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Title:

Wide-Area Network State Monitoring System Based On LoRa Communication.

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Abstract

To meet the requirements of long range, small amount of data transmission, better data correctness and less delay, a wide-Area Network State Monitoring System approach based on LoRa communication is discussed in our Project. The objective is to study and test the performance of Two communication techniques used in wide area monitoring system, a single input single output (SISO) system and a multiple input multiple output system (MIMO) in terms of Bit Error Rate (BER) with varying the signal to noise Ratio (SNR). In addition, we study the Wide Area Monitoring system based on LoRa communication. The IEEE 14-bus power system with Phasor Measurement Units (PMUs) placed at selected buses is considered. The simulation results demonstrate that the MIMO system overtake the SISO system for better Bit Error Rate. Furthermore, the value of the reporting rate has been varied for both systems in MATLAB to see the effect on the data correctness and the results show that the Bit Error Rate value decreases with the increase of reporting rate. Finally, we dealt with a modified LoRa MATLAB code emulator to investigate the data error and delay. The results show that LoRa Technology has better performance in terms of delay and error.

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Abbreviations

SCADA	Supervisory Control and Data Acquisition.
DG	Distributed Generation.
AMI	Advanced Metering Infrastructure.
DA	Distribution Automation.
ABB	Asea Brown Boveri.
DSM	Demand Side Management.
WASGM	The Wide Area Smart Grid Model Architecture.
REG	Renewable Energy Generation.
GPS	Global Positioning System.
WAS	Wide Area System.
SG	Smart Grid.
PMU	Phasor Measurement Unit.
PDC	Phasor Data Concentrator.
W.A.M.	Wide Area Measurement.
WAMS	Wide Area Measurement System.
RTU	Remote Terminal Unit.
PLC	Programmable Logic Controller.
ICT	Information Communication Technology.
HMI	Human Machine Interface.
MTU	Mater Terminal Unit.
SPMS	Synchronized Phasor Measurement System.
AC	Alternating Current.
SMT	Synchronized Measurement Technology.
IEEE	the Institute of Electrical and Electronics Engineers.
WAM	Wide Area Monitoring.
A.T.M.	Asynchronous Transfer Mode.

P.L.C.	Power Line Communication.
G.P.R.S.	General Packet Radio Service.
L.V.	Low Voltage.
G.S.M.	Global System for Mobiles.
SISO	Single Input Single Output.
MIMO	Multiple Input Multiple Output.
BER	Bit Error Rate.
SNR	Signal to Noise Ratio.
OFDM	Orthogonal Frequency Division Multiplexing.
ADWGN	Additive White Gaussian Noise.
ICI	Inter-carrier Interference.
UE	User Equipment.
LTE	Long Term Evolution.
MAC	Medium Access Control.
PDSCH	Physical Downlink Shared Channel.
IoT	Internet of Things.
LoRa	Long Range.
LPWAN.	Low Power Wide Area Network.
NB	Narrow Band.
EMS	Energy Management Systems.
SINR	Signal to Interference plus Noise Ratio.
CSS	Chirp Spread Spectrum.
ISM	industrial, scientific, and medical netowrk.
VSWR	the active Voltage Standing Wave Ratio.

Symbols

SNR_m	The Signal to Noise Ratio of the m^{th} subcarrier.
eNodeB	E-UTRAN NodeB (the evolution of the element Node B in UTRA)
Mbps	megabits per second.

kbps	kilobits per second.
mA	Milliampere.
uA	Microampere.
m	meter.

General introduction:

Power system is becoming more and more complex, mainly due to the increase of new technologies and the demand of using clean energy. Wide-area monitoring, wide-area control and wide-area protection utilize Wide Area Networks and turn out to be the next-generation key to improve power system planning, the modern power grid is considered to be the most complex human-made system, which is monitored by wide-area monitoring system. Providing time-synchronized data of power system operating states, wide-area monitoring system will play a crucial role in next generation smart grid protection and control. wide-area monitoring system helps secure efficient energy transmission as well as reliable and optimal grid management. As the key enabler of a smart grid, numerous sensors such as PMU and current sensors transmit real-time dynamic data, which is usually protected by encryption algorithm from malicious attacks, over wide-area-network to power system control centers so that monitoring and control of the whole system is possible [1].

Nowadays high data rate techniques have gained considerable interests in communication systems. Electric grid was designed to operate as a vertical structure consisting of generation, transmission, and distribution and supported with controls and devices to maintain reliability, stability, and efficiency. However, system operators are now facing new challenges including the penetration of Renewable Energy Resource in the legacy system, rapid technological change, and different types of market players and end users. The next iteration, the smart grid, will be equipped with communication support schemes and real-time measurement techniques to enhance resiliency and forecasting as well as to protect against internal and external threats. The design framework of the smart grid is based upon unbundling and restructuring the power sector and optimizing its assets [2].

The need to meet the requirement for better data correctness and small amount of data with less possible delay in communication flow and for enhancing the data transfer in Wide Area Monitoring system based on different technologies and driven by the demand for increasingly sophisticated connectivity anytime, anywhere, Spatial diversity techniques like SISO and MIMO communication systems has emerged as one of the largest and most rapidly growing sectors of the global telecommunications industry.

New communication technology has been applied for embedded wireless communication that enables long-distance, long battery life, large system capacity and low hardware costs to meet the IoT needs ,LoRa is presented and can be regarded as physical layer technology which uses a linear modulated chirp pulse to spread the data waveform over the communication frequency channel. For LoRa communication the resulting signal has low noise levels, enabling high interference.In addition, it has very high energy efficiency and low price.

The aim of our project is to use different communication technologies to ameliorate data transfer in terms of data completeness and correctness in Wide Area Monitoring system by using the software MATLAB for the simulation. We started by two spatial diversity techniques which are SISO and MIMO systems after that we mainly studied the transmitted and the received signal of the IEEE-14 bus standard power system based on LoRa emulator code on MATLAB.

This study is divided into three main chapters:

-Chapter one provides general introduction to Smart Grid, including Definition of the smart Grid and Comparison of Today's grid with Smart Grid, different technologies for wide area system (Measurements, Monitoring, Communication).

-Chapter two deals with a Simulation in MATLAB software for a modified Communication System for the different transmission techniques that give data correctness for different values of Signal to Noise Ratio.

-Chapter three illustrates the main obtained simulation results for Bit Error Rate in different communication techniques in wide area monitoring system for the IEEE 14-bus power system and compare between transmitted signal and received signal in terms of the error and delay based on LoRa emulator code.

CHAPTER 1

Smart Grid

- *Introduction*
- *Definition*
- *Comparison of Today's Grid with Smart Grid*
- *The Wide Area Smart Grid Model Architecture (WASGM)*
- *Wide Area Measurement Technology*
- *Wide Area Monitoring*
- *Communication Network in Wide Area*
- *Conclusion*

1.1. Introduction:

Because of its broad scope, Smart Grid means different things to different people.

The traditional power grid consists of power plants that generate bulk electric power. Transmission substations collocated at generation plants step up the voltage levels for high-voltage transmission lines which carry electric power over long distances with high efficiency. A transmission system of transmission substations and transmission lines is deployed to carry power closer to the consumers. Before the power is delivered to the consumers, voltage levels are reduced (stepped down) at distribution substations. These distribution substations transfer power to the consumers over feeders (also called distribution lines). A simplified illustration of a traditional power grid is shown in Fig. 1.1.

The high-level architecture of today's electric grids looks much the same as when this one-way electric power delivery system was developed and deployed at the end of the nineteenth century. Communication network technology introduced in the latter part of the twentieth century supported the deployment of Supervisory Control and Data Acquisition (SCADA) systems. These SCADA systems allowed operations personnel to remotely monitor and control transmission and distribution substation equipment from utility operations centers, enhancing operational efficiency. In addition, communication networks found use in the remote support of automated circuit breakers known as teleprotection systems.

The need for clean energy with large-scale deployment of renewable sources of energy, peak power reduction for environmental and economic reasons, grid modernization, and consumer participation in energy management are some of the motivations for the development of the Smart Grid. While Smart Grid is a natural evolution of the electric power grid, the process has experienced a sense of urgency within the last decade.

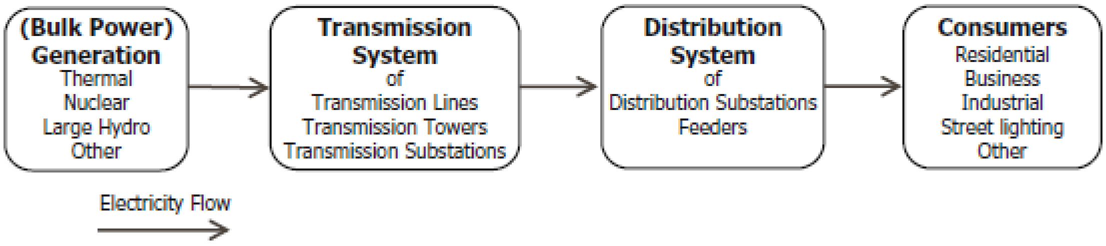

Fig. 1.1. A simple schematic of traditional electric power grid.

As the Smart Grid evolution continues, a large number of new grid elements and functions will be integrated into the grid. Examples include the following:

1. Renewable and other alternate sources of energy will be deployed throughout the grid. When deployed at sufficiently high densities, these distributed generation (DG) sources can significantly alter the flow of power in the electric grid, stressing legacy components and controls designed primarily to support the one-way flow of energy from bulk power producers to consumers.
2. Advanced Metering Infrastructure (AMI), also known as “smart meters,” will be deployed at consumer locations. In addition to measuring consumption, smart meters measure voltages, power, reactive power, and other quantities.
3. SCADA connectivity will be extended beyond substations to support the monitoring and control of reclosers, capacitor banks, and other elements in the distribution grid, a functionality known as distribution automation (DA).
4. New measurement devices (called synchrophasors) will be deployed throughout the transmission grid. These devices measure the real-time flow of power and are useful in the control of power flowing across the transmission grid, including power flowing across national boundaries.

A large number of new grid operations and functions will also be developed –most requiring communication with the new grid elements as well as with the existing SCADA and other application endpoints. Communication networks used to support these functions will be expanded, modernized, and integrated as the Smart Grid evolves. The “intelligence” of the Smart Grid relies upon the real time exchange of measurement and control data among a vast web of devices installed in homes and businesses; within the distribution and transmission grids, at substations, control centers, and generation stations, and other facilities. Thus, a high-performance, reliable, secure, and scalable communication network is an integral part of the Smart Grid evolution [3].

1.2. Definition:

Smart Grid concept has been vision/initiated by different organizations and authors. Likewise, development of an acceptable definition of the Smart Grid has been attempted by different organizations and authors. In general, two different approaches have been adopted to define the Smart Grid. It is defined based on either (i) identifying the advantages offered by the grid (solution prospective) or (ii) what components the grid is consisted of (components' prospective) [5]. However, Asea Brown Boveri Ltd (ABB), in an internal white paper, based the definition of the Smart Grid on **its capabilities and operational characteristics** rather than the use of any particular technology. They took the view that deployment of Smart Grid technologies will occur over a long period of time, adding successive layers of functionality and capability onto existing equipment and systems. ABB argued that although technology is the key, it is only a means to an end; therefore, the Smart Grid can and should be defined by broader characteristics [4].

A selection of definitions for the Smart Grid reported in literature is given in the Table below:

Table. 1.1 : Selected Smart Grid Definitions [5].

Organization/ author	Grid/ concept	Definition
Climate Group (2008)	Smart Grid	A "smart grid" is a set of software and hardware tools that enable generators to route power more efficiently, reducing the need for excess capacity and allowing two-way, real time information exchange with their customers for real time demand side management (DSM). It improves efficiency, energy monitoring and data capture across the power generation and T&D network.
Adam and Wintersteller (2008)	Smart Grid	A smart grid would employ digital technology to optimise energy usage, better incorporate intermittent "green" sources of energy, and involve customers through smart metering.

Miller (2008)	Smart Grid	The Smart Grid will: Enable active participation by consumers Accommodate all generation and storage options Enable new products, services and markets Provide power quality for the digital economy Optimise asset utilisation and operate efficiently Anticipate and respond to system disturbances (self-heal) Operate resiliently against attack and natural disaster
Franz *et al.*, (2006)	eEnergy	Convergence of the electricity system with ICT technologies
EPRI (2005)	Intelli-Grid	The IntelliGrid vision links electricity with communications and computer control to create a highly automated, responsive and resilient power delivery system.
DOE (2003)	Grid 2030	Grid 2030 is a fully automated power delivery network that monitors and controls every customer and node, ensuring a two-way flow of electricity and information between the power plant and the appliance, and all points in between. Its distributed intelligence, coupled with broadband communications and automated control systems, enables real-time market transactions and seamless interfaces among people, buildings, industrial plants, generation facilities, and the electric networks.

From a solution perspective, the smart grid is characterised by:

- More efficient energy routing and thus an optimised energy usage, a reduction of the need for excess capacity and increased power quality and security.
- Better monitoring and control of energy and grid components.
- Improved data capture and thus an improved outage management.
- Two-way flow of electricity and real-time information allowing for the incorporation of green energy sources, demand-side management and real-time market transactions.
- Highly automated, responsive and self-healing energy network with seamless interfaces between all parts of the grid.

From a technical components' perspective, the smart grid is a highly complex combination and integration of multiple digital and non-digital technologies and systems. Fig.1.2 provides an overview of the main component of a smart grid: *i)* new and advanced grid components, *ii)* smart devices and smart metering, *iii)* integrated communication technologies, *iv)* programmes for decision support and human interfaces, *v)* advanced control systems. These individual grids do not need to be centralised, but can have more control stations and be more highly integrated. The integration of many grids including country-spanning ones provides economic advantages, but there are challenges regarding security if they become too centralised and interconnected.

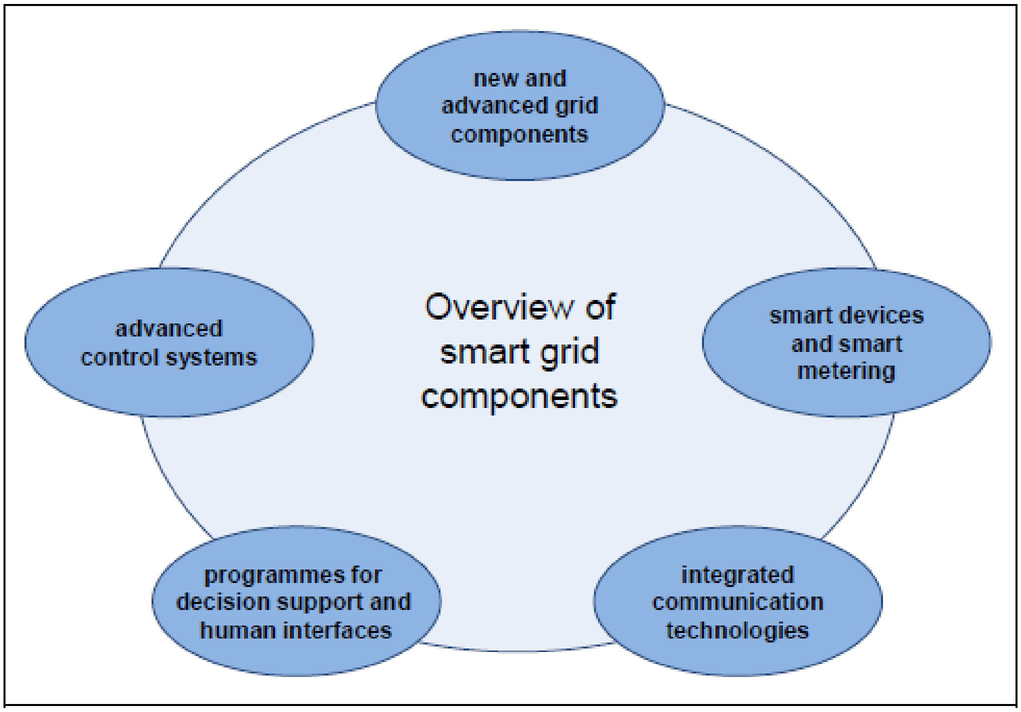

Fig. 1.2: Main components of a smart grid.

1.3. Comparison of Today’s grid with Smart Grid:

Many differences exist between today’s grid with the preferred characteristics of the smart grid; these differences are represented briefly in the table 1.2:

Table 1.2 : Comparison of Today's grid with Smart Grid [6].

Preferred Characteristics	Today’s Grid	Smart Grid
Active Consumer Participation	Consumers are uninformed and do not participate	Informed, involved consumers — demand response and distributed energy resources
Accommodation of all generation and storage options.	Dominated by central generation — many obstacles exist for distributed energy resources interconnection	Many distributed energy resources with plug - and – play convenience focus on renewables
New products, services, and markets	Limited, poorly integrated wholesale markets; limited opportunities for consumers	Mature, well - integrated wholesale markets; growth of new electricity markets for consumers
Provision of power quality for the digital economy	Focus on outages — slow response to power quality issues	Power quality a priority with a variety of quality/price options — rapid resolution of issues
Optimization of assets and operates efficiently	Little integration of operational data with asset management— business process silos	Greatly expanded data acquisition of grid parameters; focus on prevention, minimizing impact to consumers
Anticipating responses to system disturbances (self- healing)	Responds to prevent further damage; focus on protecting assets following a fault	Automatically detects and responds to problems; focus on prevention, minimizing impact to consumers
Resiliency against cyber attack and natural disasters	Vulnerable to malicious acts of terror and natural disasters; slow response	Resilient to cyber attack and natural disasters; rapid restoration capabilities

1.4 The Wide Area Smart Grid Model Architecture (WASGM):

The WASGM is an advanced electrical network with substantially enhanced communication and control features than the conventional WAS [7]. The WASGM consists of generating units, wide transmission network, wide distribution system, and Renewable Energy Generation (REG) that are inter-lined together through fast communication infrastructure [7]. The synchronized measurements are performed by the GPS at each substation of the SG through satellite data communications [8]. The basic distinguishing features of the conventional WAS and WASGM are summarized in Table 1.3.

Table 1.3 : Distinguishing features of conventional WAS and WASGM.

Conventional Was	WASGM
Centralized control	Distributed control
One-Way communication	Bi-directional communication
No consumer interactions and contentment	Consumer satisfaction and full-time Participation
Slow electro-mechanical systems	Fast digital systems
Manual monitoring and control	Self-monitoring and intelligent control
Low reliability	High reliability
No Demand Response programs (DRP_s)	DRP oriented infrastructure
Unpredictable outages and blackouts	Islanding and self-healing
Low Quality of Service (QoS)	High QoS
Low grid security	High level of smart security
Generation from primary Resources (PRs)	Generation from PRs and REG
Limited sensor oriented control	Adaptive control with sensors throughout
No Grid to Vehide $(G2V)$/Vehicle to Grid $(V2G)$ mechanism	Real-time G2V/V2G system

Fig. 1.3 depicts the WASGM architecture consisting of various areas, namely: residential, industrial, commercial, schools, airport, train station, park, food market, REG system, G2V/V2G mechanism, and data center computational hub. In the WASGM architecture, the PMUs, PDCs, and Super PDC, all integrated together for information exchange through the fast communication medium.

The WASGM is illustrated in Fig. 1.3. An intelligent system and stabilized control plays a pivotal role for achieving the high standards of monitoring and control [9]. Demand and supply balance is essential for the stability of the WASs [10]. The utility load changes substantially with the load growth that requires a wide adjustment of the controlling parameters [10]. The power market concept has brought a new era in the life of the WASGM [11]. Today the consumers are looking for more secure and reliable energy supplies [12].

By using the SG network and the demand response platform, consumers are allowed to choose energy supply from any of the supplying agencies within the deregulated market [13-14]. The control of the SG network in terms of secure and reliable operations involves the design of a complex infrastructure [15-16]. Due to the stabilized control structure, the faults and disturbances are detected and controlled through the advance monitoring devices.

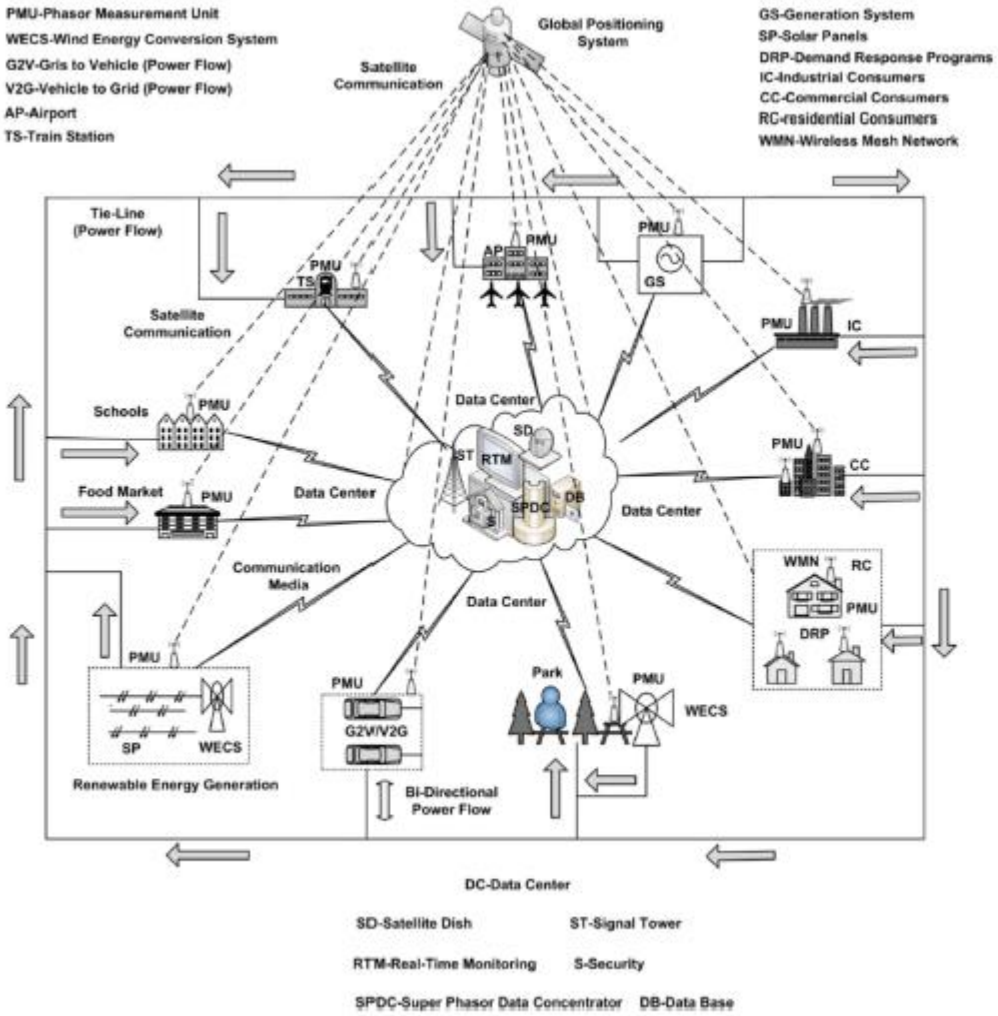

Fig. 1.3 The Wide Area Smart Grid Model (WASGM).

1.5. Wide Area Measurement Technology:

Wide Area Measurement system is an advanced measurement technology which consists of advanced information tools, operational infrastructure which facilitates the operation of the complex network by collecting Data [17]. It provides complete monitoring, control and protection. In this section the chief components of the Wide Area System are explained. PMU is an enabler of W.A.M.s, which prevents the power network from any blackout. The SCADA, PMU, PDC, etc are explained. The picture of the W.A.M. is shown in Fig. 1.4 and the components are described. Some of the Applications of WAMS are Detection of Loss in Synchronism, Temperature identification, Power System restoration.

Fig. 1.4 Picture of Wide Area Measurement System.

1.5.1 SCADA

The abbreviation for SCADA is Supervisory Control and Data Acquisition. It is an automation and control system based on Computers. The supervisory control emerged to operate and control from remote location. The control system is combined with data acquisition systems. The main functions of the SCADA are Monitoring, Data Presentation, Data Acquisition, Supervisory Control, Alarm display. It consists of both hardware and software [18]. The main components of SCADA are Remote Terminal Units (RTU), Programmable Logic Controller (PLC), Telemetry system, Data Acquisition Server, Human Machine Interface (HMI). The computer gathers data and the signal are sent to the control unit. The Sensors are either analog or digital and are interfaced with the system. These are incapable of providing the dynamic state of the power system. The data received are also not time synchronized. The information provided by SCADA is steady, low sampling density and non-synchronous. The dynamic state of the system is not provided so that immediate action cannot be taken in case of failure. The block diagram of SCADA is shown in Fig. 1.5 The Mater Terminal Unit is the main part of the SCADA system which is the server, All the communications, data from RTU are managed and stored, commands and interfacing with the operators are managed by the MTU.

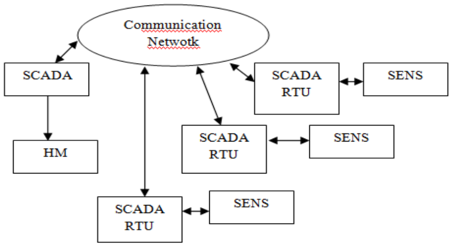

Fig. 1.5 Block Diagram of SCADA.

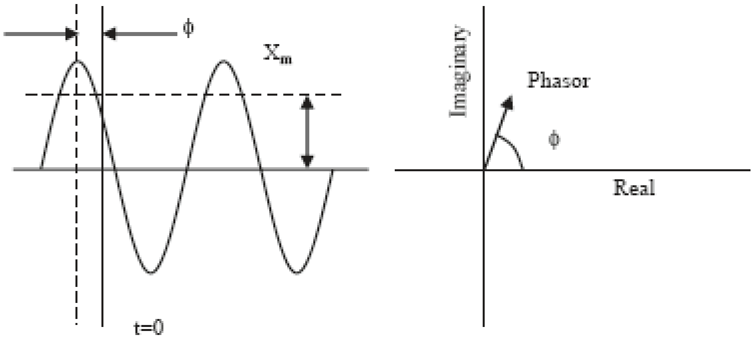

Fig. 1.6 Phasor Representation of Sinusoidal waveform.

1.5.2 Synchronized Phasor Measurement System (SPMS)

The Synchronized Phasor Measurement Unit was firstly developed in mid-1980’s. It measures the phasor of voltage, current and the local frequency and its rate of changes. This SMPS consists of three main parts namely Phasor Measurement Unit, Phasor Data Concentrator, and Communication system. The following section deals with PMU and PDC.

1.5.2.1 Phasor Measurement Unit

Phasor Measurement Unit is an enabler of WAMS. It is a device which measures the phasor of the current and voltage of the connected bus. This was developed in mid-1980s. It makes use of the GPS receiver to collect the data from the buses located at various places. The collected data are sent to the control unit through the Phasor Data Concentrator. The PMU’s provide time synchronized data and high resolution for a Wide Area Monitoring. By analog to digital converter the data samples are taken from the AC waveform and Discrete Fourier Transform is applied. The phasor representation of the voltage signals of two buses is depicted in Fig. 1.6 The PDC gathers the data from several PMU and rejects the bad data and aligns the time stamps, with respect to the common reference axis the voltages of different buses are compared and are monitored. The PMU is a microprocessor-based device using the ability of the Digital Signal processors, which measures

50/60 HZ AC waveforms at a typical rate of 48-60 samples per cycle [19]. These PMUs are optimally placed at different substations which provide time stamped positive sequence voltages and currents of all the monitored buses. For the full benefit of the SynchroPhasor Measurement the architecture involves PMUs, communication links, Phasor Data Concentrator. The block diagram of PMU is shown in Fig. 1.7 which comprises of Anti-aliasing Filter, Analog to Digital Converter, Phasor Microprocessor, Phase Locked Oscillator, Modem and the GPS [20]. The commercialization of the GPS with accuracy of timing pulses in the order of 1 micro second is made possible by many industries. By using this, high degree of accuracy is achieved. The analog input signals with respect to the voltage and current are received from the instrument transformer.

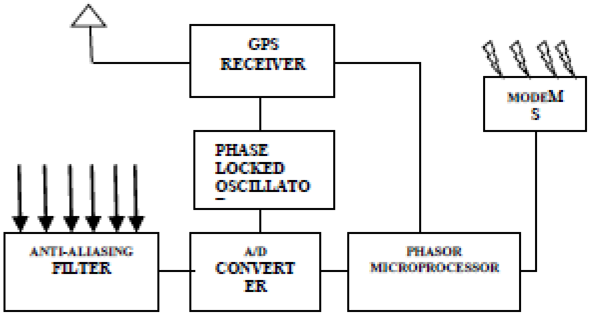

Fig. 1.7 Block Diagram of PMU

1.6. Wide Area Monitoring:

WAM collects measurements from remote locations across the power system and combines them in real time into a single snapshot of the power system for a given time. Synchronized measurement technology (SMT) is an essential component of WAM, as it allows the measurements to be accurately time stamped, primarily using timing signals from GPS. These time stamps allow the measurement to be combined easily and phase angle measurements to be made using a common reference.

PMUs were developed in the early 1980s [21] and are the most widely used form of synchronized measurement technology. PMUs measure voltage and current phasors at a rate of once per cycle and the IEEE C37.118 standard describes a required level of measurement performance [22] and a communication protocol [23] for these measurements. It is worth noting that this standard provides the option to include analogue and digital values into the measurement streams. This allows binary status signals and waveform measurements to be streamed using the protocol.

The architecture of a WAMS can be highly complex and [24, 25] provides several examples of how to design a WAMS. The latency, jitter and reliability of the communication network in a WAMS is a vital aspect of ensuring that the WAMS is suitable for supporting protection functions. The communication network must be able to ensure that the measurements supplied by the WAMS to the protection functions are received not only quickly but arrive reliably and with consistent delays to ensure that the quality of the protection is sufficient.

1.7. Communication Network in Wide Area:

According to the status of the development of wide area communications choice of fiber as a medium and the communication network in which the SDH0 carries A.T.M. can meet the communication requirements of W.A.P.S... Different communications technologies supported by two main communications media, that it’s wired and wireless can be used for data transmission between smart meters and electric utilities.

In some distance, wireless communications have some advantages over wired technology such that low cost infrastructure and connection to difficult or unreachable areas. However the nature of the transmission path may cause the signal to reduce. On the other hand wire solutions do not have interruption problems and their function is not depending on batteries as well as wireless solutions often do.

Basically two types of data infrastructure are needed for dataflow in a smart-power-grid system. The first flow is from sensor and electrical appliances to smart meters and the second is between smart meters and the utility’s data centers. Suggested in the first data flow can be accomplished through power line communication or wireless communications such that Zig Bee, 6LowPAN, Z-wave, and others [26, 27]. For a second data flow cellular technologies or in the Internet can be used. Not other than there is key limiting factors that should be taken into account in the smart metering spread out process, such that time of deployment, operational costs and the availability of the technology and rural or urban or indoor/outdoor environment etc. This technology select that fits one environment may not be suitable for the other. Currently when the most electric power companies construct or reconstruct the power private communication networks the A.T.M. modes approved. And communication media is mainly optical fiber which lays material foundation for W.A.P.S... Power line communication (P.L.C.) is a technique that uses the existing power lines to transmit high speed (2–3 Mb/s) data signals from one device to other. The P.L.C. has been the first choice for communication with the electricity meter due to direct connection with the meter and successful execution of A.M.I. in urban areas where other solutions struggle to meet the needs of utilities. P.L.C. systems based on the L.V. distribution network have one of the research topics for smart-power-grid applications in China. In the typical P.L.C. network smart meters are connected to the data concentrator through power lines and data is transferred to the data center through cellular network technologies. Example any electrical device such that a power line smart transceiver based meter can be connected to the power line and used to transmit the metering data to central location. France has launched the "Lanky meter project" that includes updating 36 million meters to Lanky smart meters P.L.C [28].

Technology is chosen for data communication between the smart meters and the data concentrator while G.P.R.S. technology is used for transferring the data from data concentrator to the utility's data center. P.L.C. technology to transfer smart meter data to nearest data concentrator and G.S.M. technology to send the data to data centers the Italian electric utility.

An illustration of architecture of the Smart Grid communication network is shown in Fig 1.8.

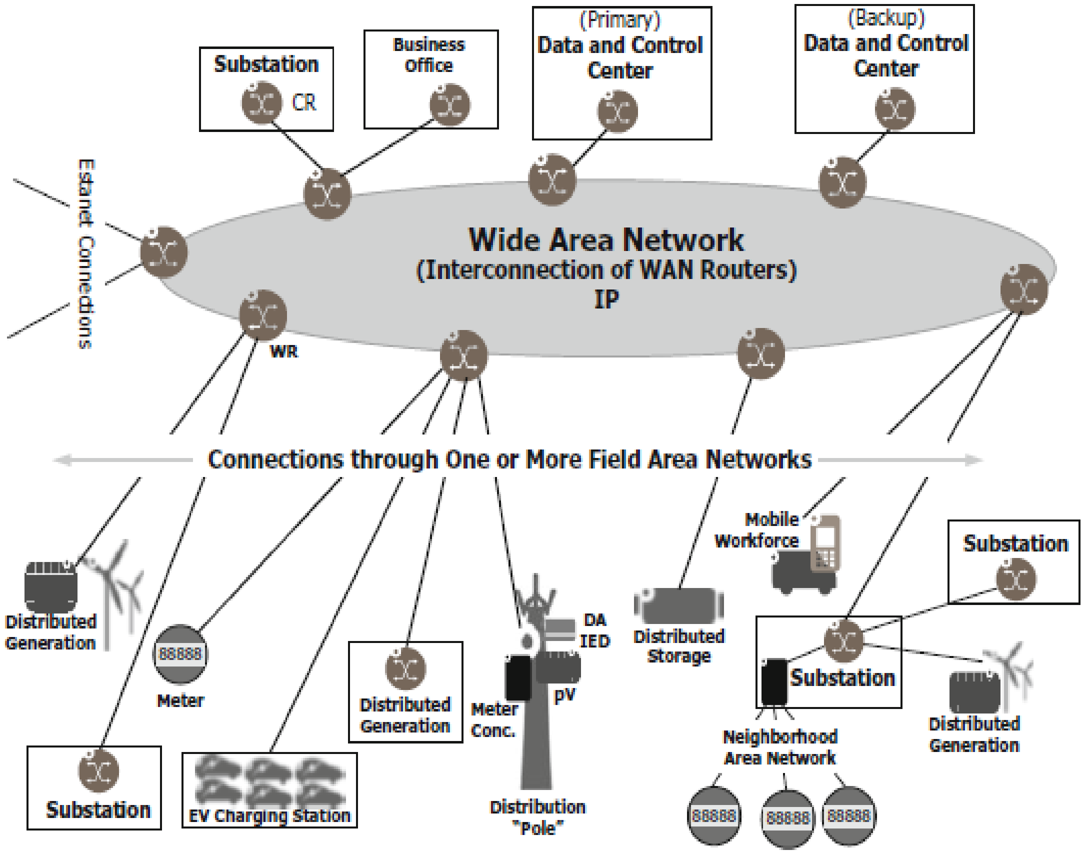

Fig. 1.8 Smart Grid communication network architecture illustration.

1.8. Conclusion:

The Power System indeed lacks monitoring and control in the Voltage deviation, frequency deviation, Communication delay, natural disaster etc. Major Blackouts occurred so far show that there is a need for better monitoring. The present energy management system sets back in the time delay and lacks synchronization. This is why Wide area monitoring (WAM) is one of the most significant new developments in modern power systems. Through developments in synchronized measurement technology and the creation of phasor measurement units (PMUs), WAM is able to offer a real time view of the dynamic behavior of a power system that updates once per cycle. This information has proven an invaluable resource for creating new applications that can benefit power system protection and control.

In addition the performance of the supporting communication infrastructure, in terms of latency, delay, correctness, will determine the performance of any form of wide area monitoring.

Finally the need of developing a system with better monitoring and better communication flow in Wide-Area network state is important.

CHAPTER 2

∴ SISO and MIMO in communication network

∴ *Introduction*

∴ *Bit Error Rate and Signal To Noise Ratio in OFDM*

∴ *System description*

∴ *Comparison between SISO and MIMO systems*

∴ *Conclusion*

2.1. Introduction :

Modern wireless communication demands constant improved spectral efficiency. More number of users is needed to be accommodated in a given bandwidth with high quality standards for communication. Different diversity techniques are used for it. Spatial diversity deals with multiple number of transmitting and receiving antenna at transmitter and receiver respectively. When the same signal is transmitted or received via multiple devices, spatial diversity is formed.

SISO is the simplest antenna technology in which one antenna is used at the source (transmitter) and one antenna is used at the destination (receiver). As no diversity is applicable in SISO case, multipath fading[29] is a prominent issue in this category of communication[30-32].

The most significant technological developments in communication are using Multiple Input Multiple Output (MIMO) antenna architectures[33]. In a MIMO system, multiple element antenna arrays are deployed at both the transmitter and the receiver. The suitability of a MIMO wireless system for spatial multiplexing is largely dependent on the characteristics of the wireless channel, the antenna configuration and the ability of the receiver to accurately recover the channel coupling matrix coefficients. The communications challenge lies in designing the sets of signals simultaneously sent by the transmit antennas and the algorithms for processing those observed by the receive antennas, so that the quality of the transmission (i.e., bit error probability) and/or its data rate are superior to those supported by traditional single antenna systems[34]. These gains can then provide increased reliability, reduced power requirements and higher composite data rates. What is especially exciting about the benefits offered by MIMO technology is that they can be attained without the need for additional spectral resources, which are not only expensive but also extremely scarce.

MIMO has been shown to offer significant improvements in spectral efficiency and link reliability through spatial multiplexing and space-time coding, respectively. Under conducive channel conditions (such as rich scattering), the receiver exploits differences in the spatial signatures of the multiplexed streams to separate the different signals, thereby realizing a capacity gain.

2.2. Bit Error Rate and Signal To Noise Ratio in OFDM :

Signal –to-noise ratio (SNR) is defined as the ratio of the desired signal power to noise power. SNR indicates the reliability of link between the transmitter and receiver. In OFDM based multicarrier modulation system, the channel bandwidth is wide and interference is not constant over the whole band in use. It is very likely that there is variation of spectral content over the OFDM sub carriers i.e. some part of spectrum is more affected by interference than the other parts of spectrum The most meaningful criterion for evaluation of performance of communication systems is the bit error rate(BER). The Bit Error Rate (BER) is the number of acceptable errors you are prepared to tolerate. This ratio is closely linked to the Signal-to-Noise-Ratio (SNR) which is measured in decibels (dB).In case of orthogonal communications systems, the main sources affecting its BER performance are additive white Gaussian noise(AWGN) and Inter-carrier Interference(ICI). In most of the cases, the ICI is assumed to have a normal distribution; however such assumption is not accurate theoretically. With the help of well developed conventional single carrier communication systems, the BER expression of OFDM systems can be obtained without knowing the ICI distribution function.

we derive the expression for the SNR and BER for downlink OFDM systems in noisy fading Doppler channels. The SNR of the m^{th} subcarrier is given as:

$$\mathrm{SNR}_{\mathrm{m}}=\frac{P_{Dm}}{P_{Im}+P_{Nm}} \qquad [35].$$

Where P_{Dm} is the average power of the desired signal, P_{Im} is the average interference power and P_{Nm} is the average noise power. The average power of the desired, interference and noise is defined a P_{Dm} = E |D_m |2, P_{Im}= E |I_m|2, and P_{Nm}= E |N_m|2 respectively. Hence, the average SNR on the mth subcarrier is formulated as:

$$\mathrm{SNR}_{\mathrm{m}}=\frac{\mathrm{E}[|\mathrm{D_m}|^2]}{\mathrm{E}[|\mathrm{I_m}+\mathrm{N_m}|^2]} \qquad [36].$$

Where the average power of the desired signal is calculated as:

$$\mathrm{E}[|D_m|^2]=\mathrm{E}\left[\left|c_0 a_{m,i}{}^2\right|^2\right] \quad [37].$$

2.3. System description :

The goal of a wireless communication system is to serve as many users with the highest possible data rate given constraints such as radiation power limit and operating budget. To improve the data rate, the key is to improve the signal to noise ratio (SNR). To serve more users, the key is to reuse the resources.

The Long Term Evolution downlink simulator simulates the downlink communication from one E-UTRAN NodeB (eNodeB) to one User Equipment (UE) using a WINNER channel or an AWGN channel. There are four main parts of the simulator: transmitter (eNodeB), channel, receiver (UE) and the simulator.

The LTE downlink simulator is mainly modeled in the physical layer and partly in the Medium Access Control (MAC) layer. In terms of physical channel, the simulator focuses on the Physical Downlink Shared Channel (PDSCH). Moreover, the simulator operates in terms of sub-frames, i.e. the generation and transmission of signals are in the form of sub-frames[38].

Using MATLAB simulink, we have worked on Natalia Molinero Mingoranc’s model[39].that was modified in order to study and compare the data correctness in a communication network by changing the signal to noise ratio, using different antennas technologies(SISO,MIMO 2×2, MIMO4×4).

2.3.1 SISO System:

The Simulink model shown in Fig. 2.1 shows two SISO transmitter-channel-receiver, employing both single-carrier modulation and orthogonal frequency division multiplexing (OFDM) simulated in Matlab. additive white Gaussian noise added in order to control the changement in SNR and see the BER obtained.

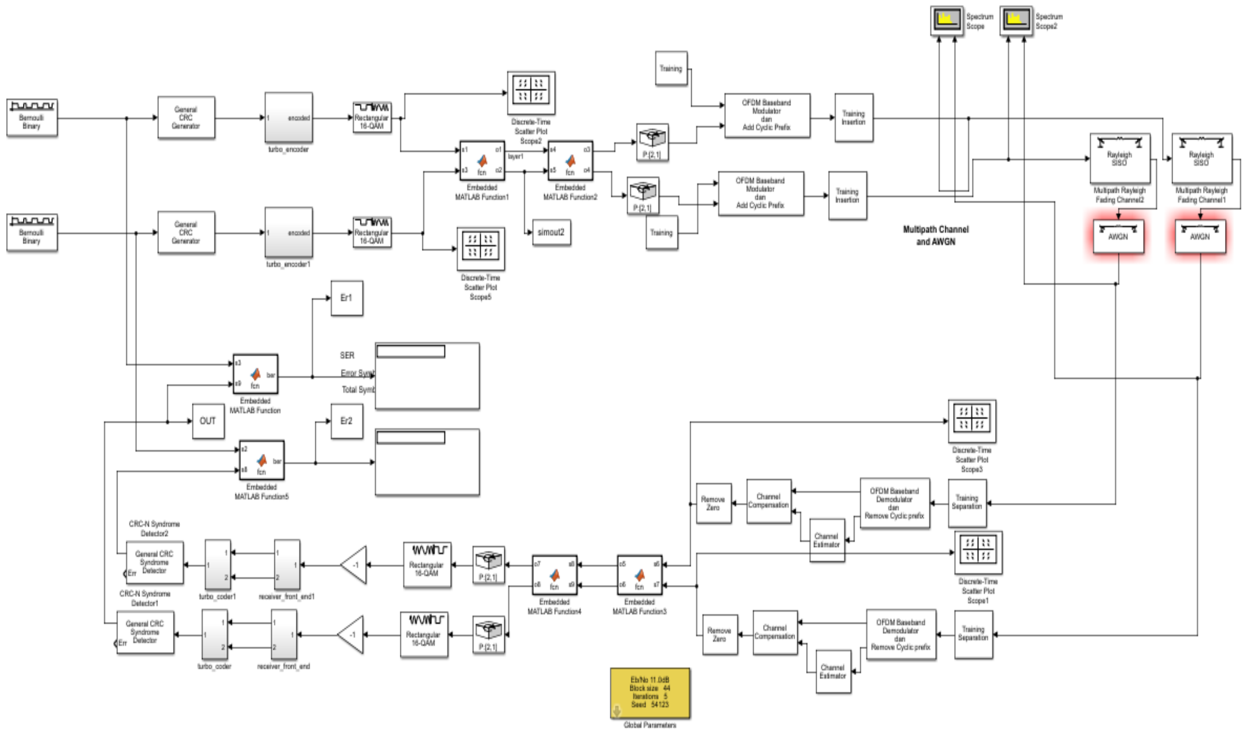

Fig. 2.1 Simulink model of SISO system.

2.3.2 MIMO 2×2 System:

The simulink model illustrated in Fig. 2.2 shows Multiple-Input-Multiple-Output (MIMO 2×2) systems, which use two antennas at the transmitter and receiver ends of a wireless communication system. Multiple antennas use the spatial dimension in addition to the time and frequency ones, without changing the bandwidth requirements of the system. Using the fading Rayleigh channel.

The parameters of the Rayleigh Channel and the noise in the AWGN channel can be selected, then the changement in the signal's spectrum and in the constellation is observed. In addition, the BER is obtained.

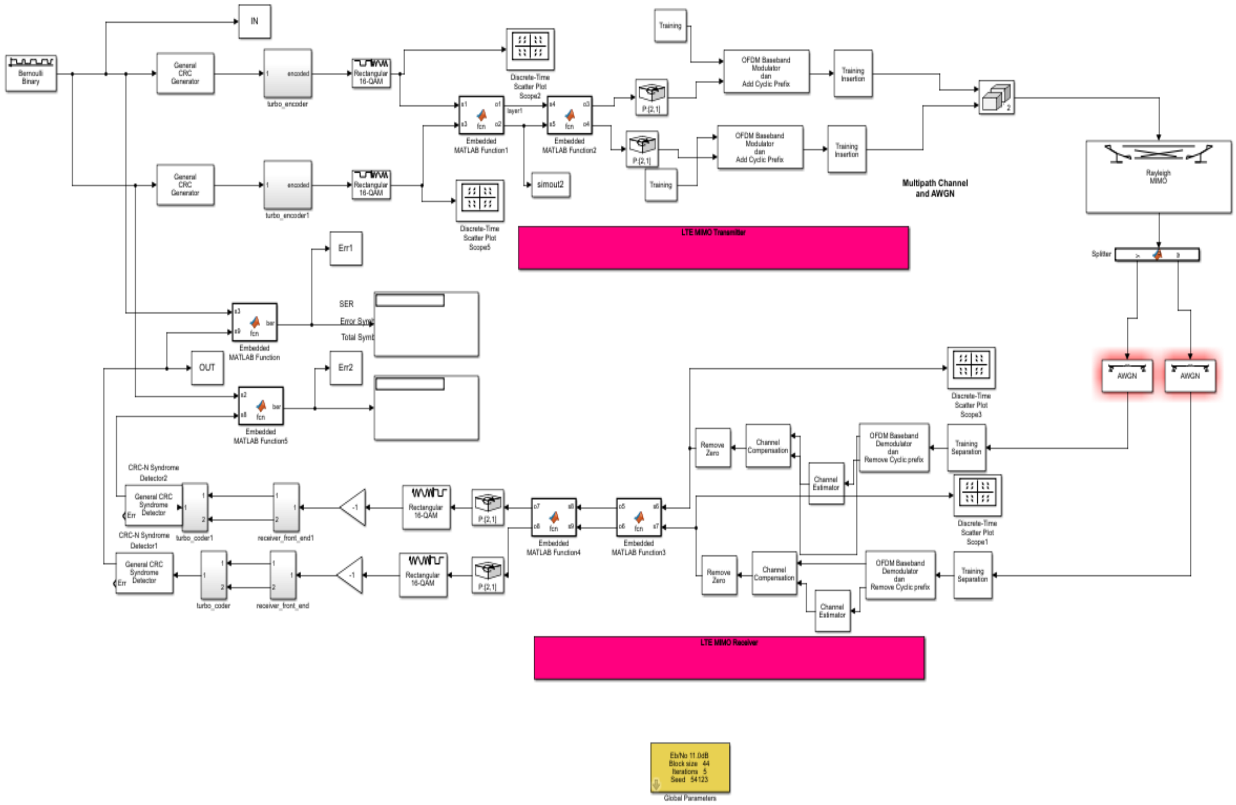

Fig. 2.2 Simulink model of MIMO 2×2 system.

2.3.3 MIMO 4×4 System:

Fig. 2.3 represent the LTE downlink simulator that simulates the Diversity performance of MIMO 4×4 system. Both the transmitter and the receiver of the LTE downlink are implemented. The transmitter is implemented according to the specifications. It supports turbo coding, rate matching, MIMO 4×4 and OFDM . This MIMO communication system using the fading Rayleigh channel. Similar to MIMO 2×2 system the parameters of the Rayleigh Channel and the noise in the AWGN channel can be selected. the BER obtained by simulations.

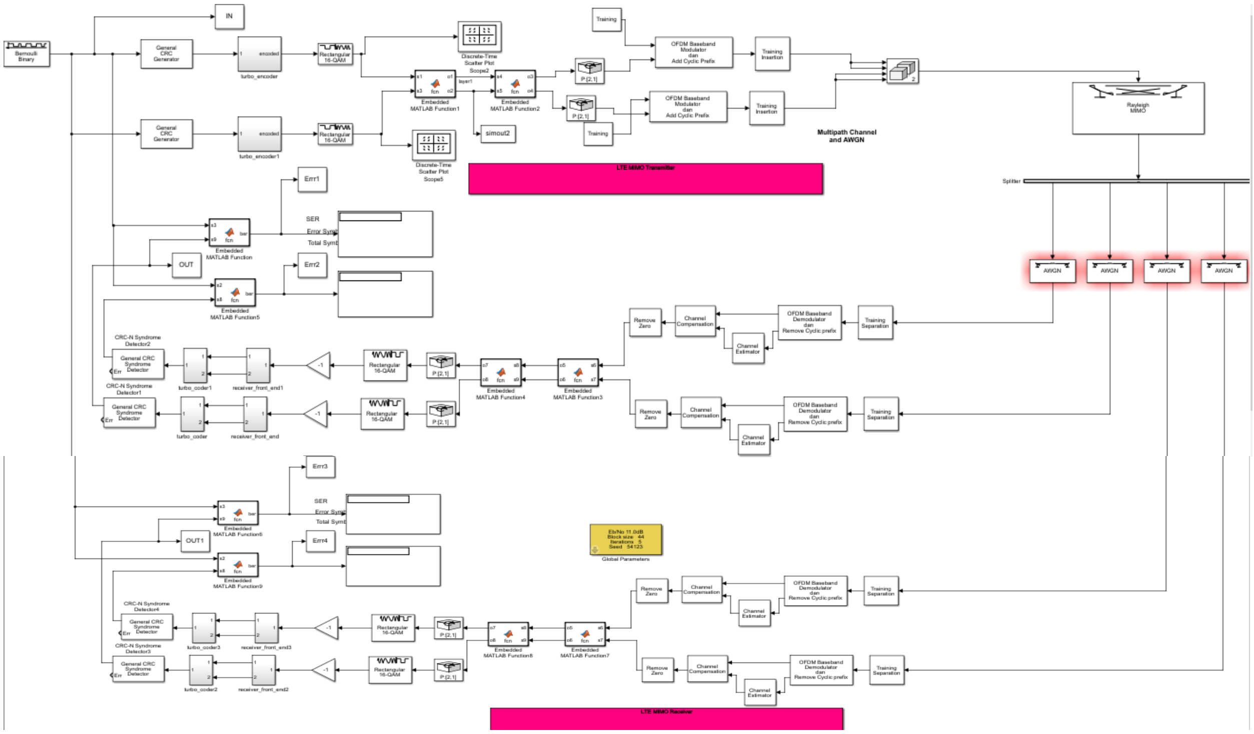

Fig. 2.3 Simulink model of MIMO 4×4 system.

2.4. Comparison between SISO and MIMO systems:

In this section, we study the simulation results**.**Table 2.1 gives the comparative analysis of BER results obtained for three Simulink models using bit error rate block by varying signal to noise ratio SNR of the AWGN block. The same amount of data is sent over the three systems with fixed time delay taken in different systems. the Discrete path delay vector specifies the time delay for each path. For SISO system the path delay [0 2 10^{-6}] and [0 2 10^{-2}],[0 2 10^{-2}] for MIMO2×2 and MIMO4×4 respectively.

Table 2.1 bit error rate based on the changement of signal to noise ratio.

	BER		
SNR	SISO	MIMO 2×2	MIMO 4×4
0	0.013182208581208	0.013158421010529	0.013154000311553
1	0.013178945684345	0.013143369583064	0.013165894096893
2	0.013174840749582	0.013149263848365	0.013166841389530
3	0.013174840749582	0.013153684547341	0.013165683587418
4	0.013173051419044	0.013159368303167	0.013163367983192
5	0.013176209061169	0.013161052378967	0.013161157633705
6	0.013179261448557	0.013163683747405	0.013155579132616
7	0.013174419730632	0.013165999351630	0.013153053018916
8	0.013183471638058	0.013164946804255	0.013153158273653
9	0.013178629920132	0.013165262568468	0.013151789962066

10	0.013179998231720	0.013158315755792	0.013154316075766
11	0.013181998071733	0.013154842349454	0.013151579452591
12	0.013182103326470	0.013149474357840	0.013152210981016
13	0.013182103326470	0.013150632159953	0.013154947604191
14	0.013181892816995	0.013154105566291	0.013153789802078
15	0.013181471798045	0.013152210981016	0.013159263048429
16	0.013178524665395	0.013152210981016	0.013157999991579
17	0.013178103646445	0.013151789962066	0.013153053018916
18	0.013182313835945	0.013152000471541	0.013156947444204
19	0.013183050619108	0.013150632159953	0.013157578972629
20	0.013183155873845	0.013150842669428	0.013157157953679
21	0.013183261128583	0.013150421650478	0.013157052698942
22	0.013183261128583	0.013152000471541	0.013156210661041
23	0.013182524345420	0.013151789962066	0.013155894896829
24	0.013182419090683	0.013151158433641	0.013155473877879
25	0.013182524345420	0.013152210981016	0.013155158113666
26	0.013182208581208	0.013152210981016	0.013155789642091
27	0.013182945364370	0.013151053178903	0.013155263368404
28	0.013182208581208	0.013151368943116	0.013155579132616
29	0.013182208581208	0.013151579452591	0.013155579132616
30	0.013183682147533	0.013152000471541	0.013156105406304

Fig. 2.4 shows a comparison between the bit error rate for several values of signal to noise ratio for the three systems that was simulated on MATLAB.

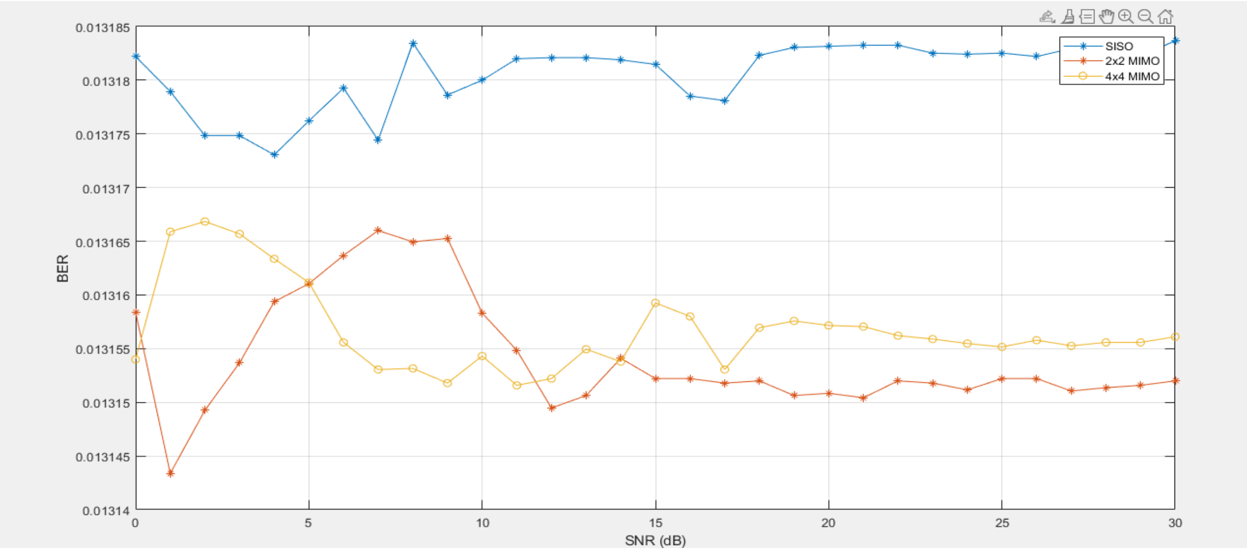

Fig. 2.4 Bit Error Rate versus Signal to Noise Ratio for SISO,MIMO2×2 and MIMO4×4 Systems.

From the resulting plot we can see that:

- -The bit error rate of SISO system model is varying between 0.013173051419044 and 0.013183682147533 , by applying different values of signal to noise ratio to this model (the values of SNR are taken from 0 to 30 as iterations), the same is done for all the remaining models.

- -The MIMO2×2 BER is varying between 0.013143369583064 and 0.013165999351630.
- -The MIMO4×4 BER is varying between 0.013151789962066 and 0.013166841389530.

We realize that by the increase of SNR to a large extent a simultaneous decrease in bit error rate in both MIMO 2×2 and MIMO 4×4 in the other side As the SNR increase, BER constantly increase for SISO curve.

There is no much difference of the BER between the MIMO 4×4 and those of MIMO 2×2 however simulation results show that BER of both systems is less than SISO for every given value of SNR.

Note: The delay path for both MIMO2x2 and MIMO4x4 is the same based on NATALIA’s MIMO SIMULINK Model path delay that have been deduced and used for her system, due to this we found that there are some errors related to MIMO4x4 in terms of BER for different values of SNR.

2.5. Conclusion :

Different diversity techniques can be implemented for spatial diversity. Technical comparison of these techniques is required to implement any of them into real time technology or standards. A set of different Bit Error Rate values was found out using Single Input Single Output (SISO) and Multiple Input and Multiple Output (MIMO) antenna systems. We compared the results and concluded that MIMO system has low Bit Error Rate (BER) than SISO system. From above comparison and analysis, we come across the fact that MIMO system delivers higher data rate than SISO system due to transmission of multiple data symbols simultaneously transmitting independent data streams in the same frequency band.

CHAPTER 3

∴ *Wide Aera monitoring based on LoRa Communication*

∴ *Introduction*

∴ *Description of LoRa Communication*

∴ *SISO and MIMO Systems in Wide Area Monitoring*

∴ *LoRa Transmission and Monitoring*

∴ *Conclusion*

3.1. Introduction :

With the rapid growth of IoT technology, it has been applied to an increasing number of fields, such as intelligent agriculture, industrial automation, smart city, smart home, *etc.* [40]. Currently, the most widely used ZigBee, Bluetooth, 2G, 3G, 4G, and other communication technologies have their own pros and cons [41][42]. Xing *et al*. proposed a greenhouse intelligent information monitoring system using ZigBee wireless sensor. This system used ZigBee wireless sensor to collect field environmental parameters and realized centralized monitoring, data display, data storage, and data mining [43]. Shen *et al*. enabled traffic information detection using Bluetooth communication, *i.e.*, to transmission of vehicle position, speed, *etc.* information via Bluetooth [44]. Zhang *et al*. proposed wireless sensor monitoring nodes powered by solar panels and realized real-time, accurate, and remote transmission data using GPRS technology [45]. However, ZigBee and Bluetooth are short-range radio technologies and are not suitable for long-range transmission scenarios. 2G, 3G, 4G, and other solutions based on cellular communication can provide a wider coverage, but they consume too much energy and increase the operating costs [42].

To solve these problems, LPWAN has emerged and gained wide attention from researchers which have analyzed low-power and long-range wireless technology, implemented a networking scheme and tested the performance of LoRa wireless transmission technology [46]. Shi *et al*. proposed a smart parking system using NB-IoT communication technology, which can effectively improve the utilization rate of the existing parking facilities [47]. Anand *et al*. presented a remote monitoring mechanism for the water level in a storage tank using NB-IoT [48]. The above studies show that LoRa has the advantages of high stability, ultralong transmission, ultralow power, and low cost [49].

Wide-area monitoring, wide-area control and wide-area protection utilize Wide Area Networks and turn out to be the next-generation key to improve power system planning, operation and protection in the smart grid. These applications employ the system broad data and wisely chosen local information to oppose the spread of harming disturbances [50]. Wide-area monitoring, control and protection applications present higher data resolution and shorter response time than the classical supervisory control and data acquisition (SCADA) and energy management (EMS) systems. Wide-area monitoring, control and protection applications provide high-resolution data contrary to SCADA/EMS which offers a measurement update interval of several seconds (or even minutes).

The IEEE Standard for Synchrophasors for Power Systems (IEEE Std.C37.118 provides definitions of measurement and data transmission formats for real-time data reporting in electric power systems [51]. For wide-area monitoring applications, the size containing measurements made by a PMU has a minimum message of 52 bytes. The required response time for wide area monitoring applications is in the range of milliseconds to minutes, and the requirement on communication system reliability is very high.

Due to the importance of the communication infrastructure in the success of smart grid implementation and operation, there has been a variety of research works in the literature focusing on this topic, so the suitable communication technologies for transmission-level systems for a long-distance are important[52].

Multiple-input multiple output (MIMO) techniques are being widely adopted in the current fourth generation (4G) telecommunication systems and they are expected to be a key technologies for the fifth-generation (5G) communications. MIMO systems take advantage of the multipath nature of the propagation channel. However, the antenna properties turn out to affect correlations among channel coefficients. MIMO, as a currently well established technology, offers considerable benefits, such as improving link quality and largely attainable data rates [53-54]. When antenna array elements are made closer one another, the effect of electromagnetic mutual coupling between them becomes a common phenomenon. The mutual coupling can dangerously deteriorate the performance of the array in the form of signal-to-interference-noise ratio (SINR) reduction and the signal processing algorithm non- convergence [55-56]. It precisely degrades some parameters such as the carrier frequency offset [57], channel [58], and angle of arrival estimations [59]. Also, the awful effect of mutual coupling on the active reflection coefficient of a MIMO antenna is another result that cannot be ignored [60]. Furthermore, the active voltage standing wave ratio (VSWR) may reach intolerable values. Despite the negative effects of mutual coupling. the MIMO system performance deterioration, it can be exploited for array calibrations as in [61-62]. The mutual coupling modifies the antenna characteristics in an array, and hence affects the MIMO system performance (e.g., capacity, error rate, and spectral re-growth). The system performance can be partly improved by adjusting out the mutual coupling using digital techniques but without improving the SINR. Thus, it is very imperative to lessen the mutual coupling when it comes to MIMO antenna design.

3.2. Description of LoRa Technology:

As one of IoT communication technologies, LoRa is a kind of ultra-long distance wireless transmission technology based on the spread spectrum transmission techniques and CSS (chirp spread spectrum) modulation, which is one of the IoT communication technologies. Its name comes from the abbreviation of "long range". It can be seen from the name, the biggest feature of LoRa is the long distance communication. LoRa's spread spectrum technology changes the balance between transmission power consumption and transmission distance, and completely changes the situation in the field of embedded wireless communication. This technology presents a new communication technology that enables long-distance, long battery life, large system capacity and low hardware costs to meet the IoT needs [63].

The Table 3.1 below compares some parameters including transfer rate, transmission range, power consumption and cost between some popular wireless technologies. Accordingly, LoRa has shown its superiority in many aspects. Its only weakness is the data rate. However, in wireless sensor network applications, this is not an issue.

Table 3.1 : The comparison of some wireless technology [64].

	T_X Range	T_X Rate	T_X Power	Sleep Power	cost
Bluetooth	15 m	3 Mbps	20 mA	16 μA	low
Wifi (CC3200)	150 m	3 Mbp	75 mA	3.5 mA	high
3G/4G (U8300)		14 Mbp	800 mA	50 μA	high
ZigBee (REX 3DP)	100-200 m	250 Kbps	200 mA	0.4 μA	low
LoRa (SX1278)	3000 m	2.4 Kbps	110 mA	2.0 μA	low

LoRa specifically developed by Semtech to work in 433.868 or 915 MHz ISM Band (depend on the regional placement) with transmission rate between 0.25kbps-50kbps [65]. The parameters that possibly changed in LoRa modulation are Bandwidth, Spreading Factor and Code Rate. The spreading factors are - in short - the duration of the chirp. LoRa operates with spread factors from 7 to 12. SF7 is the shortest time on air and SF12 will be the longest. Each step up in spreading factor doubles the time on air to transmit the same amount of data [66] [67].

3.3. SISO and MIMO Systems in Wide area Monitoring:

3.3.1 Systems Description:

Part I: Power and Measurement System:

The work simulates a small scale wide area monitoring system, the power system used in our work is the IEEE 14 bus standard system[68], the placement of PMUs is important as we want to make the entire system observable, with zero injection at bus 7, we only need 3 PMUs placed at bus 2,6 and 9. Fig. 3.1 represents The MATLAB SIMULINK model of the IEEE 14 bus standard system with the appropriate placement of PMUs.

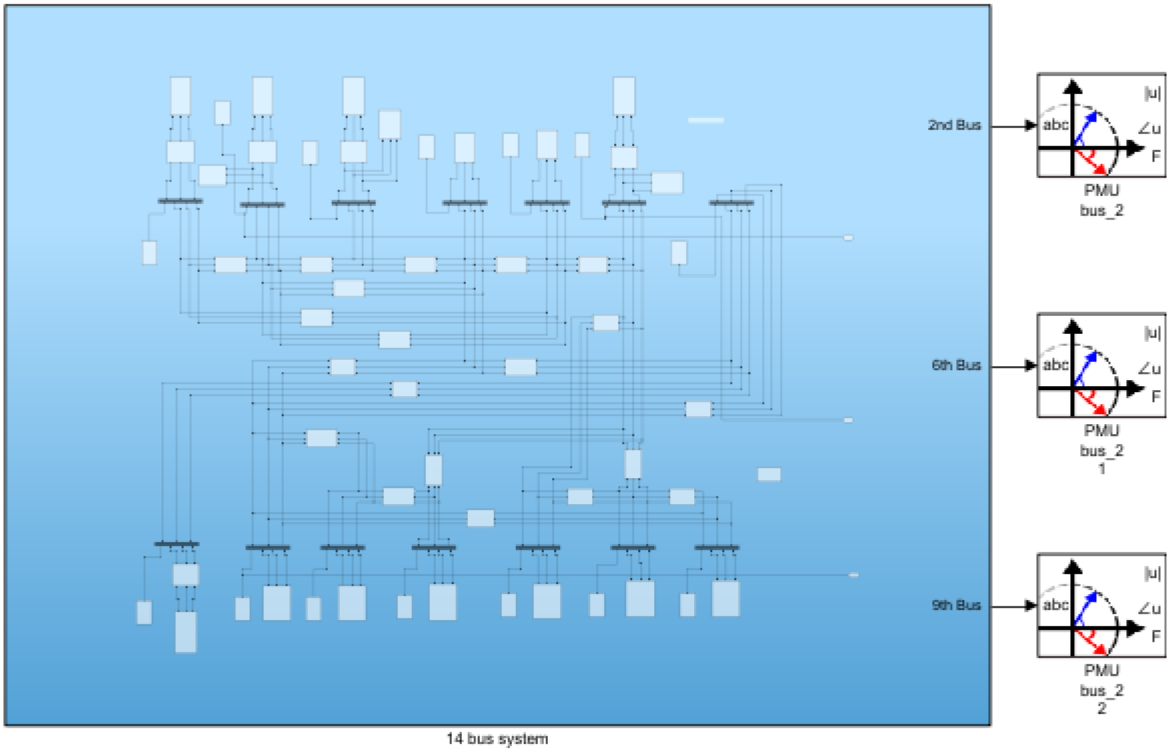

Fig. 3.1 IEEE 14 bus standard system with the appropriate placement of PMUs.

The data collected from the 2nd, 6th and the 9th bus is measured by each PMU and displayed as shown in Fig. 3.2, Fig. 3.3 and Fig. 3.4 .

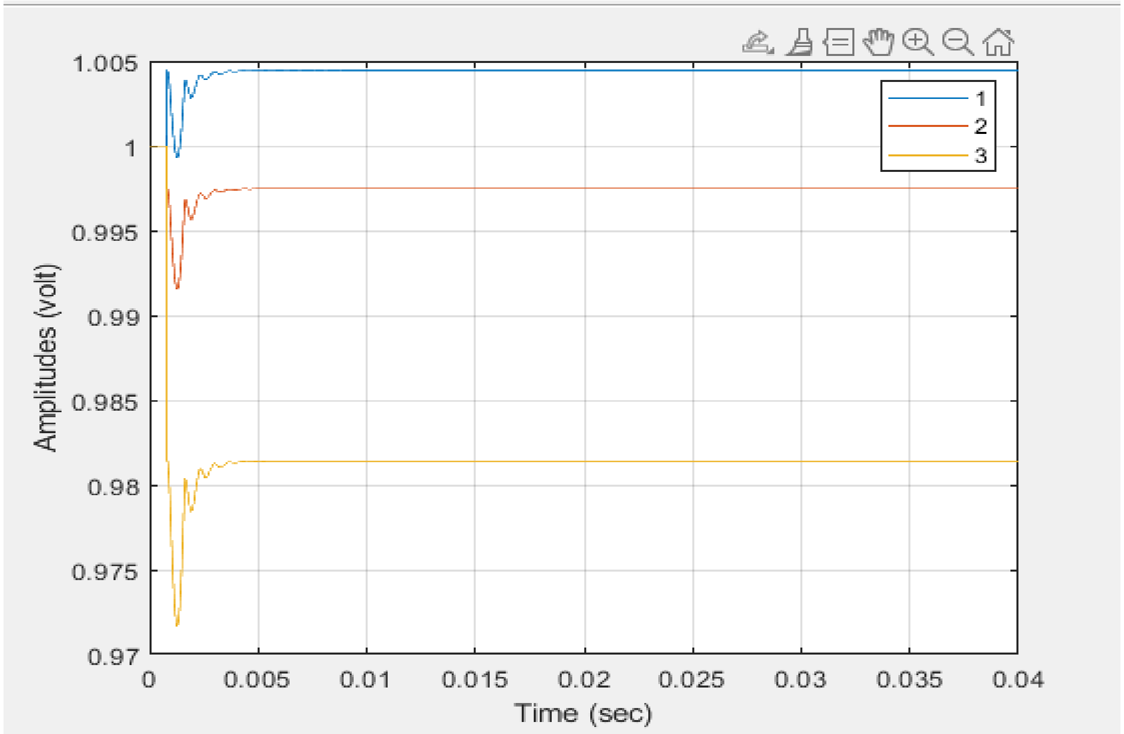

Fig. 3.2 The amplitude measurements obtained from bus 2,6 and 9 respectively.

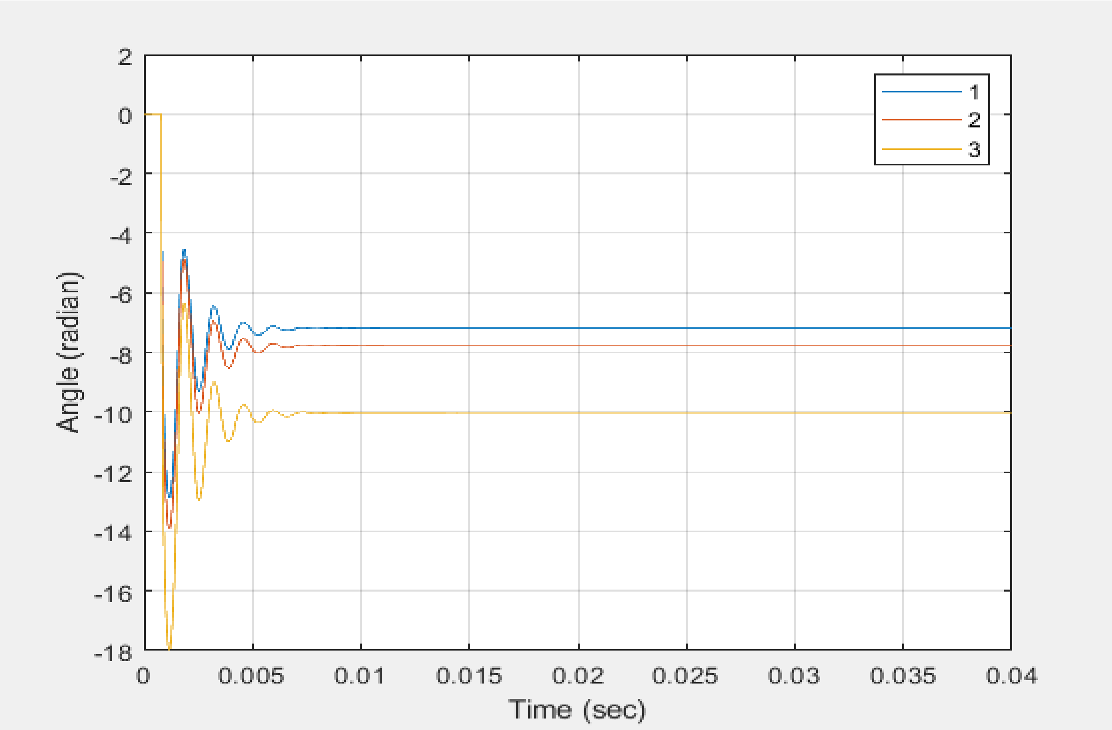

Fig. 3.3 The angle measurements obtained from bus 2,6 and 9 respectively.

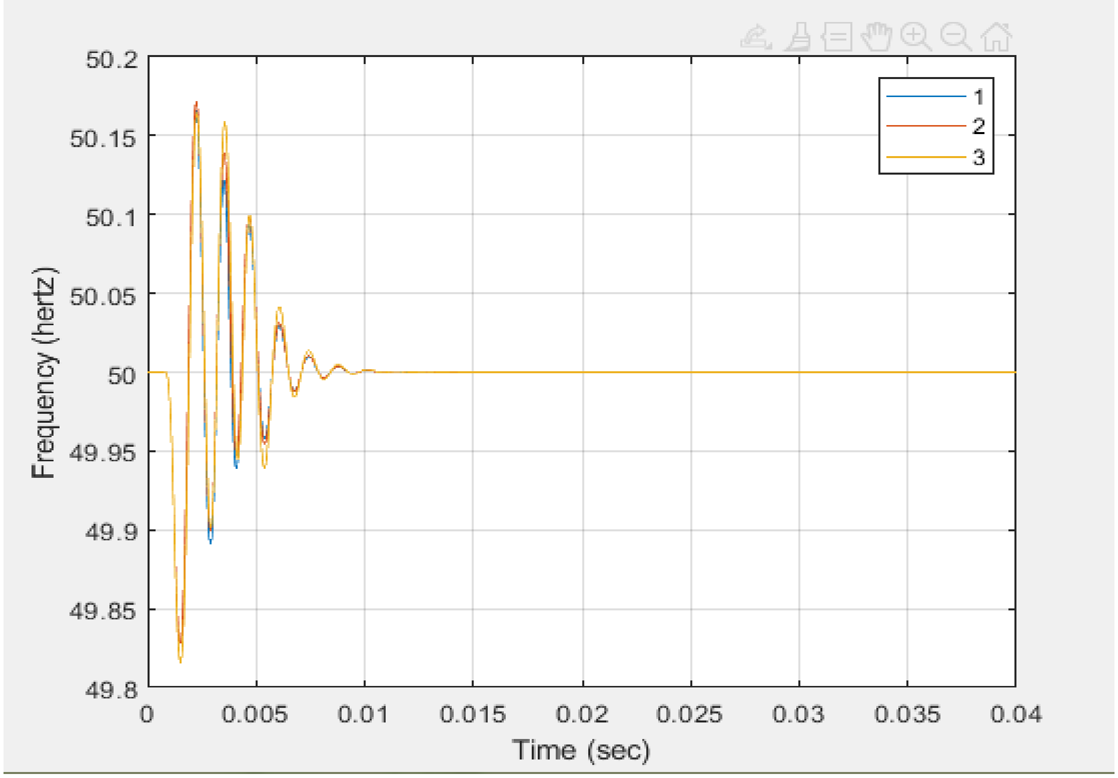

Fig. 3.4 The Frequency measurements obtained from bus 2,6 and 9 respectively.

Part II: Communication System:

In this part we worked on SISO and MIMO communication Simulink model techniques, the data collected from each PMU is sent through both SISO and MIMO channel, the three PMUs are synchronized using GPS clock, the state of all the power system is estimated by using the received data from these three PMUs, to compare the performance of both SISO and MIMO Systems in terms of Bit Error Rate, BER (data correctness) we vary the SNR (signal to noise ratio) of the Additive White Gaussian Noise (AWGN) block and study at the same time the effect of this changement on the BER. It should be noted that the carrier frequency of the two SIMULINK models was taken 868 MHz which is related to LoRa technology, it’s also needed to know that for both systems the path delay is [1.5s ,1.45s,1.85s] for SISO and [1.23s,1s,1.63s] for MIMO System related to the 2nd ,6th and 9th bus respectively.

3.3.1.1 SISO system description:

The SIMULINK model shown in fig. 3.5 consist of a three SISO transmitter-channel-receiver, in the SISO channel, the data for each PMU measurement is sent as a stream.

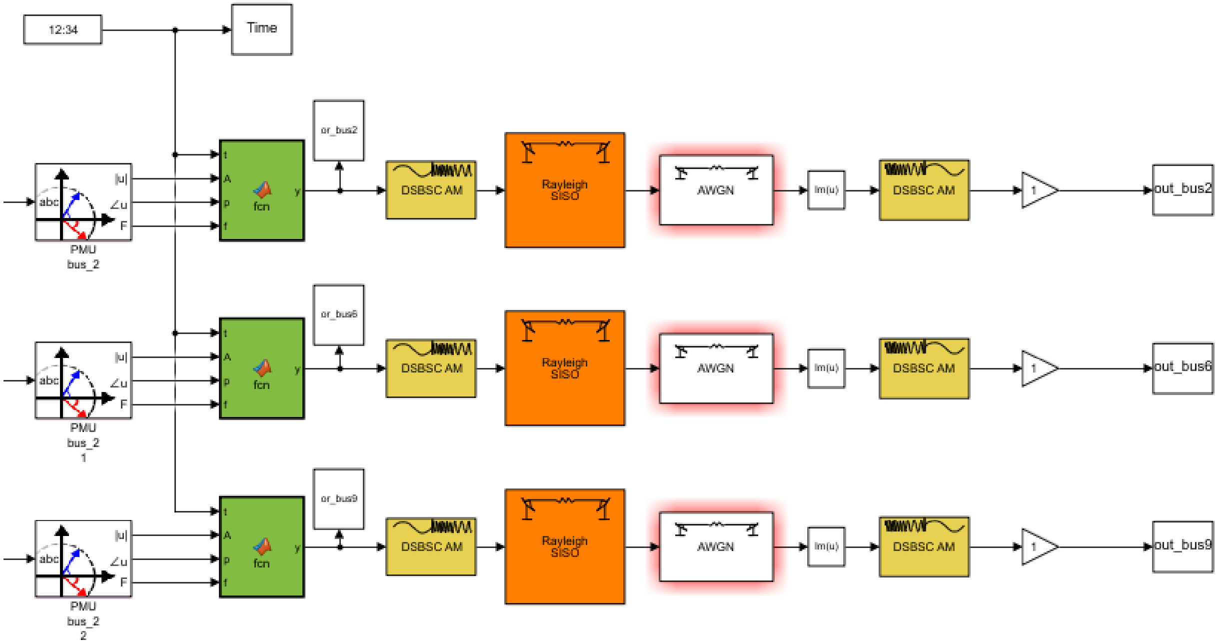

Fig. 3.5 The SISO MATLAB SIMULINK model.

3.3.1.2 MIMO system description:

Here, the simulation shows a SIMULINK model of Multiple-Input-Multiple-Output technique (MIMO) .The data is split into two streams (sent at two antenna) and combined back at the receiver with the same manner .The maximum combining is used to ensure that the data undergoes the minimum possible error. The MIMO channel is assumed to exhibit a Rayleigh fading which is close to reality. At the receiver end the data is collected and the bit error rate (BER) is obtained.

The model is illustrated in fig. 3.6

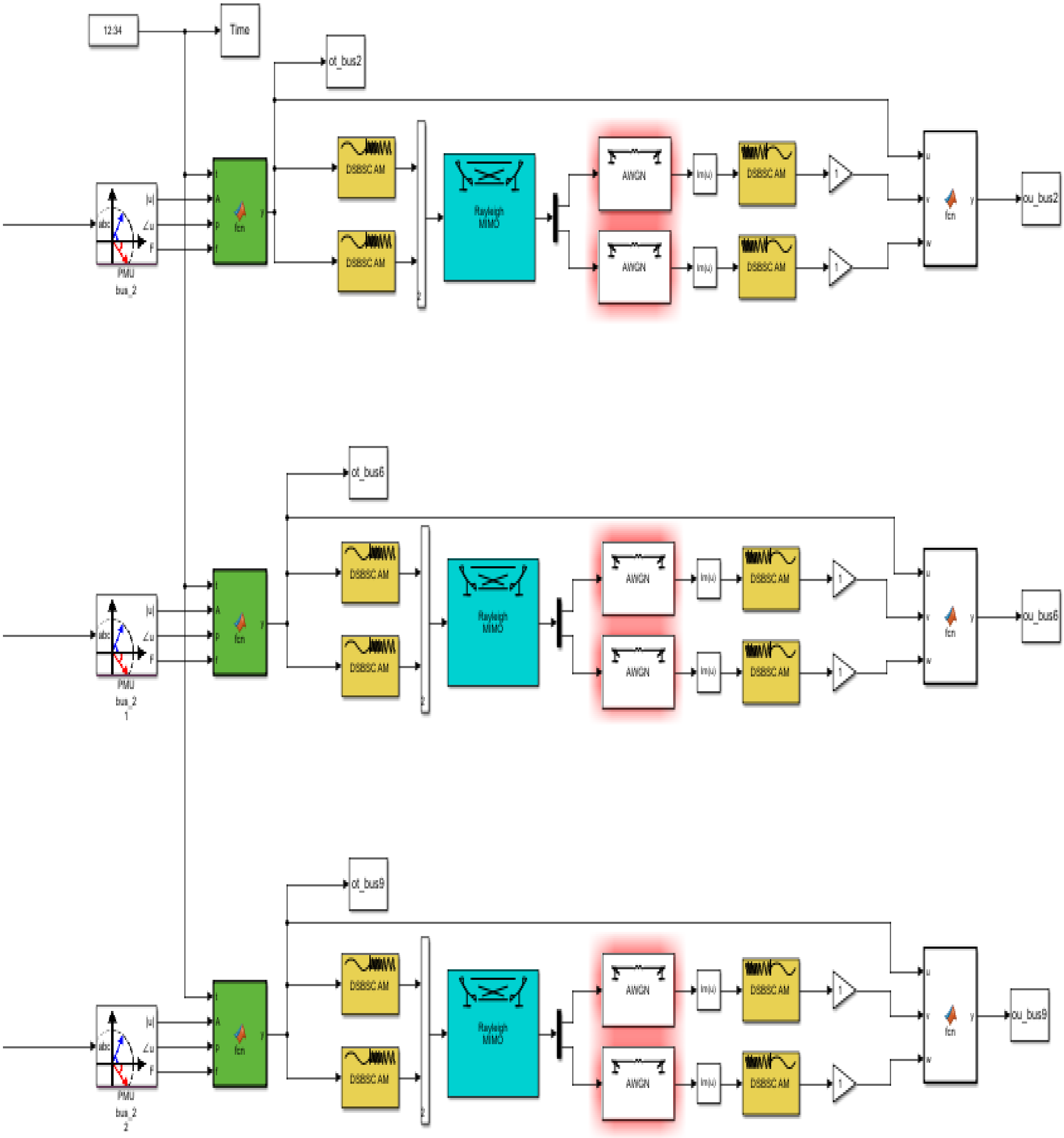

Fig. 3.6 The MIMO MATLAB SIMULINK model.

3.3.2 Results and discussion for MIMO and SISO systems:

The Table below gives the comparative analysis of the bit error rate (BER) results obtained for three buses as follow 2nd bus,6th bus and 9th bus for the SISO system model ,by varying the signal to noise ratio (SNR) of the AWGN block.

Table 3.2. BER versus the changement in SNR results for SISO system.

	Bit Error Rate (BER)		
	SISO		
SNR	2nd bus	6th bus	9th bus
0	0.348893984308837	0.348350082850389	0.320479072467318
1	0.361288691033954	0.359188193055289	0.344213737005597
2	0.371874820838528	0.368576488114723	0.364366133440194
3	0.380949207908161	0.376719646503270	0.381607672611098
4	0.388740508490685	0.383808392402795	0.396409478245423
5	0.395497785218864	0.389987256262884	0.409192296496020
6	0.401331988454207	0.395394076217269	0.420251676481346
7	0.406395220279063	0.400128568183006	0.429819374726471
8	0.410796233650619	0.404286097076098	0.438133394597935
9	0.414645915486811	0.407933971703432	0.445370845846653
10	0.418014084198038	0.411136087707177	0.451705878837224
11	0.420960476186394	0.413958167935200	0.457245293996013
12	0.423540955564858	0.416453494354426	0.462116698423454
13	0.425800932795336	0.418657906790256	0.466399842716963
14	0.427788349200827	0.420609077450628	0.470166094918930
15	0.429541242552355	0.422335002843464	0.473479825604608
16	0.431089318122307	0.423866405857734	0.476396235850788
17	0.432462940146125	0.425228155343830	0.478969925886847
18	0.433682196089322	0.426438928606334	0.481247210467425
19	0.434763585003738	0.427516221099338	0.483263678180815
20	0.435723967858493	0.428473232349055	0.485053291220365
21	0.436578722677582	0.429324205559355	0.486643757613001
22	0.437338662476368	0.430079686980193	0.488055818461239
23	0.438014140487245	0.430751230288355	0.489310593189985
24	0.438614868908539	0.431347588629485	0.490427138405318

25	0.439148515779864	0.431876761264463	0.491420750996961
26	0.439622061281196	0.432345560560475	0.492303935922426
27	0.440040277234343	0.432760989105768	0.493090003408863
28	0.440410798693733	0.433128772714586	0.493788965882722
29	0.440739002161285	0.433454761461750	0.494410006871054
30	0.441029359724782	0.433743839981741	0.494960107237239

The second Table 3.3. shows the bit error rate versus the signal to noise ratio SNR changement ,the data obtained for MIMO system related to the three buses 2nd bus,6th bus and 9th are recorded and displayed respectively.

Table 3.3. BER versus the changement in SNR results for MIMO system.

	Bit Error Rate (BER)		
	MIMO		
SNR	2nd bus	6th bus	9th bus
0	0.137060844986704	0.097555267754482	0.123740625521566
1	0.146873341405679	0.106189720156615	0.145380843215277
2	0.155126326336017	0.113733991599692	0.164166363355600
3	0.162519350867045	0.120584835427858	0.180936699134482
4	0.168963485876632	0.126152698494933	0.195015224019944
5	0.174110199401717	0.131271140070922	0.207621403483290
6	0.178720502070493	0.135747720176218	0.218650978415381
7	0.183527036682651	0.139708905732708	0.228104848618969
8	0.187178117428703	0.143263439668139	0.236205641031498
9	0.190312416841348	0.146289054811895	0.243914239904598
10	0.193392054783618	0.148555275457478	0.250356226221652
11	0.195637455752306	0.150469340061529	0.256025624287062
12	0.197650531171115	0.152012623265108	0.261080414913858
13	0.199432651094306	0.153241964961063	0.265706239791426
14	0.200991432243605	0.154320059540956	0.269690952902411
15	0.202322945535997	0.155186344446059	0.272925462488176
16	0.203432289273202	0.155797045744997	0.275713778721967
17	0.204443430902107	0.156495170755104	0.278193968726504
18	0.204896092394010	0.156884540365087	0.280402529932328
19	0.205616110065247	0.157439180994126	0.282189917216715

20	0.206094272354961	0.158080793801335	0.283982302172432
21	0.206341065380111	0.158586435723110	0.285478132724848
22	0.206841376725966	0.159107487260072	0.286783298662106
23	0.207175902806641	0.159511479469778	0.287587314521414
24	0.207309198311364	0.159993843504687	0.288628040534245
25	0.207387934549493	0.160420463893717	0.289488662919636
26	0.207513346386996	0.160703312969180	0.290047618759673
27	0.207793344026407	0.160988894243409	0.290552756601098
28	0.207987894567230	0.161284094772825	0.291018957983761
29	0.208148975147106	0.161546203997626	0.291360413745107
30	0.208282807752671	0.161779541720817	0.291820558948947

Fig. 3.7 shows the Bit error rate for each data bus sent through both SISO and MIMO system for different values of Signal to noise ratio (we have taken 1 as iteration step, till SNR= 30).

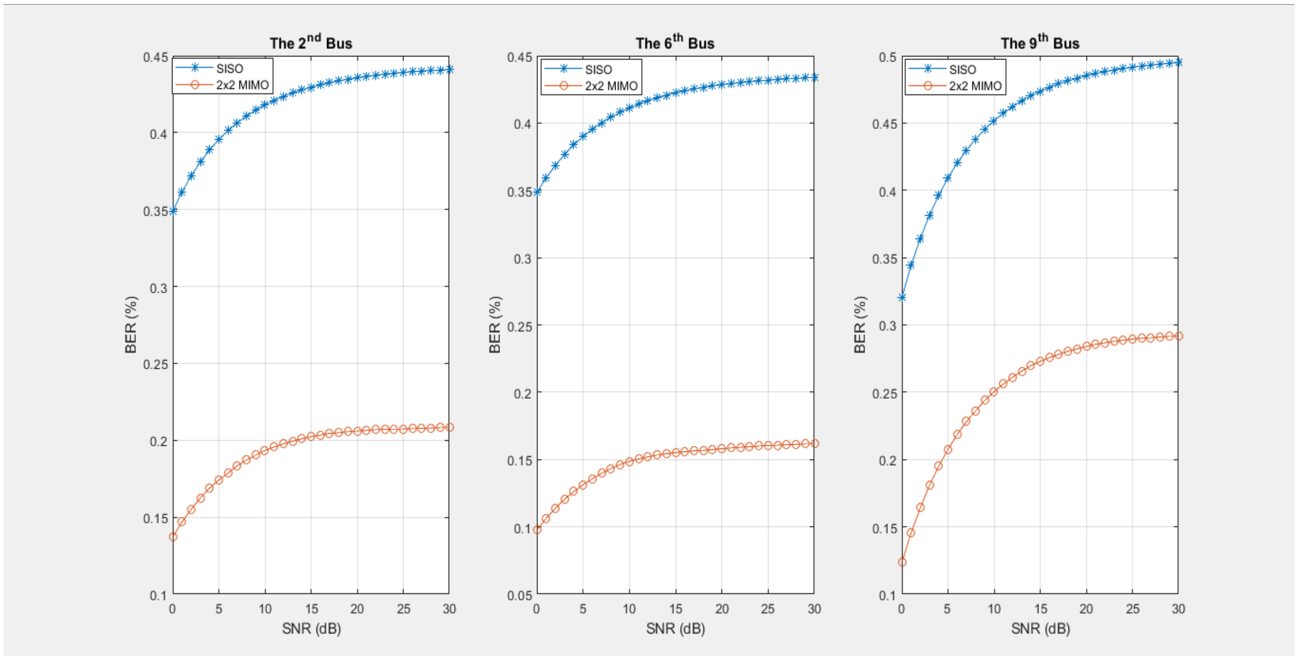

Fig. 3.7 Bit Error rate versus the Signal to Noise Ratio(SNR).

For SISO system:

- The Bit Error Rate for the 2nd bus is increasing as SNR increases, BER = 0.348893984308837 for SNR =0, BER= 0.441029359724782 for SNR=30.

- for 6th bus we can see the same, that is for different values of SNR there is an increase of BER, as SNR take the value of 0 the BER is equal to 0.348350082850389 and for SNR= 30 , BER=0.433743839981741 .
- the data bus for 9th bus goes up from 0.320479072467318 till it reaches the value of 0.494960107237239 at SNR=30.

For MIMO system:

- For the 2nd bus the Bit Error Rate is rise from 0.137060844986704 for SNR=0 until 0.208282807752671 for SNR=30,
- The BER obtained for the 6th bus describe an increasing between 0.097555267754482 to 0.161779541720817 for different Signal to noise Ratio.
- An increasing in the Signal to noise ratio is proportional to the Bit Error Rate changement for the 9th bus .

Applying the same Signal to Noise Ratio for both SISO and MIMO System Simultaneously results in different Bit Error Rate values for both models and it can be seen clearly that the MIMO system Overtake The SISO System in terms of data correctness (BER) which lead to better result compared to the other System.

Reporting rate:

The reporting rate (Rt) , that determines the length of the interval over which an event will be reported, is related to the sample time using a reporting rate factor k, as follows:

$$Rt = k \times Ts \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.1)$$

(Ts): The sample time of the block, in seconds, is a function of the nominal frequency fn and the sampling rate Nsr.

The previous SIMULINK Model related to the power system (IEEE 14-bus) emulates under a Sample time equal to 0.1ms and a reporting rate factor of 1.

We changed the reporting rate ,by changing the reporting rate factor (k) of each PMU block placed at different bus location (2nd bus,6th bus and 9th bus) of the power system in the SIMULINK Model.

The following results shown in Fig. 3.8 are obtained after running both SIMULINK models (SISO and MIMO Systems) for different values of SNR and for a different value of reporting rate factor *k* (*k=2)*

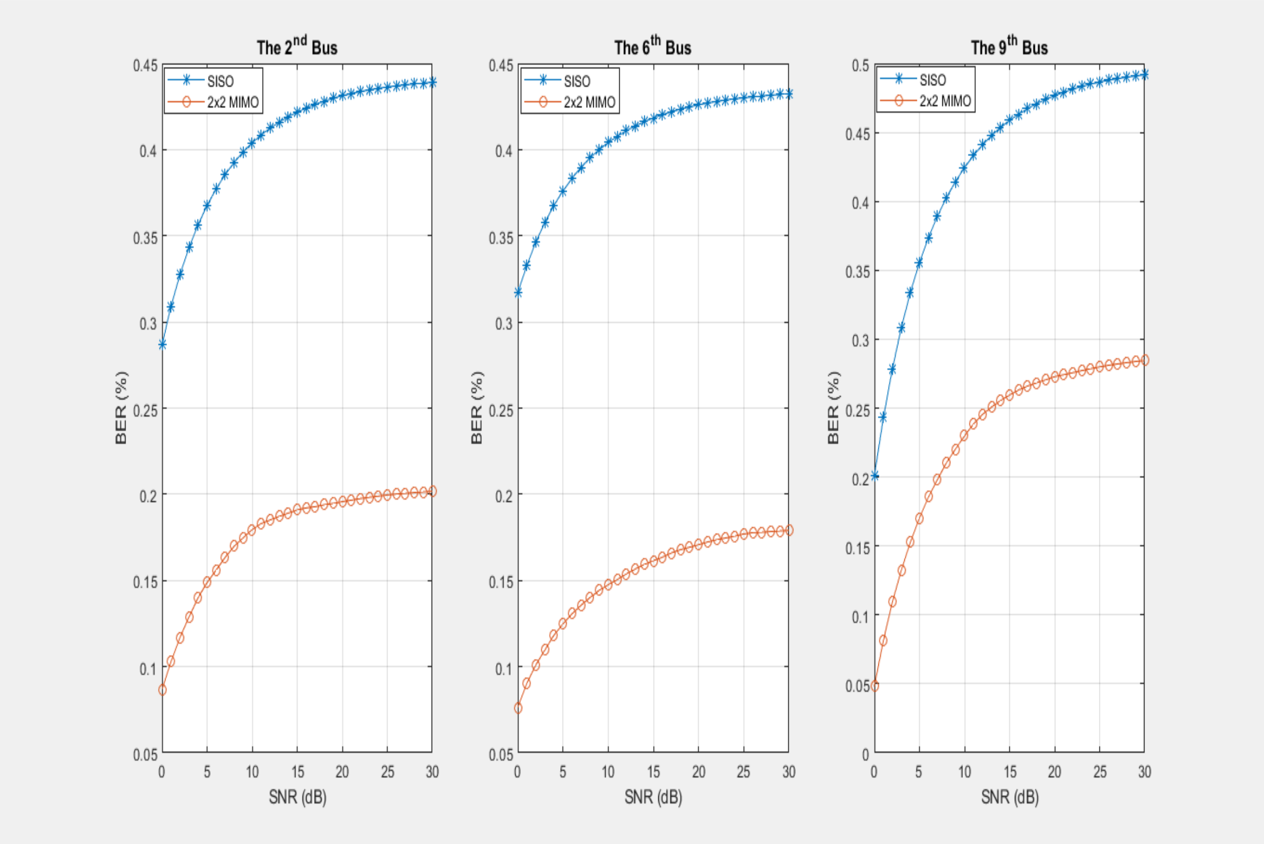

Fig. 3.8 Bit Error rate versus the Signal to Noise Ratio(SNR) for *k =2*.

From above curves we can see that the results obtained in terms of data correctness are better than the previous ones for both SISO and MIMO SIMULINK Models which means that the Bit Error Rate for the new value of reporting rate factor *k* was found to be less than the values obtained for reporting rate factor equal to 1, and goes up with the increase of Signal to noise ratio.

3.4. LoRa Transmission and Monitoring:

3.4.1. LoRa MATLAB Coding:

In this part we present the main LoRa Transmission coding by using the same measurement obtained in the system illustrated in Fig.3.1.

The measurement are sent by using the Function LoRa_Tx and received by the function LoRa_Rx on MATLAB which are an open source access code[69], our work is based on the modified pilot file that is changed into 3 different files to allow transferring of real values measurement's for the 2nd bus,6th bus and the 9th bus as shown in Table 3.4, Table 3.5 and Table 3.6 respectively.

Table 3.4. Pilot code for 2nd bus.

```
SF = 10 ;
BW = 125e3 ;
fc = 915e6 ;
Power = 14 ;
L=70;%input('L = ');
n=600;%input('n = ');
%% Sampling
Fs = 10e6 ;
Fc = 921.5e6;
mod=mod(L:n);
phi=phi(L:n);
freq=freq(L:n);
for i=1:n-L
message = [1000*(mod(i)-0.95) 10*abs(phi(i)+10) 100*freq(i)-4900] ;
%% Transmit Signal
signalIQ = LoRa_Tx(message,BW,SF,Power,Fs,Fc - fc) ;
c=clock;
ti(i)=3600*c(4)+60*c(5)+c(6);
%% Received Signal
message_out = LoRa_Rx(signalIQ,BW,SF,2,Fs,Fc - fc);
R_mod(i)=message_out(1)/1000+0.95;
R_phi(i)=-message_out(2)/10-10;
R_freq(i)=message_out(3)/100+49;
c=clock;
tf(i)=3600*c(4)+60*c(5)+c(6);
end
delay2=sum(abs(tf-ti)/length(ti));
Error2=(sum(abs(R_mod-mod))+sum(abs(R_phi-phi))+sum(abs(R_freq-
freq)))/(n- L+1);
v=ti(1);u=tf(1);
```

Table 3.5. Pilot code for 6th bus.

```
%% Sampling
mod1=mod1(L:n);
phi1=phi1(L:n);
freq1=freq1(L:n);
for i=1:n-L
message1 = [1000*(mod1(i)-0.95) 10*abs(phi1(i)+10) 100*freq1(i)-
4900] ;
%% Transmit Signal
signalIQ = LoRa_Tx(message1,BW,SF,Power,Fs,Fc - fc) ;
c=clock;
ti1(i)=3600*c(4)+60*c(5)+c(6);
%% Received Signal
message_out1 = LoRa_Rx(signalIQ,BW,SF,2,Fs,Fc - fc);
R_mod1(i)=message_out1(1)/1000+0.95;
R_phi1(i)=-message_out1(2)/10-10;
R_freq1(i)=message_out1(3)/100+49;
c=clock;
tf1(i)=3600*c(4)+60*c(5)+c(6);
end
delay6=sum(abs(tf1-ti1)/length(ti1));
Error6=abs(R_mod1-mod1(1:end-1))+abs(R_phi1-phi1(1:end-
1))+abs(R_freq1-freq1(1:end-1));
er=sum(Error6(:,1))/(n-L);
v1=ti1(1);u1=tf1(1);
```

Table 3.6. Pilot Code for 9th bus.

```
%% Sampling
mod2=mod2(L:n);
phi2=phi2(L:n);
freq2=freq2(L:n);
for i=1:n-L
message2 = [1000*(mod2(i)-0.95) 10*abs(phi2(i)+10) 100*freq2(i)-
4900] ;
%% Transmit Signal
signalIQ = LoRa_Tx(message2,BW,SF,Power,Fs,Fc - fc) ;
c=clock;
ti2(i)=3600*c(4)+60*c(5)+c(6);
%% Received Signal
message_out2 = LoRa_Rx(signalIQ,BW,SF,2,Fs,Fc - fc);
R_mod2(i)=message_out2(1)/1000+0.95;
R_phi2(i)=-message_out2(2)/10-10;
R_freq2(i)=message_out2(3)/100+49;
c=clock;
tf2(i)=3600*c(4)+60*c(5)+c(6);
end
delay9=sum(abs(tf2-ti2)/length(ti2));
v2=ti2(1);u2=tf2(1);
```

3.4.2 Simulation Results and Discussion:

After running the Simulink model and the Pilot files, the figures shown bellow are obtained for bus 2,bus 6 and bus 9 respectively in terms of amplitude, phase and frequency.

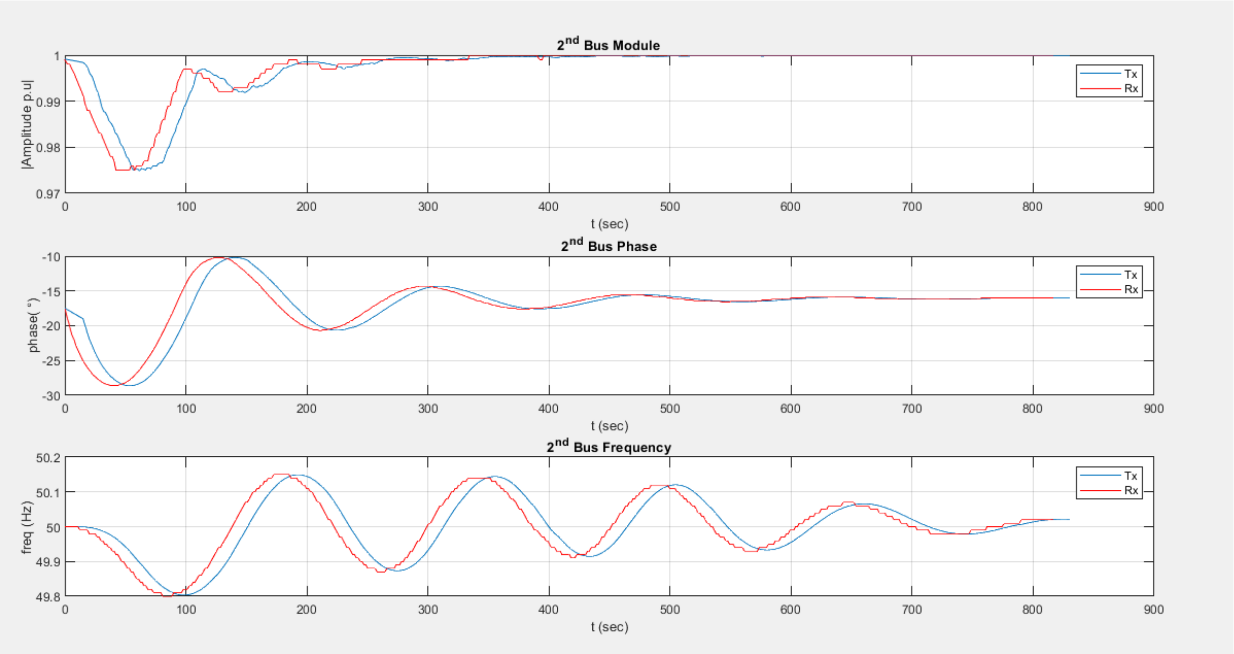

Fig. 3.9 Amplitude, Phase and Frequency for 2nd bus.

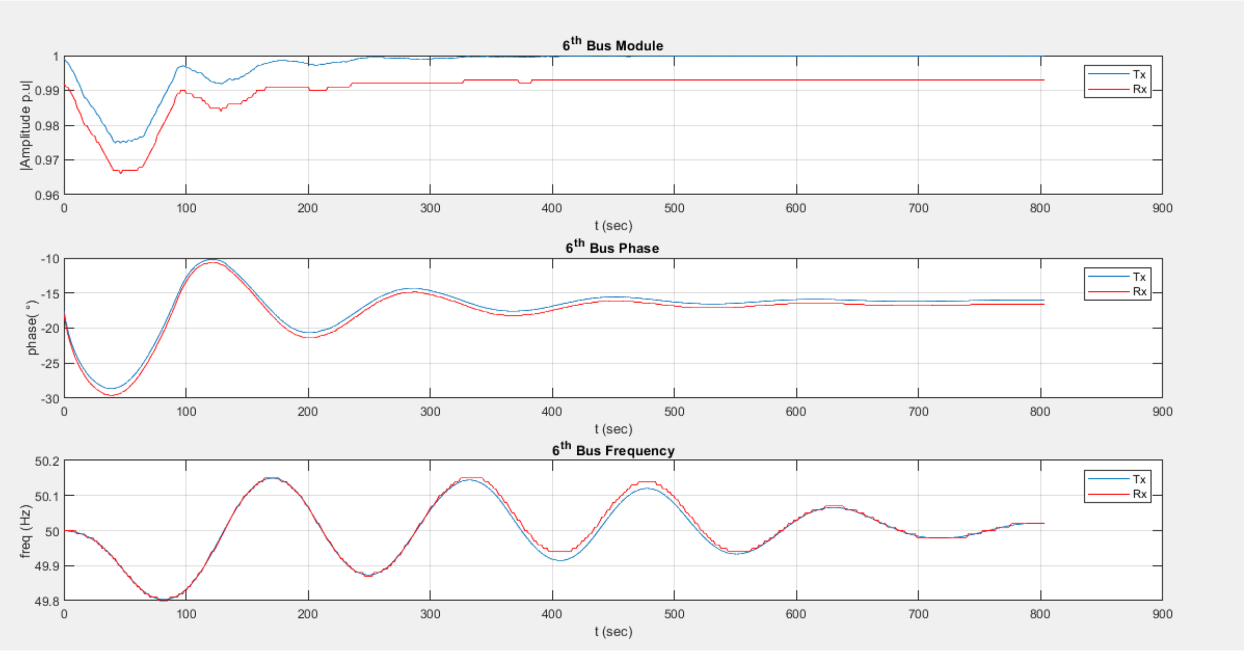

Fig. 3.10 Amplitude, Phase and Frequency for 6th bus.

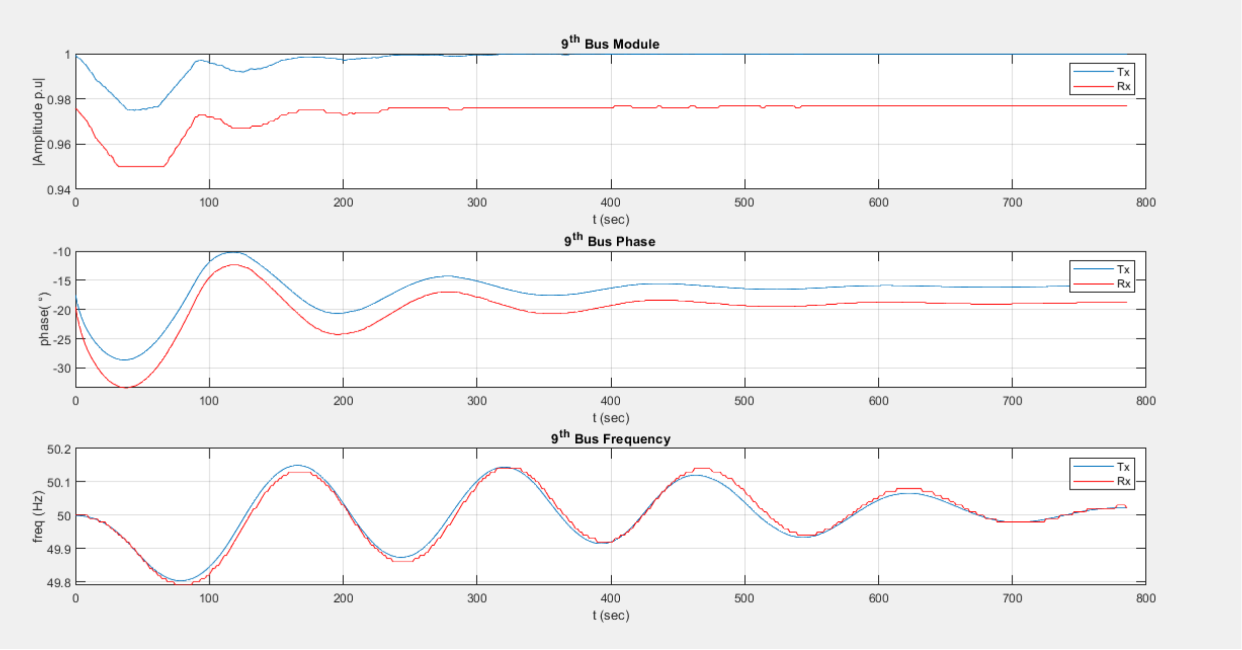

Fig. 3.11 Amplitude, Phase and Frequency for 9th bus.

From the above figures, we can see that the transmitted signal is approximately the same as the received one, with a slightly changement at some different period of time.

The simulation time is 42.000000 min and 14.400000 sec with a decision instant of 1.483674 sec

The following table gives the time delay for each bus and their corresponding transmission error.

Table 3.7 The error and delay for each bus.

	Time delay (sec)	Error
2nd bus	0.845881	0.049267413
6th bus	0.805521	0.046134732
9th bus	0.786660	0.037471326

The data in the above table shows that the time delay and the error for each bus is achieving good results for the same reporting rate at different buses in the system.

- **The effect of varying the reporting rate on error and delay:**

  We have changed the reporting rate by changing the reporting rate factor *k* =4,The following results are obtained:

The simulation time is 39.000000 min and 0.631000 sec with a decision instant of 1.459555 sec

Table 3.8 The error and delay for each bus for a reporting rate factor *k*=4.

	Time delay (sec)	Error
2nd bus	0.783991	0.016123796
6th bus	0.768762	0.015199478
9th bus	0.774819	0.016477569

From the above table we can see that the time delay and error decrease as we change the reporting rate factor which lead to a new value of the reporting rate as shown in equation (3.1), the increase of the reporting rate affect the time delay and error positively which we can say that the interval length at which the event will be reported should been taken into consideration for achieving better time delay and data error.

3.6. Conclusion:

This chapter explored in details the performance of two communication techniques used in wide area monitoring system, A set of different Bit Error Rate values was found out using Single Input Single Output (SISO) and Multiple Input and Multiple Output (MIMO) antenna systems. We compared the results and concluded that MIMO system has low Bit Error Rate (BER) than SISO system for different value of Signal to Noise Ratio. It is also seen that for improving the Bit Error Rate which means better data correctness it’s needed to increase the reporting rate by changing the value of reporting rate facto k , or the sample time Ts which the analyses have revealed that BER performance markedly depends on the choice of those parameters, moreover the transmitted and received signal based on LoRa modulation and coding scheme are almost identical which shows the benefit of the LoRa communication technology over the other technologies for achieving better error and delay time.

MOKHBI Yasser

I dedicate my dissertation work to my family. A special feeling of gratitude to my loving parents, whose words of encouragement and push for tenacity ring in my ears. My sister who has always encourage me, my three brothers whose really were my right hand in my entire life, and all my family members.

I dedicate this work and give special thanks to my best friend Mecheri Aymen, I would also thank all my friends for being always on my side, last but not least i would like to thank all the ones whose their help guide us to accomplish this work.

MECHERI Aymen

Every challenge needs self efforts as well as guidance of elders especially to Those who were very close to our hearts.

I would like to dedicate this work to to the light of my world my mother a strong and gentle soul who taught me to trust in myself,to my father for earning an honest living for us and for supporting and encouraging me to believe in my work,to my aunt for being my guardian during my educational career, to my sweet and loving sister and my three brothers and to my two Grandmothers for being my first teacher, my best friend Yasser Mokhbi who share with me this work, to my friends who have never left my side, also my classmates and all the ones who helped me accomplish this work.

Summary of the work:

In this report, we presented the different communication techniques used in wide area monitoring systems for developing smart grids and the study was mainly constructed based on LoRa communication specification for a chosen wide area power system.

Initially, general definition of smart grid, illustrating the main differences between today’s grid with smart grid are discussed, the infrastructure of the wide area smart grid model architecture is presented with the main features for wide area system design which are listed as follow measurement, communication and monitoring, some of the key parameters in wide area communication and monitoring system to be carefully considered are the data correctness which refer to the bit error rate (BER) and the delay of reporting data.

By studying the performance of a modified SIMULINK model on MATLAB software and obtaining the bit error rate (BER) for a different values of signal to noise ratio (SNR) related to each communication technique, it is clear from the results obtained that Multiple Input Multiple Output System is preferred to have advantages over Single Input Single Output System for better data correctness.

Finally, by working on the SIMULINK model of IEEE 14-bus power system on MATLAB which data measurements are transferred through both SISO and MIMO systems. The simulation results demonstrate that the MIMO system approve that the SISO system for better Bit Error Rate with varying signal to noise ratio, this confirm the latest study that was discussed in chapter 2, then the LoRa emulator code is simulated and used as a communication system to compare the transmitted and received signal for the same power system based on data error and time delay, the results show that LoRa Technology is more practical in terms of those two parameter which benefits for the designing of better communication infrastructure in wide area systems.

Further work:

Further improvements can be adapted to our work model by considering the power system state estimation, where the problem becomes more difficult when estimating the state (voltage magnitude and angle) of all the other buses in a power system on the basis of measurement carried out at few buses, we should take into account the delay of reporting data for each bus and the error followed.

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