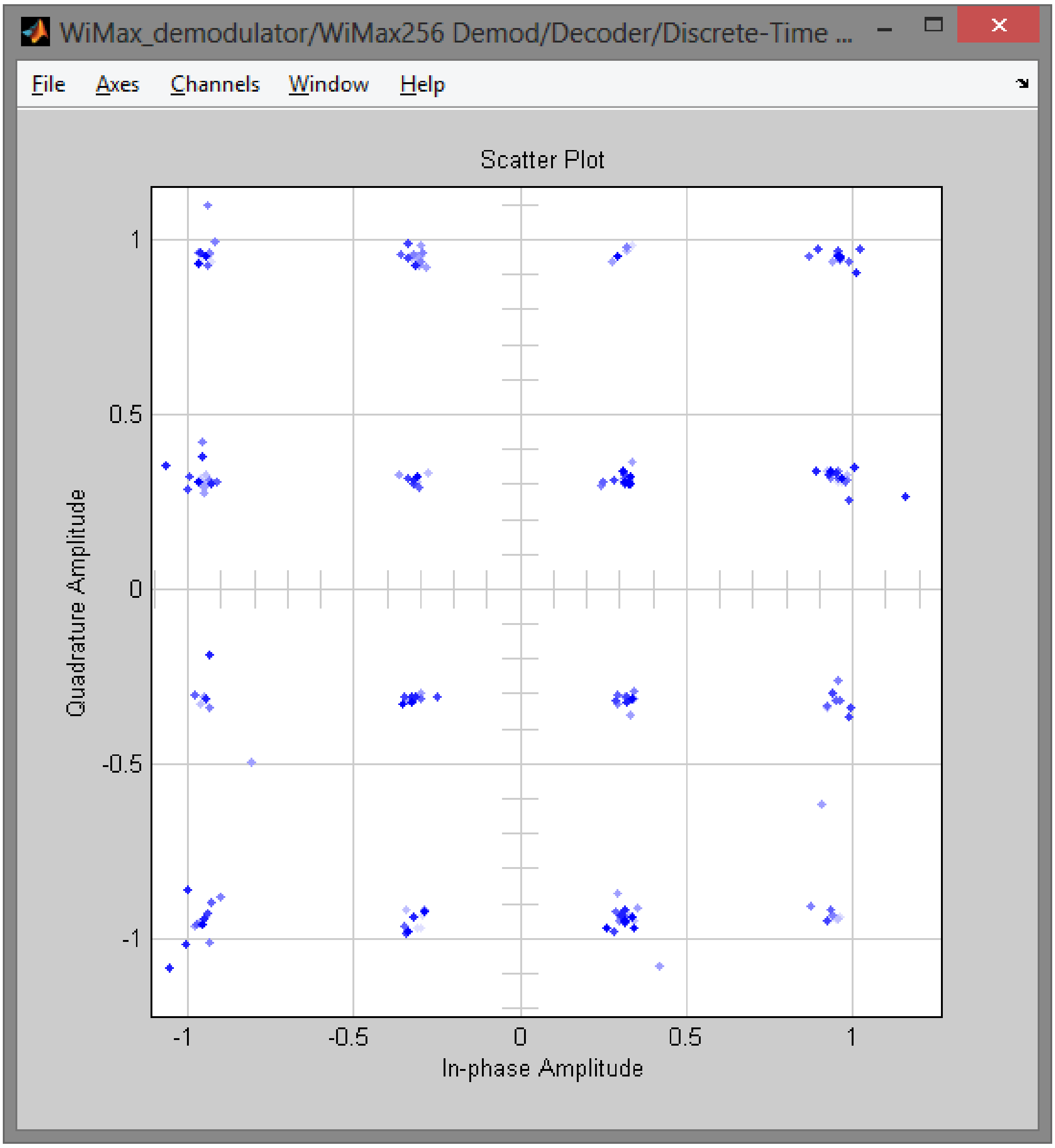


Fig. 7.19 Scatter plot @SNR=35

7.5 BER versus SNR results and discussions

BER vs SNR graph will show the performance of the system model that has been designed. Here for SNR value of 0 to 10, the drop in BER value is very less, but as the SNR increases, the BER falls with a good value which in turn increases the overall performance at the higher SNR values for data.

The figure 7.20 shows the BER performance of WIMAX Physical layer through AWGN channel, Rayleigh and AWGN using 16 Quadrature Amplitude Modulation (QAM) techniques. The effect of AWGN channel and fading multipath (Rayleigh) channels. Form the curve it can be clearly seen that at zero SNR almost one in 10 bits are corrupted and results in error. With the slight increase in the SNR value that is at SNR value equal to 5 the error rate was dropped not steeply but relatively. At SNR value equal to 10 one out of every hundred bits are corrupted and resulted in errors. Here the performance has been improved in compared to the previous values at SNR value equal to 15 there is relative fall in BER level in the order of greater than 10e-3 i.e., one on in every thousand bits are corrupted. Progressive fall of the BER continues with every increase of the SNR values at SNR value equal to 35.

Performance of OFDM based WIMAX Physical layer using 16 QAM modulation techniques

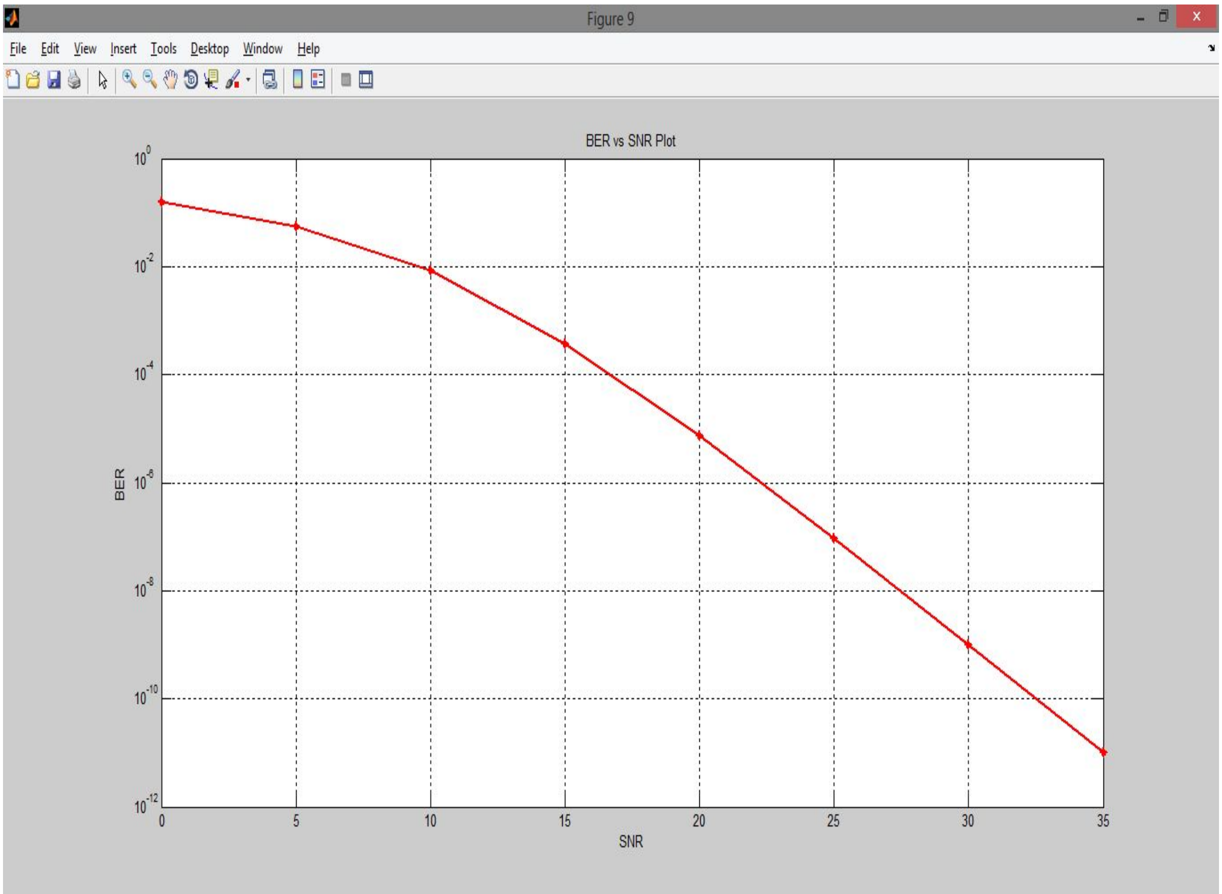
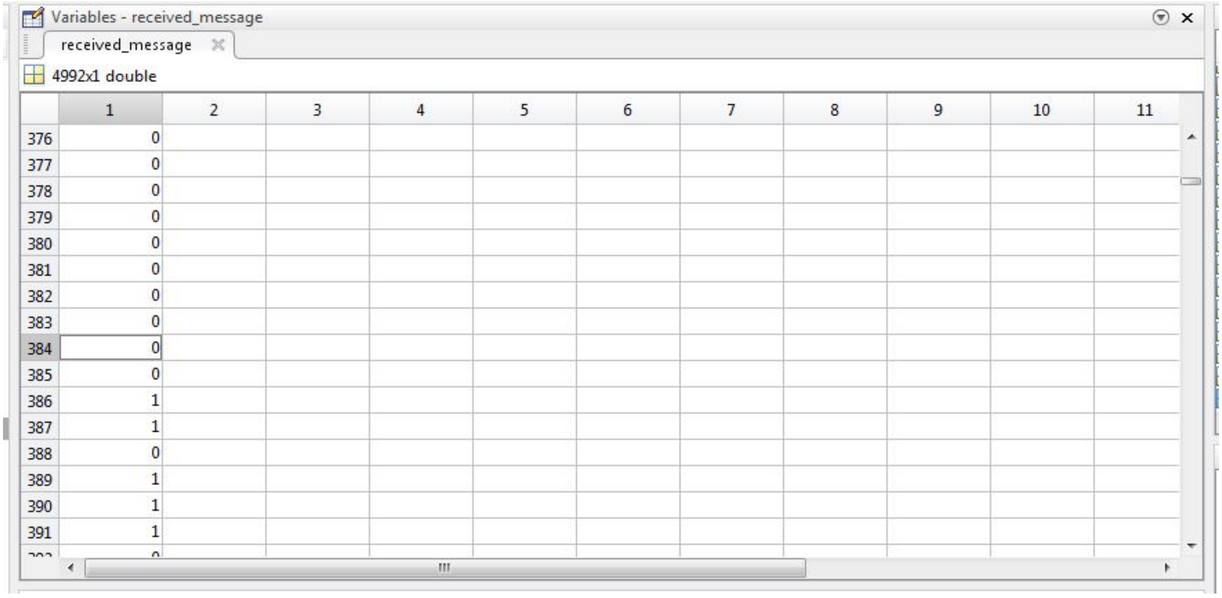


Fig. 7.20 BER vs SNR

7.6 Latency calculations

Latency generically defined as the RTT (round trip time) and also as a time period between the simulation time and response time. Here, in the present simulation, the sample frequency is chosen as 12MHz and the sample rate is 8.3e-8. When the bit time rate is multiplied with the number of bits of the delay we get the total transmission delay. That is mathematically expressed as
Total delay (bit time rate *no of bits)



	1	2	3	4	5	6	7	8	9	10	11
376	0										
377	0										
378	0										
379	0										
380	0										
381	0										
382	0										
383	0										
384	0										
385	0										
386	1										
387	1										
388	0										
389	1										
390	1										
391	1										

Table -7.1 Received messages after 384bits of transmission from the transmitting end

From the above table it can be clearly seen that the transmission time of the bit rate ends at 385 till that block there is no received bit this shows that from 0to 385 the message is transmitted and so the number of bits that are involved during the transmission delay were 384 bits. The sample rate is 8.3e-8. If we calculate the total delay by applying the formula we get 3.19e-9.Two times the total delay will give the latency mathematically represented as

Latency=2(Total Delay)

Hence the total delay is

```
1/Fb
Ans  =   8.3333e-08

>> 1/Fb*(384)
Ans  =   3.2000e-05s is the total delay

>>(1/Fb*(384))*2 = Latency

Ans  =    6.4000e-05s
```

Therefore the on calculating latency we get as 0.6micro seconds is the round trip delay which is the best desired latency for condition monitoring.

7.7 Simulation results of Radio microwave link by using radio mobile online software

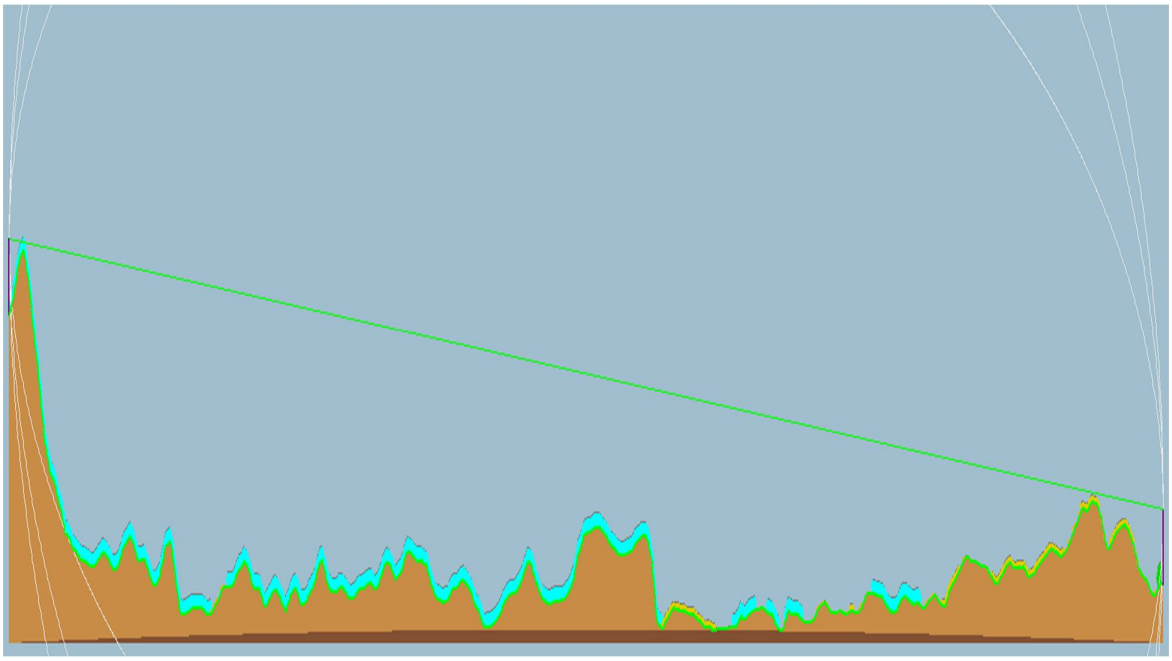


Fig 7.21 Simulation results of the microwave radio link (between two points)

7.7.1Microwave radio link

The above figure shows the radio link between the two points there is no beam that is out of the Fresnel zone hence by adjusting the antenna height that is tower height up to 50m we can obtain a perfect line of sight condition. The required reliability of the signal is 90 %.The total path loss is seen as 106.97 dB and the margin of error that is fade margin is completely a non-negative number. Here the frequency minimum is implemented that is 10 MHz as the functional frequency. The network coverage is also simulated by means of same software. The coverage is shown by choosing an elliptical antenna and the radius is 25km from the swan bank area where the base station is located and radio signal is transmitted. The figure 7.21 shows the geographical network coverage of the two locations within 25 km of radius from the centre point of the transmitting base station here the receiving repeater is located at Mt Coot-tha which is underlined for understanding sake the entire green shade shows the network coverage whereas the unshaded portion is also shown where the network is not covering.

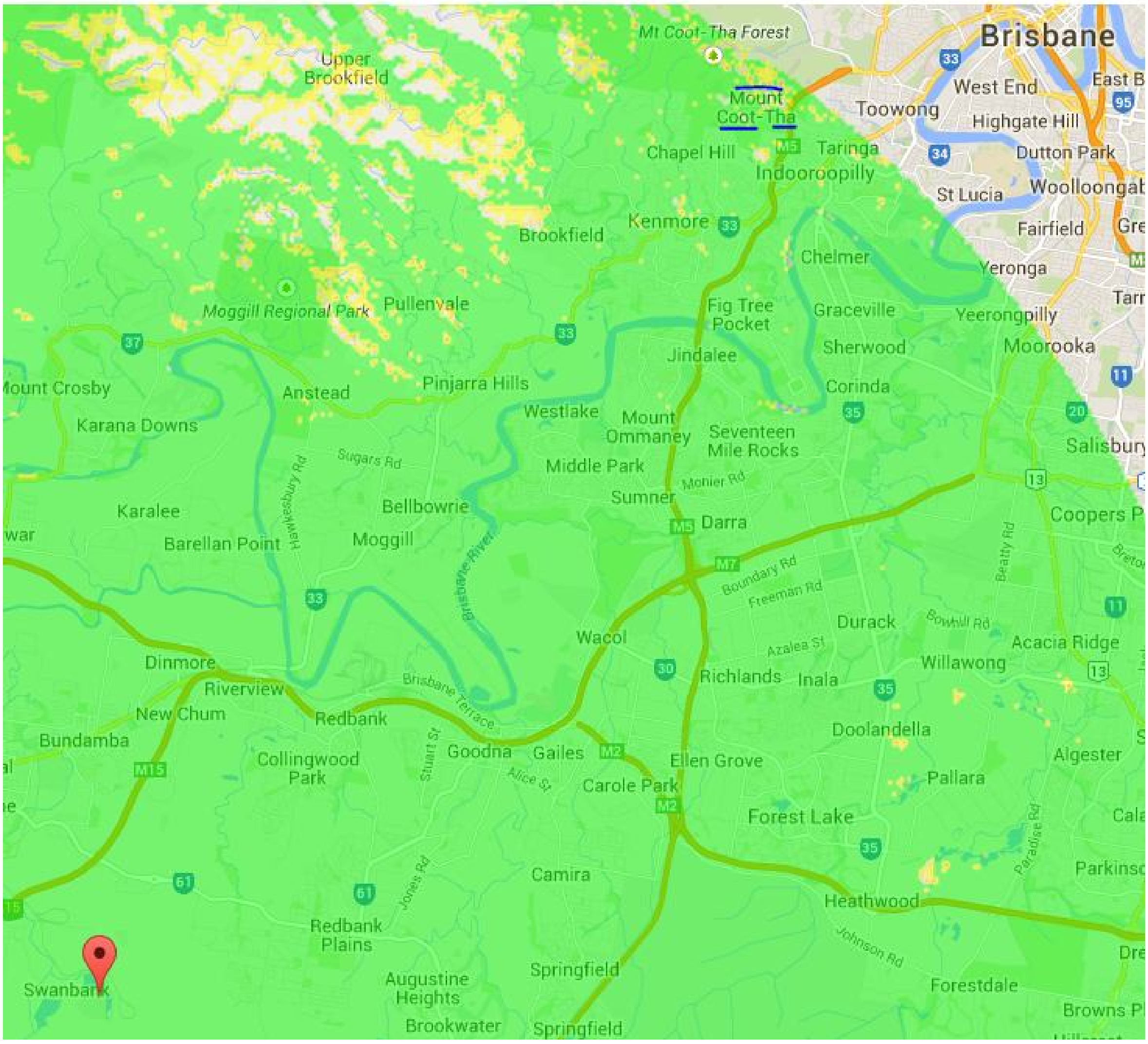


Fig. 7.22 Radio coverage of the locations Mt-Coot-Tha and Swan Bank power station.

7.8 Satellite link budget calculations

From the spread sheet calculations we got the overall link budget as shown below as we know satellite has a RTT round trip time of 480ms as for the purpose of condition monitoring this through put can be useful only for SCADA communications and because we need a latency which should be less than 10ms. By calculating the link budget in a spread sheet we have got a overall link budget. Here the fade margin we have got is 1.37 dB as the margin of error. And it is calculated for an Eb/No =10dB

Overa all link budget	Transmitting side	Reciveing side
Uplink C/No (dB)Hz	78.65	
Downlink C/No (dBHz)		90.14
Over all C/No(dBHz		78.36
Information rate (kbits/s))		5000
Over all Eb/No Required(dB		11.37
Overall Eb/no(dB)		10
MARGIN(dB		1.37

Table 7.2 Overall link budget of the optus satellite c1

8. Conclusions

The research work aimed to develop a communication model that best serves to retrofit a substation into a smart substation. WiMAX is the technology used in this thesis with Microwave and satellite as the backup technologies. On simulating the WiMAX with in different environments the out puts observed are frequency response of the estimated channel at different SNR values. 1.6micro seconds is the latency value which best suits the condition monitoring environment and well below the cut-off value that is 10ms. Even in adverse channel impairment conditions the received spectrum is able to collect the transmitted signal with very less marginal frequency error. The BER curve looks good with when plotted against variable SNR values. The Snr values ranging from 20-25 dB are acceptable. The frequency response curve occupied a large no of OFDM symbols at higher SNR values.Th satellites overall budget was acceptable with 1.37 dB as the fade margin. As a backup technology as the coverage was well and good can be best suited to ensure a network continuity .The radio link can also be used as a backup technology and can also used to send (VOIP) the radio coverage seems to fine even with less amount of transmitting power .ultimately the QOS of the WIMAX technology is best possible smart grid comms for condition monitoring purpose and they are well compatible with IEC61850 protocol. With few limitations. The estimated frequency response never been uniform with the varying SNR values. The different I/Q symbols have different gains that may leads to ICI. From the results the loss of data carriers exist under low SNR values .satellite has a 480ms RTT latency can never serve as a reliable smart grid comms technology and expensive too. The WiMAX serves as a good communication protocol for shorter distances and under limited spectrum values. The demodulator runs well only for small values of time and for a one second the simulation is too slow.

Future works

A hybrid communication infrastructure should be developed for monitoring remote substations. at lower SNR values more no of pilots are to be inserted in order to avoid loss of carriers. Low pass filters can be implemented such that the OFDM symbols are clipped and there is no Doppler spread takes place. Better research should be performed on other 3GPP such as LTE technologies. Wireless MIMO transmissions and other adaptive modulation coding techniques must be implemented. The IEC 61850 standard must me extended such that in future each and every substation should have an IEC 61850 c ompatibility and meet asset management ability. Such that every substation must be smart substation

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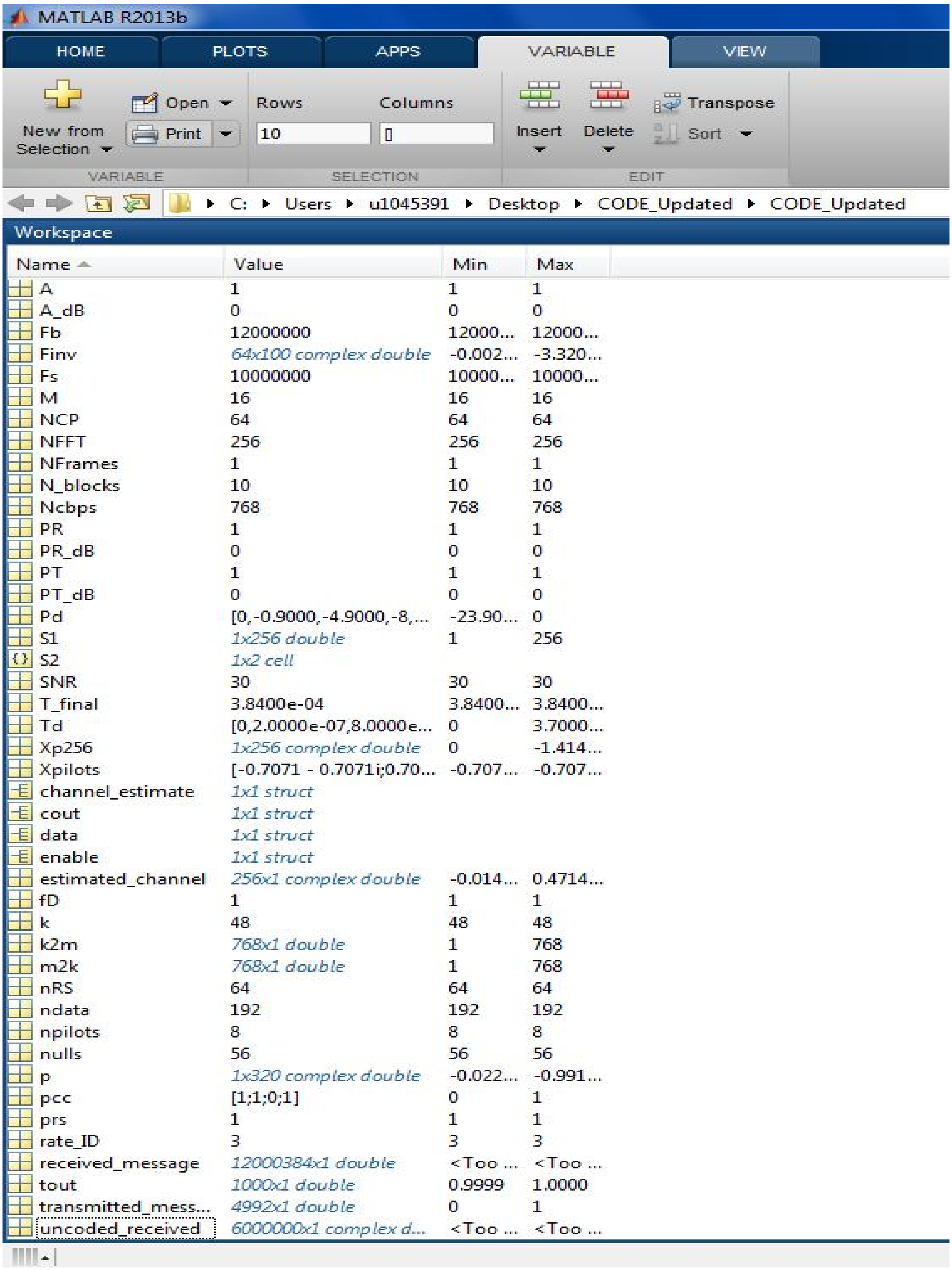
Appendices

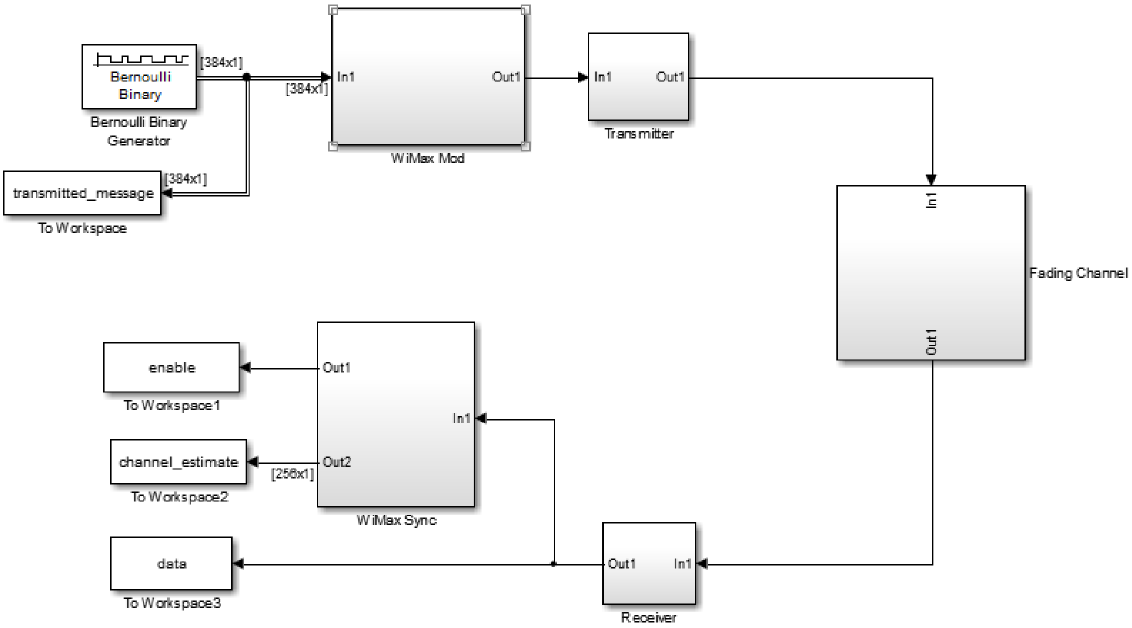
Input data



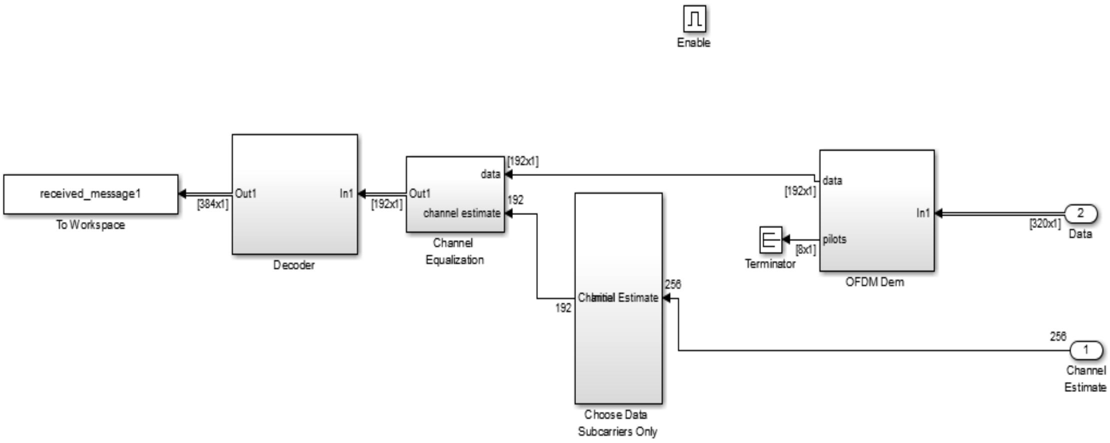
Rows: 10 Columns: []

Name	Value	Min	Max
A	1	1	1
A_dB	0	0	0
Fb	12000000	12000...	12000...
Finv	*64x100 complex double*	-0.002...	-3.320...
Fs	10000000	10000...	10000...
M	16	16	16
NCP	64	64	64
NFFT	256	256	256
NFrames	1	1	1
N_blocks	10	10	10
Ncbps	768	768	768
PR	1	1	1
PR_dB	0	0	0
PT	1	1	1
PT_dB	0	0	0
Pd	[0,-0.9000,-4.9000,-8,...	-23.90...	0
S1	*1x256 double*	1	256
S2	*1x2 cell*		
SNR	30	30	30
T_final	3.8400e-04	3.8400...	3.8400...
Td	[0,2.0000e-07,8.0000e...	0	3.7000...
Xp256	*1x256 complex double*	0	-1.414...
Xpilots	[-0.7071 - 0.7071i;0.70...	-0.707...	-0.707...
channel_estimate	*1x1 struct*		
cout	*1x1 struct*		
data	*1x1 struct*		
enable	*1x1 struct*		
estimated_channel	*256x1 complex double*	-0.014...	0.4714...
fD	1	1	1
k	48	48	48
k2m	*768x1 double*	1	768
m2k	*768x1 double*	1	768
nRS	64	64	64
ndata	192	192	192
npilots	8	8	8
nulls	56	56	56
p	*1x320 complex double*	-0.022...	-0.991...
pcc	[1;1;0;1]	0	1
prs	1	1	1
rate_ID	3	3	3
received_message	*12000384x1 double*	<Too ...	<Too ...
tout	*1000x1 double*	0.9999	1.0000
transmitted_mess...	*4992x1 double*	0	1
uncoded_received	*6000000x1 complex d...*	<Too ...	<Too ...

WIMAX Transmitter Simulink model



WiMAX receiver Simulink model



Matlab script for Coding 512

```
function [M, k, nRS, prs, pcc]=coding512(rate_ID);
% [M, k, nRS, prs, pcc]=coding512(rate_ID)
% M= MQAM modulation
% k=input block size (bytes)
% nRS=RS coded block size (bytes)
% prs=puncturing vector for RS encoder
% pcc=puncturing vector for CC encoder
% rate_ID=index to coding scheme 0-6 as in the standard

% Build structure:
% MQAM Modulation
coding_parameters(1).MQAM=2;
coding_parameters(2).MQAM=4;
coding_parameters(3).MQAM=4;
coding_parameters(4).MQAM=16;
coding_parameters(5).MQAM=16;
coding_parameters(6).MQAM=64;
coding_parameters(7).MQAM=64;

% Input block size (in bytes)
coding_parameters(1).k=12;
coding_parameters(2).k=24;
coding_parameters(3).k=36;
coding_parameters(4).k=48;
coding_parameters(5).k=72;
coding_parameters(6).k=96;
coding_parameters(7).k=108;

% RS coded block size (in bytes)
coding_parameters(1).nRS=24/2;
coding_parameters(2).nRS=48*2/3;
coding_parameters(3).nRS=48*5/6;
coding_parameters(4).nRS=96*2/3;
coding_parameters(5).nRS=96*5/6;
coding_parameters(6).nRS=144*3/4;
coding_parameters(7).nRS=144*5/6;

% RS puncturing vector
coding_parameters(1).prs=-1; % no RS (it needs a switch in the implementation
coding_parameters(2).prs=[ones(1,32),zeros(1,8)];
coding_parameters(3).prs=[ones(1,40),zeros(1,12)];
coding_parameters(4).prs=1;
coding_parameters(5).prs=[ones(1,80),zeros(1,8)];
coding_parameters(6).prs=[ones(1,108),zeros(1,4)];
coding_parameters(7).prs=[ones(1,120),zeros(1,4)];

% CC puncturing vector
coding_parameters(1).pcc=[1,1];
coding_parameters(2).pcc=[1,1,0,1];
coding_parameters(3).pcc=[1,1,0,1,1,0,0,1,1,0];
```

```
coding_parameters(4).pcc=[1,1,0,1];
coding_parameters(5).pcc=[1,1,0,1,1,0,0,1,1,0];
coding_parameters(6).pcc=[1,1,0,1,1,0];
coding_parameters(7).pcc=[1,1,0,1,1,0,0,1,1,0];

% select data for given Rate_ID
i=rate_ID+1;

M=coding_parameters(i).MQAM;
k=coding_parameters(i).k;
nRS=coding_parameters(i).nRS;
prs=coding_parameters(i).prs';
pcc=coding_parameters(i).pcc';

% end
```

Matlab script for Interleave.m

```
function  [k2m, m2k]=interleave(Ncbps)
% [k2m, m2k]=interleave(Ncbps);
% Ncbps = Number coded bits per symbol
% k2m = vector for interleaver (one based)
% m2k = vector for deinterleaver (one based)
%
% Ncbps=log2(M)*(MQAM symbols per OFDM symbol)
%   for NFFT=256, Ncbps=192*log2(M)

k=1:Ncbps;
k2m=(Ncbps/12)*mod(k-1,12)+floor((k-1)/12);  % zero based
k2m=round(k2m+1);  % one based
k2m=k2m';          % row vector

m=1:Ncbps;
m2k=12*(m-1)-(Ncbps-1)*floor(12*(m-1)/Ncbps);  % zero based
m2k=round(m2k+1);  % one based
m2k=m2k';          % row vector
% end
```

OFDM sybols.m

```
function [S1, S2]=ofdm256symbol
% [S1, S2]=ofdm256symbol
% S1, S2 are matrices of indeces ("1" based) defined as follows:
%
% let DPN=[data, pilots, null] be a 256x1 vector
% then:
% OFDM512symbol=DPN(S1);
% {data, pilots}=OFDM256symbol(S2);


% from the standard (all indeces zero based, starting with "0" for DC):
NFFT=256;
NCP=64;   % this works with NCP=64 only
```

```
dp=[1:100, 156:255];                % data and pilots subcarriers
p=[13 38 63 88 168 193 218 243];    % pilot subcarriers

n=[0, 151:155];                     % nulls subcarriers
n_pilots=length(p);                 % number of pilots subcarriers
n_data=length(dp)-length(p);        % number of data subcarriers
n_nulls=NFFT-n_pilots-n_data;        % number of null subcarriers

% Construct the vector S:
% S(i)=1 for data
% S(i)=0 for nulls
% S(i)=-1 for pilots

S=zeros(1,256);
S(dp+1)=1;
S(p+1)=-1;
S(n+1)=0;

% construct vector S1
Id=find(S==1); % indeces for data only
S1(Id)=1:n_data;

Ip=find(S==-1); % indeces for pilots only
S1(Ip)=n_data+(1:n_pilots);

In=find(S==0);
S1(In)=n_data+n_pilots+(1:n_nulls);

% construct structure S2
S2d=Id;
S2p=Ip;

S2={S2d, S2p};

% OTHER STUFF:
% n=0:NCP-1;       % vector of time indeces
% F=exp((-j*2*pi/NFFT)*k'*n);
% % [U,S,V]=svd(F,'econ');             % singular with 55 dominant singular
values (ONLY NCP=64)
% % s0=diag(S);
% % Finv=V(:,1:55)*diag(1./s0(1:55))*U(:,1:55)';
% Finv=inv(F'*F)*F';
% end
```

Preamble .m

```
unction [Xp256, p, Finv]=preamble(NCP)
% Generate Preamble for WiMax
% [Xp256, p]=preamble3(NCP)
```

```
P_ALL_p=sign(randn(1,100))+j*sign(randn(1,100));   % it needs to be replaced with values from standard
P_ALL_n=sign(randn(1,100))+j*sign(randn(1,100));   % it needs to be replaced with values from standard
P_ALL=[0,P_ALL_p,zeros(1,55),P_ALL_n];


I=1:128;
P_EVEN=zeros(1,256);
P_ODD=zeros(1,256);
P_EVEN(2*I-1)=P_ALL(2*I-1);
P_ODD(2*I)=P_ALL(2*I);

Xp256=sqrt(2)*P_EVEN;
xp=ifft(Xp256);
xp=xp*sqrt(256);        % same normalization as in the OFDM mod


% whole preamble with cyclic prefix
p=[xp(193:256),xp];

% Construct matrix Finv to estimate channel impulse response
k=[1:50, 78:127];  % vector of frequencies
n=0:NCP-1;       % vector of time indeces
F=exp((-j*2*pi/128)*k'*n);
Finv=inv(F'*F+0.0001*eye(NCP))*F';
% end
```

Matlab script for Demodulator.m

```
% end
function [estimated_channel, data]=to_demodulator(enable, channel_estimate, data)
e=squeeze(enable.signals.values);
I=find(e==1);
start=min(I);
N=length(channel_estimate.time);
estimated_channel=channel_estimate.signals.values(:,1,start);
data.time=data.time(1:N-start+321);
data.signals.values=data.signals.values(:,:,start-320:N);
```

matlab script for WiMAX 256 parameters

```
unction [NFFT, NCP, ndata, npilots, nulls, Xpilots]=WiMax256parameters
% [NFFT, NCP, ndata, npilots, nulls]=WiMax512parameters

% 256 WiMax
% FFT Size
NFFT=256;
% Ciclic Prefix
NCP=64;

% data, pilots, nulls to OFDM symbol
ndata=192;
```

```
npilots=8;
nulls=56;
% pilots
Xpilots=sign(randn(npilots,1))+j*sign(randn(npilots,1));
Xpilots=Xpilots/sqrt(2);      % normalize to unit power
% end
```

Matlab script for estimating BER Vs SNR and frequency response at various SNR values.

```
clc;
clear all;
close all;
warning off;

load('Input_Data.mat')

% SNR_ln=length(SNR_db);
% h = waitbar(0,'Please wait for Processing...');
% for ij=1:SNR_ln
%% SNR=0
SNR=0;figure;
sim('WiMax_transmitter');
Txd_Data=transmitted_message;
sim('WiMax_demodulator');
Rcvd_Data=received_message;
[bErr,rat(1)]=biterr(Txd_Data,Rcvd_Data);
BErr1=bErr/length(Rcvd_Data);
save BErr1
% waitbar(ij/SNR_ln,h)
% end
%% SNR=0
SNR=5;figure;
sim('WiMax_transmitter');
Txd_Data=transmitted_message;
sim('WiMax_demodulator');
Rcvd_Data=received_message;
[bErr,rat(2)]=biterr(Txd_Data,Rcvd_Data);
BErr2=bErr/length(Rcvd_Data);
save BErr2
%% SNR=0
SNR=10;figure;
sim('WiMax_transmitter');
Txd_Data=transmitted_message;
sim('WiMax_demodulator');
Rcvd_Data=received_message;
[bErr,rat(3)]=biterr(Txd_Data,Rcvd_Data);
BErr3=bErr/length(Rcvd_Data);
save BErr3
%% SNR=0
SNR=15;figure;
sim('WiMax_transmitter');
Txd_Data=transmitted_message;
sim('WiMax_demodulator');
Rcvd_Data=received_message;
[bErr,rat(4)]=biterr(Txd_Data,Rcvd_Data);
```

```
BErr4=bErr/length(Rcvd_Data);
save BErr4
%% SNR=0
SNR=20;figure;
sim('WiMax_transmitter');
Txd_Data=transmitted_message;
sim('WiMax_demodulator');
Rcvd_Data=received_message;
[bErr,rat(5)]=biterr(Txd_Data,Rcvd_Data);
BErr5=bErr/length(Rcvd_Data);
save BErr5
%% SNR=0
SNR=25;figure;
sim('WiMax_transmitter');
Txd_Data=transmitted_message;
sim('WiMax_demodulator');
Rcvd_Data=received_message;
[bErr,rat(6)]=biterr(Txd_Data,Rcvd_Data);
BErr6=bErr/length(Rcvd_Data);
save BErr6
%% SNR=0
SNR=30;figure;
sim('WiMax_transmitter');
Txd_Data=transmitted_message;
sim('WiMax_demodulator');
Rcvd_Data=received_message;
[bErr,rat(7)]=biterr(Txd_Data,Rcvd_Data);
BErr7=bErr/length(Rcvd_Data);
save BErr7
%% SNR=0
SNR=35;figure;
sim('WiMax_transmitter');
Txd_Data=transmitted_message;
sim('WiMax_demodulator');
Rcvd_Data=received_message;
[bErr,rat(8)]=biterr(Txd_Data,Rcvd_Data);
BErr8=bErr/length(Rcvd_Data);
save BErr8

load('BErr1.mat')
BErr(1)=BErr1;
load('BErr2.mat')
BErr(2)=BErr2;
load('BErr3.mat')
BErr(3)=BErr3;
load('BErr4.mat')
BErr(4)=BErr4;
load('BErr5.mat')
BErr(5)=BErr5;
load('BErr6.mat')
BErr(6)=BErr6;
load('BErr7.mat')
BErr(7)=BErr7;
load('BErr8.mat')
BErr(8)=BErr8;
Bit_Err=sort(BErr,'descend');
SNR_db=0:5:35;
```

```
BERtheory = berfading(SNR_db,'qam',M,4);
figure;
semilogy(SNR_db,Bit_Err,'-*r','LineWidth',2);
semilogy(SNR_db,BERtheory,'-*r','linewidth',2,'markerfacecolor','w');
xlabel('SNR');ylabel('BER');
grid on
title('BER vs SNR Plot');
```