Sudan University of Science and Technology

College of Post Graduate Studies

Catastrophic Risks Analysis for Telecommunication System in Petro Energy Company - Sudan

تحليل مخاطر الكوارث في أنظمة الاتصالات بشركة بتروانرجي – السودان

A thesis submitted in partial fulfillment of the requirements for degree of *M.Sc* in Telecommunication Engineering

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الآيــة

قال تعالى:

وَيَسْأَلُونَكَ عَنِ الرُّوحِ قُلِ الرُّوحُ مِنْ أَمْرِ رَبِّي وَمَا أُوتِيتُم مِّن الْعِلْمِ إِلاَّ قَلِيلاً (٨٥) وَلَئِن شِئْنَا لَنَذْهَبَنَّ بِالَّذِي أَوْحَيْنَا إِلَيْكَ ثُمَّ لاَ تَجِدُ لَكَ بِهِ عَلَيْنَا وَكِيلا (٨٦) إِلاَّ رَحْمَةً مِّن رَّبِّكَ إِنَّ فَضْلَهُ كَانَ عَلَيْكَ كَبِيرًا (٨٧)

صدق الله العظيم

سورة الإسراء

Dedication

To My Mother, My Father for their continuous guidance, kindness, and believing on me. With my best wishes and ask God to keep them healthy.
To My Wife, My children, as a great thanks to their unlimited support, love and patience until I reach this stage.
To My Brothers and Sister for their help and advice.
To my Teachers and Friends for their advices and cooperation.

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I would like also to express my deepest appreciation to my colleagues at Petro Energy Company, ***Engineering & Construction Department, Pipeline Technical Service Department and Information Technology Department.*** *for providing the required data for this project and providing consultancy whenever needed.*

Abstract

In industries like oil and gas, Telecommunication Networks used multiple communication technologies to eliminate any possibilities of failures, when the network is operational, in case of catastrophic situation these networks have strict and tight requirements for robust. Accordingly availability of the transmission network is essential, even short interruptions especially during catastrophic risks may cause considerable economic losses and major environmental impacts.

In reality the network can face multiple of problems, which can halt or interrupt communication for seconds, minutes, hours and in some cases days.

In this thesis, the robustness of transmission networks for oil and gas facilities is evaluated for normal and catastrophic risk situations to avoid maximum interruptions in communication by comparing the major three technologies (Optical, Microwave LOS, and Satellite VSAT) in terms of availability, repair and replacement time and costs, applying Failure Modes and Effect Analysis (FMEA) to consider any future technological requirements during risk situation.

The results of the analysis show that the oil fields transmission technologies have some predetermined trends, impacts and risks associated with different kind of manmade and natural hazards at different geographic locations, which can be prevented by applying Failure Modes and Effect Analysis (FMEA) with a combination of transmission technologies for both normal as well as catastrophic situations.

This thesis highlights the importance of robustness related to repair and replacement time and costs due to catastrophic calamities and will serve the oil industry to make an efficient decision while designing or extending transmission networks for Oil and Gas facilities.

المستخلص

في الصناعات النفطية يتم استخدام تقنيات اتصالات متعددة و ذلك نسبة للحد من احتمالات حدوث اعطال في انظمة الاتصالات. اثناء مرحلة استخدام الشبكة وفي حالة الكوارث بالتحديد يجب ان تكون هذه الشبكات في افضل متانة متطلبة. وفقا لذلك توفر شبكة الاتصالات أمر ضروري، وانقطاعاها حتي لفترات قصيرة خصوصا خلال المخاطر الكارثية قد يسبب خسائر اقتصادية فادحه وتأثيرات بيئية كبيرة.

في الواقع شبكات الاتصالات في حقول النفط تواجهها مشاكل متعددة, والتي يمكن ان تؤدي الى ايقاف او انقطاع الاتصالات لثواني, دقائق, ساعات, وفي بعض الأحيان الي ايام.

في هذا البحث سوف اتناول دراسة المخاطر في شبكات الاتصالات في الاحوال العادية وفي الاحوال الكارثية و التأكد من مدي متانتها و عملها بكفاءة عالية في هذه الظروف. و سوف يتم المقارنة بين ثلاثة أنواع من تقنيات الاتصالات المتوفرة في الحقول النفطية و هي (الالياف الضوئية, المايكروويف والاتصالات بالأقمار الصناعية), و سوف يتم المقارنة في كل من توفر الشبكة باستخدام طريقة تحليل الاعطال السنوية و مدي تأثيرها, المدة الزمنية و تكاليف اصلاح الاعطال في الأحوال العادية و الأحوال الكارثية.

النتائج و التحاليل أثبتت ان كل التقنيات تتأثر جدا بالمخاطر المتوقعة و التي غالبا ما تكون بفعل الطبيعة او بواسطة الأخطاء البشرية المتعمدة و غير المتعمدة, و التي يمكن التقليل من تأثيراتها بواسطة نظام توفر الشبكة باستخدام طريقة تحليل الاعطال السنوية و مدي تأثيرها, في كلا الحالتين العادية و الكارثية.

أيضا البحث تناول نقاط الضعف و المتانة في كل تقنيه علي حدي ومدي تأثرها في حال المخاطر الكارثية من أجل اخذها الاعتبارات في كل تصميم أو تحديث لشبكات الاتصالات في صناعة النفط و الغاز.

Table of Contents

List of Figures

List of Tables

Abbreviations

Abbreviation	Meaning
BBC	Baleela Main Base Camp (Petro Energy Company).
BOPD	Barrels Oil Per Day.
BV#2, BV#3, ...	Block Valve station along the pipeline (Petro Energy)
BW	Band Width
CapEx	Capital Expenditures
CC	Cable Cuts
CCTV	Closed-Circuit Television system
CNPC	China National Petroleum Company
C/N	Carrier to Noise Ratio
CP#2, CP#3, ...	Cathodic Protection station along pipeline (Petro Energy).
CPE	Customer Premises Equipment
CT	Calamitous Time
CTTR	Catastrophic Time to Repair
DCS	Distributed Control System
EIRP	Equivalent Isotropic Radiated Power
ESD	Emergency Shutdown System
FIT	Failure in Time.
FMEA	Failure Modes and Effects Analysis
FOC	Fiber Optic Cable
FSL	Free Space Loss
GNPOC	Greater Nile Petroleum Operation Co.
HazID	Hazards Identification.
HAZOP	Hazards and Operability
HQ	Petro Energy Head Quarter in Khartoum (Petro Energy)
IEEE	Institute of Electrical and Electronics Engineers
IM	Inter-Modulation
ITU	International Fiber Telecommunication Union
KT#6	Khartoum Terminal No. 6 at Algaili near Khartoum (Petro Energy)
Keyi, Moga, FNE, Jake, Hadida	Production fields in Block #6 (Petro Energy)
LOS	Line of Sight
MDT	Mean Down Time
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
MUT	Mean Up Time
NIST	National Institute of Standards and Technology
N/W	Network
ODF	Optical-fiber Distribution Frame
OpEx	Operational Expenditures
OTDR	Optical Time Domain Reflectometer.
PABX	Private Automatic Branch Exchange
PE	Petro Energy Exploration & Production Co.
PAGA	Public Address and General Alarm
PEP	Performance Enhancing Proxy
PS#1, PS#2, PS#3, PS#4, PS#5	Pumping stations No. 1, 2, 3, 4 & 5 along pipeline (Petro Energy)
QRA	Quantitative Risk Analysis.
RAS	Reliability, Availability and Serviceability
RTU	Ring Terminal Unit
SCADA	Supervisory Control And Data Acquisition system.
SDH	Synchronous Digital Hierarchy
SLA	Service Level Agreement
SNR	Signal to Noise Ratio
STM4	Synchronous Transport Module level 4.
UPS	Uninterrupted Power Supply
TX, RX	Transmitter, Receiver
VSAT	Very Small Aperture Terminal is a two-way satellite ground station
Wireless BB	Wireless Broad Band.
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability For Microwave Access.

Chapter One

Introduction

1.1 Overview

Since 1999 oil industry has become critical to the economy and stability of Sudan Republic for both export and local consume. And with the increasing demand for new oil discoveries to increase production and the challenges of maintaining production volumes from older fields and reducing production loss; companies are being forced to search for oil in more remote regions which present a range of challenges in information exchange such as the availability of high volumes of visualization, monitoring and control for information, ability to manage extremely high capacity as data demand has grown accordingly, faster decision making based on instant update of process data which may help in the identification and prevention of potential problems.

In such cases, communications becomes a premium commodity from both a business and safety perspective playing a key role in all operations, daily supervision, dispatching and monitoring of operations, workers and security personal management independent of their location in the production area.

Communications helps “bringing the field to operator rather than sending operator to field” or at least minimize the number of people at remote fields especially in hazardous areas ensuring safety for workers and sometimes general public as well. [1]

1.2 Problem definition

It is essential that the communication systems in oil and gas production are reliable with high availability of real time data on a 24/7 (Twenty four hours daily / Seven days weekly). In reality a network can face multiple problems which can halt or interrupt communication for seconds, minutes, hours and in some cases days. In this thesis I will try to compare three transmission technologies (Optical, Microwave LOS, and Satellite) by evaluating the availability, repair and replacement time and costs in normal and catastrophic situations by means of a risk analysis to improve the robustness. Also even under the most extreme conditions since even short interruptions can cause considerable economic losses, Safety and environmental impacts.

1.3 Objective

The objective of this research is to evaluate the robustness of the Oil & Gas fields telecommunication networks in catastrophic situations by making risk analysis for the major transmission technologies (Optical, Satellite "VSAT" and Microwave LOS) in in normal and catastrophic situations by evaluating the availability, repair and replacement time and costs in normal and catastrophic situations by means of a risk analysis to improve the robustness.

The telecommunications systems of Petro energy oil & gas operating company was taken as a case study in this research to represent the telecommunications system in oil industry in Sudan as a whole.

1.4 Methodology and Tools

1. Exhaustive knowledge of catastrophic risks and events, their impact is been collected by searching the internet [2] and from experts in Petro Energy, Projects and Facilities department.
2. Telecommunications systems failure incidents in 2014 for Petro Energy were collected and classified following FMEA methodology for the three telecommunication technologies, as well as overall Network calculation.
3. Systems Topologies were modeled as block diagrams.
4. Availability and total down time of these systems were calculated.
5. Qualitative and Quantitative Analysis techniques are used to judge against the robustness of three communication technologies based on the catastrophic risks and their impact including Availability, repair and replacement time and cost are quantitative entities, while risks, impacts and weakness of transmission technologies.
6. Based on the results, recommendations to company for precautions, solutions and enhancement were made.

FMEA is a general procedure, but its specific details may vary with standards of each organization or industry. In this thesis, FMEA is used to measure only system availability in the normal situation and down time. So, the basic steps followed in conducting the FMEA were[2]:

1. Classifications of systems and subsystems by functions.

2. Development of block diagrams for the systems as per their networks topologies.
3. FMEA form work sheet was designed as shown in table (1.1)
4. Failure modes and incidents were listed as per company failure log during 2014.
5. Failure causes were identified to check whether they were design failure, operation failure or environment failure or other.
6. The time taken to repair the failure and the failure annual frequency were listed and time between failures was calculated accordingly.
7. The availability of each system and then for the overall system and total down time were calculated using the data in table (1.1)
8. Effects of these failure modes were described.

Table (1.1): FMEA Designed Form Sheet

No.	**Location**	**Failure/ Behavior**	**Reason**	**Time to Repair (hrs)**	**Failure Annual Rate**	**Time between Failures (hrs)**	**Solution / Treatment**	**Remark**

1.5 Thesis Layout

In Chapters 2 is generally discuss definitions and identifications of the Catastrophic risks in oil & gas and make qualitative analysis of possible risks, gives a brief description of natural and operational (manmade) risks, which can damage communication networks and result in loss of production. Chapter 3 illustrate a general description of the telecommunications system in Petro Energy. Purpose of the system, components, characteristics, compares all three technologies with respect to possible weakness which can harm the network. Chapter 4 gives the detailed analysis of availability, repair and replacement time and costs for transmission technologies. This will provide some facts which are not considered normally when a network is designed; a technology can very well be cost effective in normal conditions and most expensive in catastrophic situations. Chapter 4 also take Petro Energy E&P as case study and applied the FMEA analysis for the faults in the three telecommunication technologies. Chapter 5 deals with the final discussion, conclusions and some recommendations to the company were made as well as future works.

Chapter Two

Catastrophic Risks and Hazards

2.1 Catastrophic Risks

For a robust Oil and Gas fields transmission network, understanding of Risks and associated impacts can halt the communication of oil and gas facilities is necessary. Safety requirements are also enforce engineers to eliminate all kinds of risks involved in oil and gas operations. The following are the steps of the risk process [3].

- Plan Risk Management.
- Identify Risks.
- Perform Qualitative Risk Analysis.
- Perform Quantitative Risk Analysis.
- Plan Risk Responses.
- Control Risks.

There are 2 major catastrophic risks identified and categorized as following depends on their impacts.

1. Natural Catastrophic Problems
2. Operational Catastrophic Problems

2.1.1 Natural Catastrophic Problems:

Natural Catastrophic Problems are phenomena that occur in the environment and are external to the oil and gas infrastructure and it is operations. Natural Hazards include atmospheric, hydrologic, geologic and wildfire events that, because of their location, severity, and frequency, have the potential to affect the oil & gas infrastructure adversely. These Hazards are typically considered to be sudden, unexpected, or unusual.

The following classes of natural hazards [4]:

- Earthquakes
- Tsunamis
- Volcanoes

- Coastal Erosion
- Permafrost Thawing
- Severe Storms
- Floods
- Severe Currents
- Avalanche
- Forest Fires

The oil and gas industry has been facing natural catastrophic problems since decades and engineers are continuously developing more and more robust models to avoid the damages.

The communication systems relying on wireless transmission technologies can be vulnerable in severe weather conditions; although adequate engineering efforts are put to enhance the overall performance criteria of the oil and gas fields wireless transmission technologies. Figure 2.1 shows the map of natural catastrophic and hazards with risks:

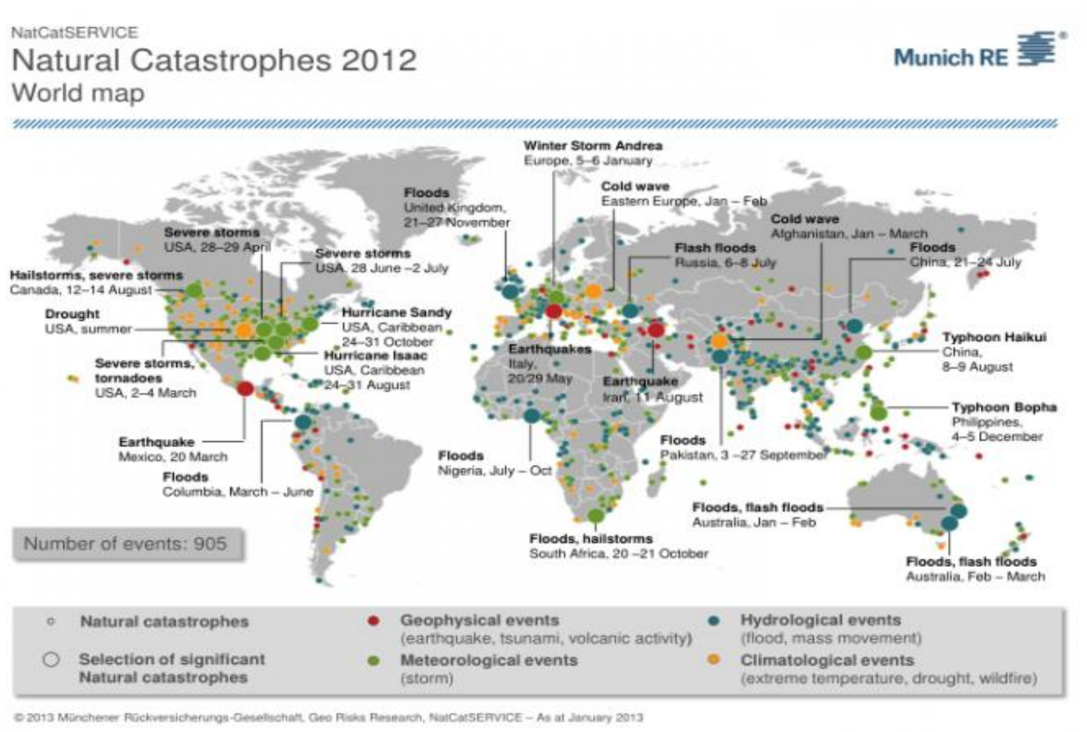

Figure (2.1): World Map of Natural catastrophic and hazards with risks. ReliefWeb [5]

2.1.2 The Natural hazards Risk Assessment:

The first step of the natural hazards screening is to identify those natural hazards. For each applicable hazard event, the equipment associated with the node will then be reviewed to determine if it is vulnerable to failure for that natural hazard. If the node passes these two screening steps (i.e., a specific natural hazard is applicable and equipment in the node is vulnerable to that hazard), likelihood and damage for the applicable natural hazards will be assessed using a detailed risk assessment model based on industry guidance for natural hazards assessment.

For this thesis case study, PETROENERGY-E&P Sudan, Located in Block(6) and most of the Facilities are located in the northwest of the Muglad basin in west Kordofan , it expected to have Natural catastrophic because of Earthquakes, Volcanoes, Severe Storms, Floods and, Forest Fires.

If the Oil & Gas field is affected by severe storm and cause damaged of the microwave LOS links, Satellite links may performed better than microwave because of technical and physical differences. Some satellite links were rigorously affected if the ground station is affected. Generally, weather impacts for satellite links are affordable during catastrophic events, as these links can be recovered within hours after the catastrophic event. While recovering microwave LOS links can take days, if the transmission network is damaged.

2.1.3 Operational Catastrophic Problems:

The Operational Catastrophic and Hazards, also called as Manmade Catastrophic Hazards, it is that relate specifically to the processes, systems, and equipment that make up the oil and gas infrastructure and can be caused by human actions or equipment or system malfunctions associated with the operations of a system. Figure 2.2 & 2.3 shows the Sample of operational catastrophic and hazards.

These events can occur within the boundaries of a plant or facility and are a result of oil and gas system operations activities and tasks,

Figure (2.2): Sample of operational catastrophic and hazards (Indian Oil depot fire| Photos-IBNLive)[6]

Figure (2.3): Sample of operational catastrophic and hazards (California: Catastrophic Methane Gas Leak)[7]

Natural events are uncontrollable and can cause severe damages despite of intelligent engineering, while manmade calamitous events can be minimized by defining rules and regulations, risk analysis, and optimization, based on the lessons learnt from the past. Problems faced due to lack of engineering, unannounced maintenance activities. Manmade problems can be further classified as:

- Intentional manmade problems
- Unintentional manmade problem

Following are the measure hazards risks identified from the operation Catastrophic problems:

- Fires and explosions (which can result from hydrocarbon releases)
- Spills and leaks (e.g., due to natural aging process – corrosion, abrasion, wear and fatigue)
- Equipment malfunctions
- Loss of infrastructure support systems (e.g., power)

- Changes in process conditions (e.g., composition– heavy oil, increased quantities of solids produced, and throughput decline)
- Human errors (due to worker fatigue, not following proper procedures, resource availability, etc.)

2.1.4 Operational Hazards Risk Assessment:

The operational hazards assessment involves estimating the infrastructure risks that can be attributed to equipment failures from mechanical failures and human errors. Failure modes will be identified for equipment in those nodes that could potentially have significant impacts, as identified by the preliminary screening of infrastructure. For these particular equipment failure modes, data will be gathered from published references and from meetings or workshops with owners/operators of the infrastructure. The data will be combined using applicable statistical methods, and a failure frequency will be estimated. The consequences of each scenario (i.e., the impact on safety, the environment, and system reliability) will be calculated accordingly.

Various methods were evaluated for use in examining operational hazards for the project. It should be noted that some approaches overlap and include elements of other methods (e.g., fault trees and event trees are tools often used in quantitative risk analysis (QRA)). Approaches considered for the operational hazards assessment include:

- Hazard identification (HazID) techniques
- Fault tree analyses
- Event tree analyses
- Detailed QRA approaches
- Consequence analysis methods (e.g., modeling for releases, fires, explosions)
- Failure modes and effects analyses (FMEAs)
- Availability assessment

Manmade problems can be more dangerous when such problems are created intentionally. There has been comprehensive research on terror activities, since the Oil and Gas industry is a building block of the world economy. In less developed countries, where governments seem ineffective against radical and fanatic groups of people, terror activities are likely to happen. Operators are more concerned about manmade vulnerabilities.

For PETROENERGY-E&P Sudan, the interruption by the local people is considered and expected to generate further manmade catastrophic problems, measure action by local people is to cut the fiber optic cable.

2.2 Inadequacies of Transmission Networks due to Catastrophic Hazards:

Deficiencies of oil and gas field transmission networks due to hazardous calamities depend on type of hazard and its magnitude, as discussed above, sometimes it will lead to total Telecommunication Losses. Here we will limit our discussion to the damages faced to the communication infrastructures. Some of the major sensitive inadequacies discussed below:

Transmission failures: Transmission failures can occur due to the equipment failure, cable damages and interruptions in link. In extreme weather conditions, the wireless transmission links can deteriorate and perform very poorly, and eventually can result in links breakdown. Transmission equipment can be damaged due to power problems, flooding, terror activities, extreme winds etc.

Emergency communication: Emergency communication like 911 services are especially designed to work in catastrophic situations for search, rescue and recovery operations; but these services can also fail, if the transmission technologies fail.

Safety: An important factor for designing a robust communication networks is to provide sufficient safety, since catastrophic events not only destroy and damage the communication systems but can be deadly for the people surround the exact field, exactly the communication services the Emergency Shutdown Systems

ESD, Fire & Gas and Fire Fighting System, Public Address and General Alarm System PAGA System.

Security: Security is also a very important issue, nowadays terror activities around the world are increasing. It is becoming more and more important to design robust networks which can survive or prevent maximum losses, in case of terror activities and make the CCTV system and timely image reporting in a good performance.

Production losses: Production is the soul of an oil field and a catastrophic event can halt the production for undefined time, depending on its magnitude and impact.

Power failures: Electrical devices require power to operate. Telecommunication devices are supported with backup power and *Uninterrupted Power Supply (UPS)* for limited time, the communication can fail if the restoration of main power takes longer than estimated time.

Survivability: Operational of Oil and Gas fields require (24/7), 24 hours per day and 7 days per week availability of communication, the survivability of such facilities is necessary. In catastrophic conditions, survivability factors no longer respond as designed and optimized. Inadequate precautions for survivability can result in huge losses. Survivability can be analyzed based on three categories [8].

1. Network availability
2. After failure survivability
3. Disaster based survivability

Network availability is calculated as hours/year for each transmission technology under normal conditions, after failure survivability deals with partial damage to communication and disaster based survivability considers worst case, where all possibilities are taken into account i.e. no damages, partial failures and total failures.

Chapter Three

Petro Energy Telecommunication Systems and Networks Vulnerabilities

3.1 Petro Energy System Description:

Petro Energy is an oil operating company owned by China National Petroleum Corporation (CNPC) and SUDAPET, investing in block#6 which is located in the northwest of the Muglad basin in west Kordofan, Block #6 covers an area of 17,875 square kilometers and the block is about 700 KM far from Khartoum. The overall average daily production is 60,000 BOPD From which 20,000BOPD is exported through Portsudan marine terminal #1 and 40,000BOPD are transported to Khartoum refinery for local consumption.

3.1.1 Overview of Oil and Gas Journey

The oil & Gas starts from the Well Heads through the flow lines and gathered in the Oil Gathering Manifolds, the separation and heating process completed in the Fields and Central Processing Facilities then the overall daily production sent though the pipeline and Pump stations to Export or Khartoum refinery, Figure (3.1) below indicate the oil Journey in Petro Energy.

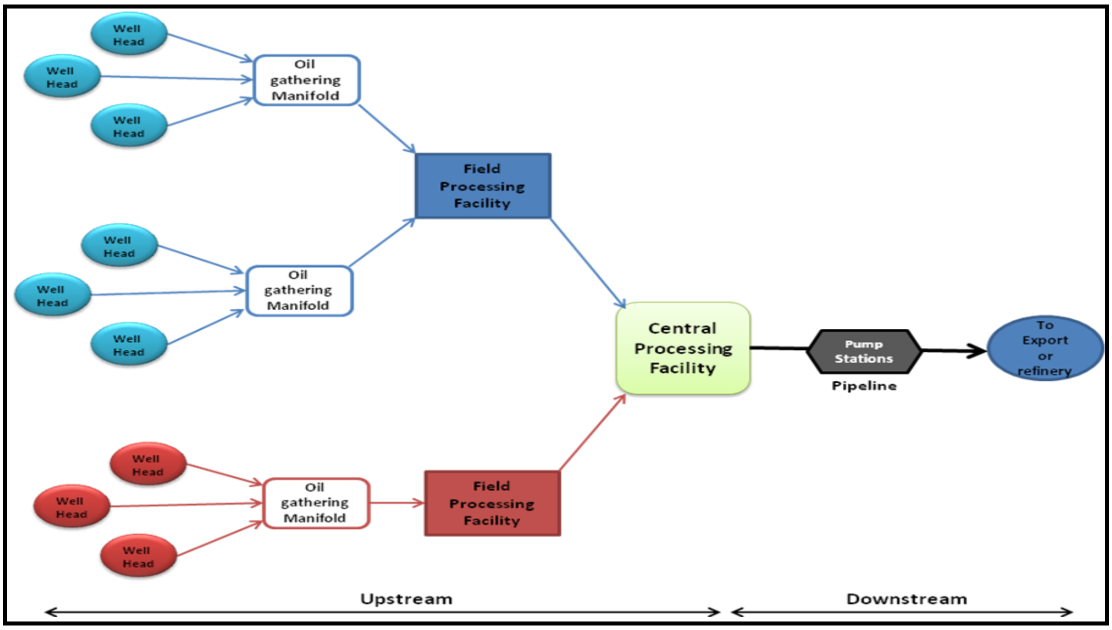

Figure (3.1): Oil from Origin to Destination

3.1.2 Purpose of Telecommunications Systems

The purpose of telecommunication systems in Petro Energy is to provide the necessary voice and data communications through reliable telecommunication service for each facility in the field and the oil pipeline and meet the basic telecommunication requirement of production management and maintenance management as below:

- Communication between the Plant and Operation locations.
- Communication between company and outside world with the Partners, Vendors, etc... .
- Communication with mobile operating equipments, vehicles and personnel (exploration, patrolling and emergency repairs)
- Support computer data networks in office.
- Data transmission service for control systems (mainly DCS and SCADA system to realize whole-field remote supervision and control)

Typical Systems used are:

1. Fiber Optic Transmission System (Primary backbone)
2. Satellite Transmission System (VSAT)
3. Microwave system
4. Radio Communication System
5. Telephone/ PABX & Public Telephone Network
6. Computer Data Network (LAN)

Main Characteristic for these systems are shown in table no. (3.1)

Table (3.1): Main Characteristics of Telecommunications Systems used in Petro Energy

#	System	Capacity	Data/Voice
1	Fiber Optic Transmission System	622 MB/s	Both
2	Satellite Transmission System (VSAT)	4.8 MB/s	Both
3	Microwave system	54MB/s	Data + VOIP
4	Radio Communication system		voice
5	Telephone/ PABX & Public Telephone Network	600 lines	voice
6	Computer Data Network (LAN)	10GB (From backbone server to core switch) 1 GB (distribution to clients)	Data

As per the described before this thesis will concentrate in the study of the infrastructure communication systems of Fiber optic, Microwave LOS and, Satellite (VSAT). Description as follows:

3.1.3 Fiber Optic Transmission System

Fiber optic system which is based on Synchronous Digital Hierarchy (SDH) STM-4 (622M) is the primary telecommunication system since:

- It provides direct connection with large carrying capacity (the bandwidth surpasses the needs of today's applications and gives room for future growth).
- Low power loss which allows for longer transmission distances.
- Low interference since it is not subject to environment changes.
- Safe and does not present any spark hazards in oil fields.
- Secured since optical Fibers are difficult to tap though companies' sensitive and confidential data is protected.

Structure:

A ring structured Fiber optic system covering the main Processing Fields and pump stations and along the pipeline (sometimes buried with the pipeline in the same trench) consisting of 12 core direct burial single mode armored fiber optic cable with approximately total length of 915 KM and Fiber Optic Transmission Equipments along the Fiber optic cable path.

3.1.4 Satellite (VSAT) System (Back-up Telecommunication System)

The VSAT System is designed to be as telecommunication back-up for both data and voice communication in the case of failure of Fiber Optic main communication backbone.

When fiber optic system failure is detected the traffic automatically switched to VSAT system via the router (dynamic routing protocol).

The satellite is used to provide data and voice communications between the stations, control centers in field and the main earth station (central management of the network) in Khartoum Terminal KT#6.

Traffic speed is relatively slow compared to the fiber optic with less capacity. Band width of 4.8 MHz is leased from authority and annual fees are paid.

The bandwidth is allocated dynamically by the network management system for the voice and data so as to be fully utilized. To overcome the capacity problem; usually the Internet is disabled to utilize the available capacity for the urgent traffic until the Fiber optic system recovered.

3.1.5 Microwave System

Microwave is also used as a redundant system for Fiber optic in the upstream together with the VSAT. And to connect wells RTUs to the processing facility for wellheads speed monitoring and control.

It acts as point to point communication within short distances not more than 50 KM.

3.2 Vulnerabilities of Transmission Technologies

Before going into technical details of catastrophic vulnerabilities of major transmission technologies, it is important to first characterize these technologies in normal situations.

Transmission technologies provide very good performance and efficiency, according to vendor specifications until and unless something goes wrong. Some parameters specified by vendors regarding damages and failures are MUT, MDT, maximum and minimum temperatures etc.

Microwave LOS technology provides more bandwidth to support different kind of services, satellite has a limited bandwidth but more robust against various geo-calamities, while optical communication fulfills the bandwidth requirements but is difficult to install and repair.
Complexity of optical communication grows as the network grows, with more traffic utilizing the transmission network, and cost of the network also increases with distance. Operations and maintenance activities become difficult with increasing number of add drop multiplexers. Any damage caused to the fiber core carrying most of the traffic can affect all other nodes in the network, since in many cases they share the bandwidth on the same core. Similarly microwave LOS has its limitations due to weather problems, distance between the field, limited coverage and installation costs. Weather problems and distance, form the major limitations of microwave technology. Intermediate repeaters and regenerators are needed for distances longer than 70 km. Satellite communication is an exception, since satellite links have bandwidth limitations, latency problems, and are costly. Satellite has the major advantage of geographical coverage of anywhere and everywhere, while with the advancing coding techniques and Performance Enhancing Proxy (PEP) application satellite operators claim better performance. Table 3.2 gives an overall impression of three major technologies and their characteristics in normal conditions.

Table (3.2): Transmission network characteristics in normal conditions

NO.	Properties	Optical	Microwave LOS	Satellite
1	Easy Installation and movements	×	✓	✓
2	Maintenance	✓	✓	✓
3	Safety concerns	✓	✓	✓
4	Security concerns	✓	✓	✓
5	Up gradation	✓	✓	✓
6	BW utilization	✓	✓	×
7	Geographical area coverage	×	×	✓
8	Complexity	×	✓	✓
9	Weather problems	✓	×	×
10	Power Feed	✓	✓	✓
11	Latency	✓	✓	×
12	Technology aspects	✓	✓	✓
13	Total costs (Installation + Operating)	×	✓	×

3.2.1 Vulnerabilities of Optical technology:

Optical technology is often considered as costly and complex, but very efficient in terms of reliability and bandwidth.

Vulnerabilities of optical transmission links are either related to the transmission equipment or the optical cable. Transmission equipment is always installed in 1+1 configuration with some additional spares in the storage. Even in case of equipment failure, networks remain alive because of this 1+1 configuration. Optical cable remains vulnerable to external threats. The following problems can be observed in an optical network due to catastrophic situations.

- Transmission equipment failure
- Optical cable break down
- Permanent cable damage

3.2.2 Vulnerabilities of Satellite Communication

Satellite communication is mostly utilized as an emergency backup, as it tends to be more robust against catastrophic failures. Satellite communication has fewer chances of equipment failures and network outages during and after the catastrophic events. As a matter of fact, satellite communication is reliable but at the cost of delay or latency. Geographical coverage of satellite communication is an added advantage over microwave LOS and optical communication. Satellite communication has less

vulnerability due to natural catastrophic problems on earth but very sensible to the space weather problems.
The major vulnerabilities of satellite communications are as follows:

- Antenna displacement
- Equipment failure
- Power failure
- Longer outages
- Satellite lost
- Weather effects

Like other technologies, satellite links are also affected due to severe weather conditions on earth. Communication dishes and towers get damaged, antenna alignment gets disturbed due to severe weather conditions; fractional variations in antenna alignment angles might affect the overall link performance. Flooding, fire and explosions due to weather can also damage the transmission equipment.

3.2.3 Vulnerabilities of Microwave LOS technology

Microwave LOS is the most widely used transmission technology all over the world, although microwave technology is open to all kind of weather problems. Microwave LOS provides reasonable bandwidth and operational costs. Depending on geographical location and weather conditions, microwave LOS networks can be designed efficiently. Although Table 3.2 reveals some limitations under normal conditions, microwave LOS has always attracted oil and gas industry as the major transmission technology and the reason is its low operational and maintenance costs.

Vulnerabilities of microwave LOS technology due to catastrophic problems can be:

- Equipment failure
- Signal attenuation
- Power failure
- Antenna displacement
- Weather problems

3.3 Disaster Recovery and Cost

In the previous section, vulnerabilities of transmission networks due to catastrophic events were discussed. In this section, disaster recovery and related costs of the transmission technologies are discussed. After the catastrophic events, systems must be back in service to continue production. For a robust transmission technology, the repair and the replacement activities should be easy, quick and cost effective. It is important to know the time to repair for each technology for a similar kind of catastrophic impact. In general, the time to repair and replace the transmission network can be estimated from the installation and maintenance time, which most of the time is vendor specific. Following are the three major parameters, which define the robustness of a transmission network after the catastrophic event.

- Easy repair and replacement
- Time to repair
- Cost to repair

These parameters cannot be specified in particular, as these factors depend on the type and magnitude of impact on the respective network. In general, these transmission technologies have different repair and replacement requirements, and time to repair or reinstall, and related costs, are also different. These difficulty levels, time to repair and costs can be approximated from the installation and maintenance activities during normal conditions. An optical link requires more time and man hours than satellite and microwave LOS links. Similarly microwave LOS requires more time than a satellite network. Similarly the cost to repair or replace damaged accessories for satellite networks is less than that a microwave LOS, and microwave LOS costs are less than optical communication. Table 3.3 shows the repair and replacement time and cost relationship between the transmission technologies due to catastrophic damages.

Table (3.3): Relation between transmission technologies, Time, Cost, and difficulties of Repair

No	Parameter	Relation
1	Easy repair and replacement	X<Y<Z
2	Time to repair and replacement	X<Y<Z
3	Cost to repair and replacement	X<Y<Z
X= Satellite, Y= Microwave LOS, Z= Optical		

Tables 3.2 and 3.3 give the relationship between these transmission technologies damages due to catastrophic events. Obviously this relationship is not always true but depends on several factors i.e. distances between the facility, type and severity of damage, availability of resources, geographical location etc.

3.4 Comparison in normal and catastrophic situations

In normal conditions, all three technologies give acceptable availability and robustness. Distinguishing technical aspects and installation and operating costs might attract one technology over another. Typically, microwave LOS is chosen as cost effective and robust, if the facilities are near to each other, provided suitable weather conditions according to the statistics of ITU rain regions. Similarly depending on the seismic changes due to geographical location and the type of reservoirs, the operators deploy optical solutions because of its enormous bandwidth advantage. Satellite communication is always considered as an emergency backup or the state of the art technology for the moving rigs. Satellite communication also has some major advantages over microwave LOS and optical networks. The oil fields communication infrastructure also may be damaged due to the heavy rains followed by flood.

Chapter Four

Network Robustness and Case Study

4.1 Network Robustness:

The transmission technologies are often described as robust and cost effective based on efficiently engineered availability or reliability models, low cost solutions and simple 1+1or 1:1 dedicated mechanisms of path protection. This approach can be disastrous if manmade and natural calamities are excluded in calculations. Before digging into the robustness issues related to the catastrophic calamities; the next section briefly gives an overall impression of robustness related attributes and their dependability. In general, robustness is the vigorous performance of any system in normal and unfavorable situations. A number of terminologies are defined and used for robustness. Some of the major attributes which are used to define robustness are reliability, security, survivability, availability, safety, dependability, integrity, fault tolerance etc. Although these attributes are different, their aims and objectives are interrelated. Further these attributes can be classified as quantitative and qualitative in our perspective; such as reliability and availability are quantitative while safety and security are qualitative. Table 4.1 shows the robustness related attributes; some attributes are measurable and some are immeasurable [9].

Table (4.1): Robustness related attributes

Quantitative attributes (measurable)	Qualitative attributes (Immeasurable)
Availability	Accessibility
Fault- Tolerance	Accountability
Integrity	Authenticity
Maintainability	Confidentiality
Perform ability	Non Repudiation
Reliability	Safety
Unreliability	Security
Unavailability	Testability

The definitions of above attributes are not really fixed; although some of them are well defined by the regulatory and standardization bodies e.g. ITU, IEEE and NIST etc. in respective contexts. The interdependencies of these attributes due to certain overlapping characteristics on each other demand a fair analysis of the relationship among these attributes. In [9] such relationships between six core concepts (dependability, survivability, fault-tolerance, reliability, availability and security) are discussed. Figure 4.1 shows that dependability and survivability, and availability and reliability have more or less similar goals to achieve, while some of the concepts from all six attributes are related to each other.

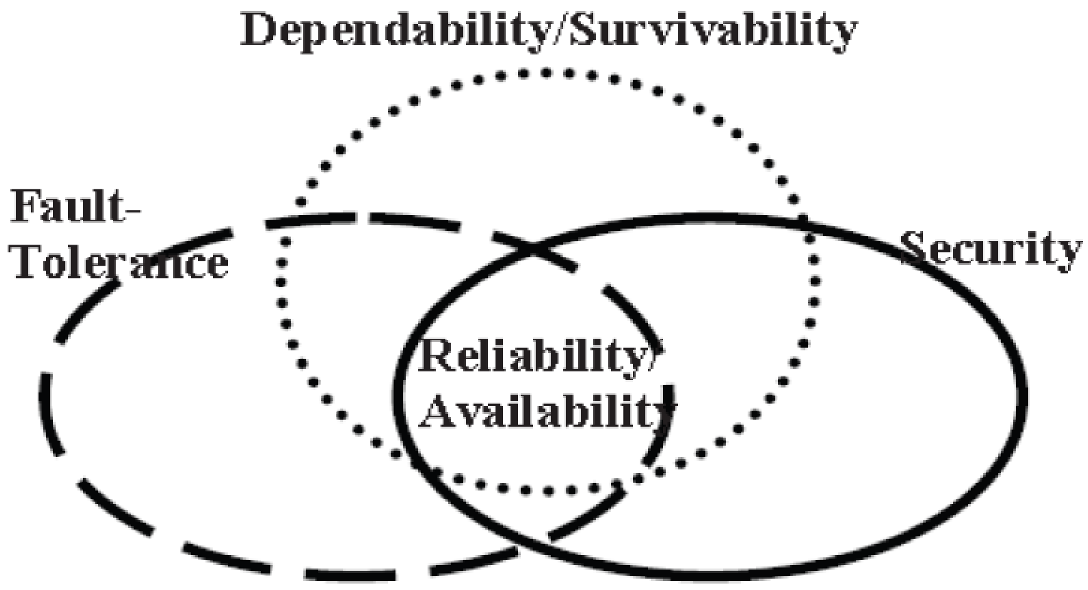

Figure (4.1): Relationship between robustness attributes

The analysis of robustness is a very complex and unclear phenomenon. Depending on the problem definition, type of application, sensitivity of network and minimum specific requirements, the approach to evaluate robustness also varies. The robustness related attributes mentioned above have emerged as a result of different approaches applied by scientific community and industry, depending on respective requirements. It is certainly very important to understand the notion of the problem before applying any particular method to solve it.

In this thesis, communication transmission technologies are analyzed with respect to their performance and recovery related in normal and catastrophic conditions. In [9] a simple model characterizing the network metric in order to evaluate the problem is discussed. Such models help to develop justifiable methodology while evaluating any problem in the network given initial problem definition. Figure 4.2 shows the measurable metrics characterizing objective analysis of the network.

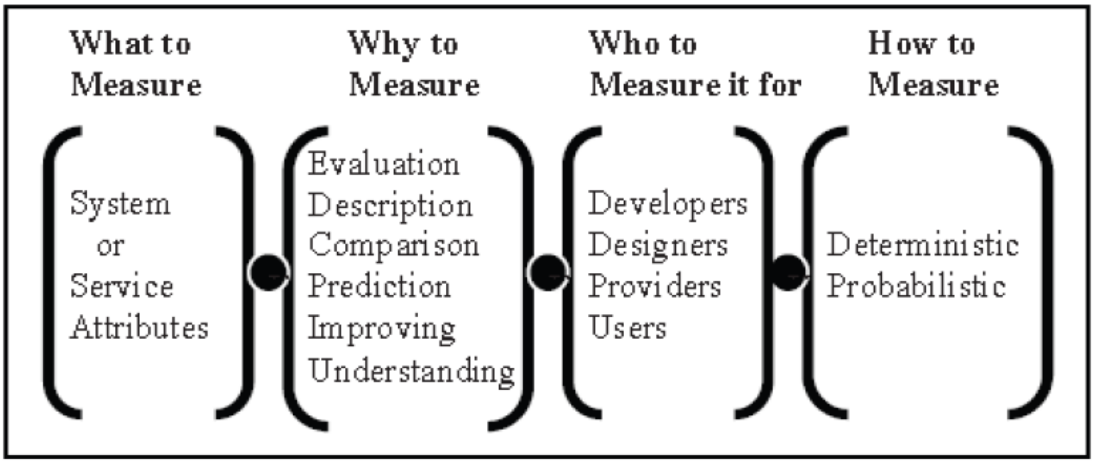

Figure (4.2): Network metrics for objective analysis

In this thesis, the analysis of robust of the transmission technologies is no different than the typical evaluation methods. In fact the approach applied is quite dynamic and practical. In the previous chapters, catastrophic calamities, their impacts and the vulnerabilities due to such events were discussed in detail. Now, the practical approach is applied to compare three technologies in terms of robustness related to catastrophic events. First, the general approach is applied to drive availability/reliability results in normal situations for each technology using Failure Modes and Effects Analysis (FMEA). Next, considering natural and manmade catastrophic situations, the repair or replace time and costs are discussed in order to have a fair analysis of each transmission technology in catastrophic situations.

4.2 Reliability, Availability and Serviceability (RAS)

4.2.1 Reliability :

Reliability is defined by International Telecommunications Union (ITU-T) as "The ability of an item to perform required function under given conditions for a given time interval." Put more simply, it is "The probability that an item will work for a stated period of time".

Reliability can also be defined as the probability that a system will produce correct outputs up to some given time (t). Reliability is enhanced by features that help to avoid, detect and repair hardware faults. A reliable system does not silently continue and deliver results that include uncorrected corrupted data. Instead, it detects and, if possible, corrects the corruption.

Reliability can be characterized in terms of mean time between failures (MTBF), with reliability = exp (-t/MTBF)

A system is more reliable if it is fault tolerant. Fault tolerance is the ability of a system to continue functioning when part of the system fails. Fault tolerance is achieved by designing the system with a high degree of hardware redundancy. If any single component fails, the redundant component takes its place with no appreciable downtime [10].

4.2.2 Availability

Availability is closely related to Reliability, and is also defined in ITU-T as "The ability of an item to be in a state to perform a required function at a given instant of time or at any instant of time within a given time interval, assuming that the external resources, if required, are provided."

Simply availability means the probability that a system is operational at a given time, i.e. the amount of time a device is actually operating as percentage of total time it should be operating. High availability systems may report availability in terms of minutes or hours of downtime per year. Availability features allow the system to stay operational even when faults do occur. A highly available system would disable the malfunctioning portion and continue operating at a reduced capacity. In contrast, a less capable system might crash and become totally nonoperational. Availability is typically given as a percentage of the time a system is expected to be available, e.g., 99.999 percent ("five nines")[11]

There are many views of measuring availability, even for systems of little consequence to the production chain. Yet, the heavy linkage of systems and services also requires that we consider availability as an end-to-end topic, i.e., can work be completed, are all of the applications, databases, systems and networks up in the chain. The "Classical Availability" formula in equation {1}often seems to be the most practical. [12]

Availability =(Time Available / Time Promised) * 100 ……………………….. {1}

A product is said to be available when it is in an operative state. The total time in the operative state (also called uptime) is the sum of the time spent in (1) active use and (2) in standby state. The total time in the non-operative state (also called downtime) is the sum of the time spent (3) under active repair (*i.e.*, diagnosis and remedy), and (4) waiting for spare parts, paperwork, etc." Therefore, availability can be expressed as a mathematical ratio shown in equation {2}:

Availability = (Up time / Up time + Down Time) * 100 ………………………… {2}

As most often this deals with components, we reference this as the component availability formula, again described as a ratio as shown in equation {3}:

Availability = (MTBF / MTBF + MTTR) * 100 ………………………………… {3}

Availability is different from reliability in that it takes repair time into account. An item of equipment may not be very reliable, but if it can be repaired quickly when it fails, its availability could be high. [13]

4.2.3 Availability Calculation

System Availability is calculated by modeling the system as an interconnection of parts in series and parallel. The following rules are used to decide if components should be placed in series or parallel:

- If failure of a part leads to the combination becoming inoperable, the two parts are considered to be operating in series (Figure 4.3)
- If failure of a part leads to the other part taking over the operations of the failed part, the two parts are considered to be operating in parallel(Figure 4.4)

- **Availability in Series**

Figure (4.3): Part X and Part Y in Series Operation

As stated above, two parts X and Y are considered to be operating in series if failure of either of the parts results in failure of the combination. The combined system is operational only if both Part X and Part Y are available. From this it follows that the combined availability is a product of the availability of the two parts. The combined availability is shown by equation {4}:

$A = A_x A_y$ ………………………………………………………………………….{4}

The implications of the above equation are that the combined availability of two components in series is always lower than the availability of its individual components. In series operation, if a very high availability Part Y was used, and a low availability Part X, then the overall availability of the system will be pulled down by the low availability of Part X. This just proves the saying that a chain is as strong as the weakest link. More specifically, a chain is weaker than the weakest link.

- **Availability in Parallel**

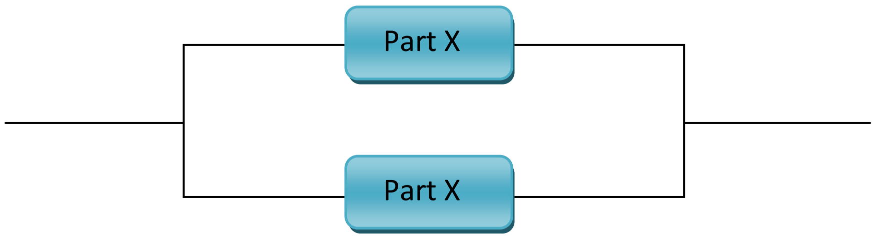

Figure (4.4): Part X and its redundant in Parallel Operation

As stated above, two parts are considered to be operating in parallel if the combination is considered failed when both parts fail. The combined system is operational if either part is available. From this it follows that the combined availability is 1 - (both parts are unavailable). The combined availability is shown by equation {5}:

$$A = 1 - (1 - A_x)^2 \quad \{5\}$$

The implications of the above equation are that the combined availability of two components in parallel is always much higher than the availability of its individual components. In parallel operation, if a very low availability Part X was used, the overall availability of the system is much higher. Thus parallel operation provides a very powerful mechanism for making a highly reliable system from low reliability. For this reason, all mission critical systems are designed with redundant components [14].

Availability is typically measured in "nines." For example, a solution with an availability level of "three nines" is capable of supporting its intended function 99.9 percent of the time, equivalent to an annual downtime of 8.76 hours per year on a 24*7*365 (24 hours a day/seven days a week/365 days a year) basis. Table (4.2) lists common availability levels that many organizations attempt to achieve.

Table (4.2): Correlation between Availability and Annual Downtime

Availability percentage	**Yearly downtime for (24-hour day)**	**Yearly downtime for (8-hour day)**
90%	876 hours (36.5 days)	291.2 hours (12.13 days)
95%	438 hours (18.25 days)	145.6 hours (6.07 days)
99%	87.6 hours (3.65 days)	29.12 hours (1.21 days)
99.9%	8.76 hours	2.91 hours
99.99%	52.56 minutes	17.47 minutes
99.999%	5.256 minutes	1.747 minutes
99.9999%	31.536 seconds	10.483 seconds

4.2.4 Serviceability (Maintainability)

Serviceability or maintainability is the simplicity and speed with which a system can be repaired or maintained; if the time to repair a failed system increases, then availability will decrease. Serviceability includes various methods of easily diagnosing the system when problems arise. Early detection of faults can decrease or avoid system downtime. For example, some enterprise systems can automatically call a service center (without human intervention) when the system experiences a system fault. The traditional focus has been on making the correct repairs with as little disruption to normal operations as possible.

4.2.5 Relationship between Availability and Reliability

Availability is the probability that a system is not failed or undergoing a repair action when it needs to be used. At first glance, it might seem that if a system has a high availability then it should also have a high reliability. However, this is not necessarily the case. Reliability measures the ability of a system to function correctly, including avoiding data corruption, whereas availability measures how often the system is available for use, even though it may not be functioning correctly. For example, a server may run forever and so have ideal availability, but may be unreliable, with frequent data corruption.

Therefore, not only is availability a function of reliability, but it is also a function of maintainability. Table (4.3) displays the relationship between reliability, maintainability and availability. It is obvious from the table that an increase in maintainability implies a decrease in the time it takes to perform maintenance actions.

Table (4.3): Relationship between Reliability, Maintainability and Availability.

Reliability	Maintainability	Availability
Constant	Decrease	Decrease
Constant	Increases	Increases
Increases	Constant	Increases
Decrease	Constant	Decrease

It can be seen from table (4.3), if the reliability is held constant, even at a high value, this does not directly imply a high availability. As the time to repair increases, the availability decreases. Even a system with a low reliability could have a high availability if the time to repair is short. [15]

4.2.6 Some key Elements of (RAS)

- Over-engineering, which is designing systems to specifications better than minimum requirements.
- Duplication, which is extensive use of redundant systems and components.
- Recoverability, which is the use of fault-tolerant engineering methods.
- Data backup , which prevents catastrophic loss of critical information.
- Data archiving which keeps extensive records of data in case of audits or other recovery needs.
- Power-on replacement, which is the ability to hot swap components or peripherals.
- Continuous power, which is the use of an uninterruptible power supply, keeps systems operational while switching from commercial power to backup or auxiliary power.
- Backup power sources, which includes batteries and generators to keep systems operational during extended interruptions in commercial power.

4.3 Availability/Reliability of the transmission links:

Oil & Gas transmission technologies can be both wired as well as wireless. Transmission links are engineered to give optimum performance in normal operational modes; while novel approaches are applied to avoid any unavoidable situations. The system level availability is often quite robust and reliable provided predetermined vulnerabilities for wired transmission links; but for wireless links various factors like i.e. rain attenuation, fading, free space path loss, power loss etc. can heavily impact the system reliability.

4.3.1 Optical transmission links

Figure 4.5 shows the various type of equipment typically included in network availability model for optical links [17].

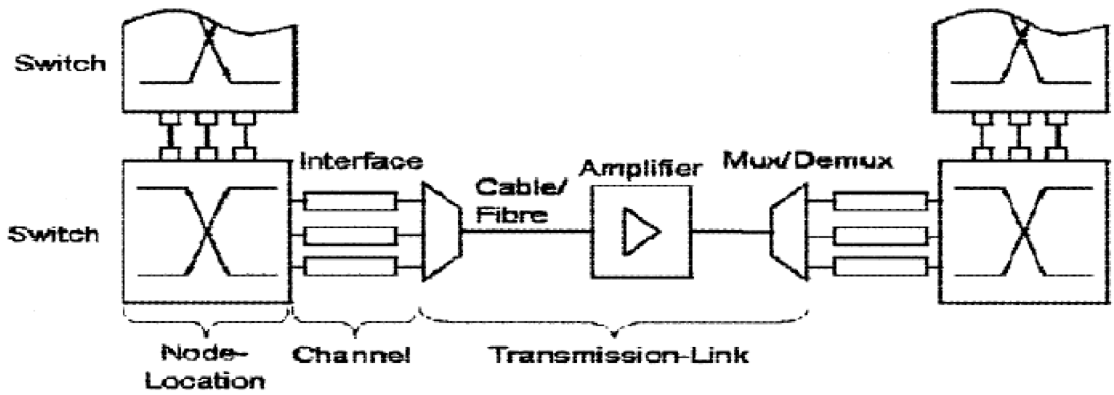

Figure (4.5): Model for optical network availability

Figure 4.5 includes optical cable, amplifiers, Wavelength Division Multiplexing (WDM) or Synchronous Digital Hierarchy (SDH) equipment and Optical Cross Connects (OCC). Availability of optical links is derived in the same manner as mentioned above; but the MTBF is often expressed in terms of Failures In Time (FIT) and the relation between MTBF and FIT is given as:

$$MTBF = \frac{10E^{09}}{FIT} \quad \text{.............................. \{6\}}$$

The optical cable failure rates depend on the type of material, length and the geographical position of the optical cable. The failure probabilities of optical cable can have distinct failure rates because of the surrounding circumstances. In [17], [18] and [19] , the MTBF of optical cables is often defined as:

$$MTBF(hours) = \frac{CC(km) \cdot 365 \cdot 24}{total\ cable\ length(km)} \quad \ldots\ldots \{7\}$$

Where cable cuts (CC) is defined as the average cable length suffering single cable cut per year.

The availability of optical links depends on the type of equipment, the cable length and cable type, connecters and recovery method. Recovery method means the immediate available arrangements for repair and replacements in catastrophic situations.

4.3.2 Satellite transmission Links

The availability of satellite communication transmission links for oil and gas facilities can be defined as:

"The proportion of time in some long interval (e.g. month, years) the transmission system and the link is available"

This definition for availability deals with the operating systems (earth stations and satellite) and the complete space link (uplink and downlink); the expressions for the overall availability of a satellite end to end transmission link can be derived as:

$$\text{Availability} = A_{ESA} \cdot A_{LA} \cdot A_{ESB} \cdot A_{SAT} \quad \ldots\ldots \{8\}$$

where,

A_{ESA} = availability of earth station A

A_{LA} = availability of space link (uplink and downlink)

A_{ESB} = availability of earth station B

A_{SAT} = availability of satellite.

The operating system availabilities can be calculated or derived based on the general availability criteria mentioned in the previous section based on the MTTR, and MTBF, while the space link between satellite and earth stations depends on several factors, i.e. transmitting and receiving powers, C/N ratios, interference from other satellites, slant angles, rain attenuation, free space and atmospheric losses etc. The link budget of satellite space links actually determines the various entities in the operating system, so in the rest of this section space link analysis are discussed in detail.

4.3.2. 1 Space link analysis

In satellite communication the space links are characterized by their quality and availability at either a receiving earth station and transmitting satellite (downlink) or a receiving satellite and transmitting earth station (uplink) by means of including transmission link impairments in uplink or downlink equations. The link power budgets of uplink and downlink determine the required transmit and receive power at either earth station or the satellite. Following are the most important attributes of a space link.

- Equivalent isotropic radiated power (EIRP)
- Transmission losses
- System noise
- Carrier to noise ratio (C/N)
- Rain attenuation
- Link power budget
- Intermodulation Noise
- Interference

Equivalent Isotropic Radiated Power (EIRP): EIRP is the product of the transmit power (Pt) and the gain of the transmitting antenna (G) and often expressed in dBW.

$$EIRP = Pt_{dBW} + Gt_{dB} \qquad \{9\}$$

Transmission Losses: EIRP is an input to the receiving end in the transmission link; while losses are observed during the transmission at the receiver end, such losses are called transmission losses. The losses can be constant as well as variable, depending on weather and atmospheric conditions. Major types of losses observed during transmission are included in the equation below [20].

$$Pr = EIRP + Gr - Losses \qquad \{10\}$$

and, $$Losses = FSL + RFL + AML + AA + PL \qquad \{11\}$$

Where,

FSL=Free space loss; RFL=Receiver feeder loss; A=Antenna misalignment loss

AA=Atmospheric absorption; PL=Polarization mismatch; G_r=Receiver antenna gain.

System Noise: The power received in satellite links is very small and needs to be amplified; if the received power is less than the system noise then the amplification will not help as it will also amplify the noise. The system noise power of a thermal system is given by:

$$N=KTB \quad \text{……………..…… } \{12\}$$

where,

K=Boltzman constant; T=System noise temperature; B=Equivalent bandwidth

Carrier to noise ratio (C/N): The link budget of satellite communication links is mainly determined by the ratio of the carrier power to the noise power at the receiver input for both uplink and downlink. Carrier to noise ratio (CNR) determines the performance measure of satellite links.

$$\frac{C}{N} = \frac{Pr}{N} \quad \text{……………..…… } \{13\}$$

Putting the equations for Pr and N derived in previous sections; the C/N ratio can be expressed in decibels:

$$\left[\frac{C}{N}\right] = [EIRP] + \left[\frac{G}{T}\right] - [Losses] - [B] - [K] \quad \text{…….…….... } \{14\}$$

This carrier to noise ratio expression can be used for uplink and downlink; where EIRP, K, Losses and G/T (*figure-of-merit*) can be represented with subscripts *u* and *d*, respectively for uplink and downlink. For uplink, EIRP of earth station, G/T of satellite receiver and B of the satellite transponder is used while free space losses and other losses are calculated for uplink frequency. Similarly for downlink, EIRP of satellite, G/T of earth station receiver, B of the receiving earth station while losses are calculated for the downlink frequency. The combined carrier to noise ratio (C/N) *c* for uplink and downlink can be given as:

$$\left[\frac{C}{N}\right]c = \frac{1}{\frac{1}{(C/N)u} + \frac{1}{(C/N)d}} \quad \text{………………..….... } \{15\}$$

where:

(C/N) *c* is the Combined Carrier To Noise Ratio.

(C/N) *u* is the Uplink Carrier To Noise Ratio.

(C/N) *d* is the Downlink Carrier To Noise Ratio.

Similarly energy per bit to noise ratio (Eb/N) can be calculated using the above expressions. Large Eb/No ratio is very important for a desired bit error rate. In [21] a relationship is derived between C/N ratio and Eb/No ratio, as given below.

$$\left[\frac{Eb}{No}\right] = \left(\frac{C}{N}\right) \cdot \left(\frac{B}{rb}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \{16\}$$

where, B=Allocated channel bandwidth in Hz and rb=Data bit rate

Rain attenuation: Offshore wireless links suffer rain effects, which degrade the signal quality. The microwave and satellite communication links face attenuation, noise temperature and polarization problems due to rain. In robust network designs, rain induced impairments can have significant impacts on received signal quality. The rain increases the system noise temperature; the electromagnetic signals suffer attenuation due to scattering and absorbing effects; and the polarization of electromagnetic signals may change as the rain droplets rotate due to wind and other forces. In practice, rain attenuation has significant effect on signal quality. The standard equation to calculate the rain attenuation is [22]:

$$Lr = \alpha R^{\beta} = \gamma L \quad \ldots\ldots\ldots\ldots\ldots\ldots \{17\}$$

Where Lr is rain attenuation (dB), R is rain rate (mm/h), L is path length (km), alpha and beta are empirical coefficients depending on frequency and elevation angle and gamma is specific rain attenuation coefficient (dB/km). Typically [23] two rain models are used in calculations, the Crane model and the ITU-R (CCIR) model. Figure 4.6 shows the signal attenuation due to rain.

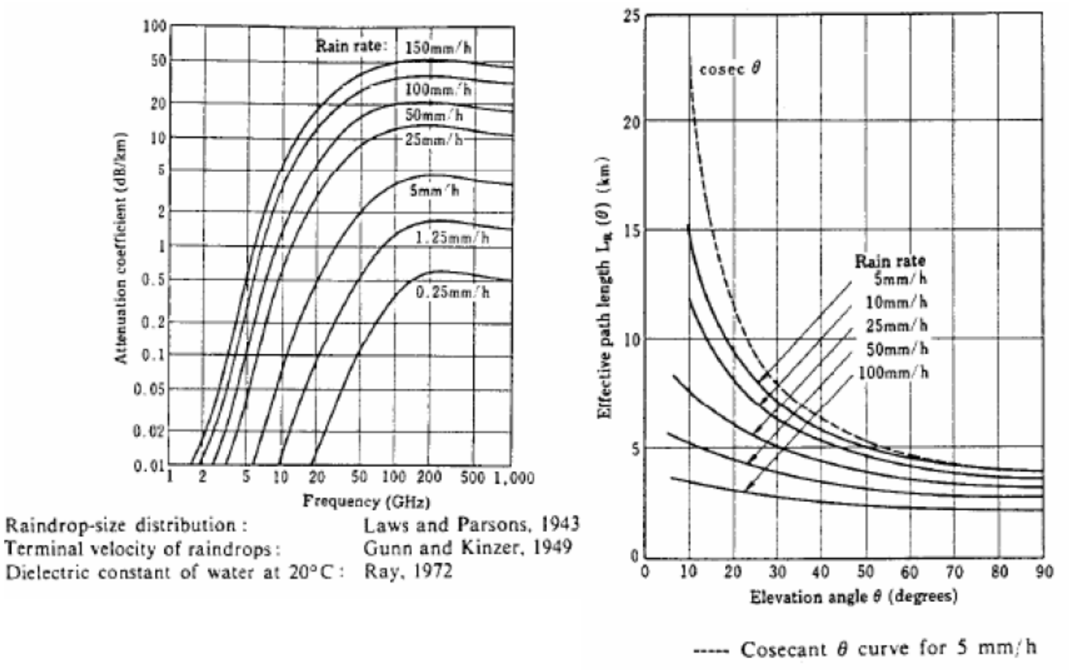

Figure (4.6): Rain attenuation - path length (right) and Attenuation coefficient (left)

Link power budget: Link power budget is normally calculated in tabular format, different parameters of transmission link including receiver and transmitter are presented in table format along with power gains and losses. The C/N ratio can also be calculated from tabular form.

Intermodulation Noise: The nonlinearities of multiple carriers passing through a device can produce intermodulation. Interference is observed when third order intermodulation products affect neighboring carrier frequencies. As the number of modulation carriers to intermodulation ratio *(C/N)IM* can be found experimentally or computationally using advanced computer methods. becomes large, the intermodulation products emerge as intermodulation noise. The carrier

$$\left[\frac{C}{N}\right]c = \frac{1}{\frac{1}{(C/N)u} + \frac{1}{(C/N)d} + \frac{1}{(C/N)IM}}$$ ……………..…..... {18}

Interference: In satellite communication interference is caused by the carriers generated from neighboring satellites and earth stations. The antenna side lobes often produce interference. The information signal carrying such noise type interference is amplified by the transponder and the receiver earth station receives the combined uplink and downlink interference as noise. Figure 4.7 shows the overall satellite communication links where uplink and downlink are separately analyzed [24]. The carrier to interference (C/I) ratio can be derived as given below in dB.

$$[C] - [I] = [EIRP]1 + [EIRP]2 + [GB] + [GB(\theta)] + [YD] \quad \ldots\ldots\ldots \{19\}$$

Where,
GB = Bore sight receiving antenna gain (on axis)
GB(θ) = Receiving antenna gain (off axis angle Θ)
YD = Polarization discrimination

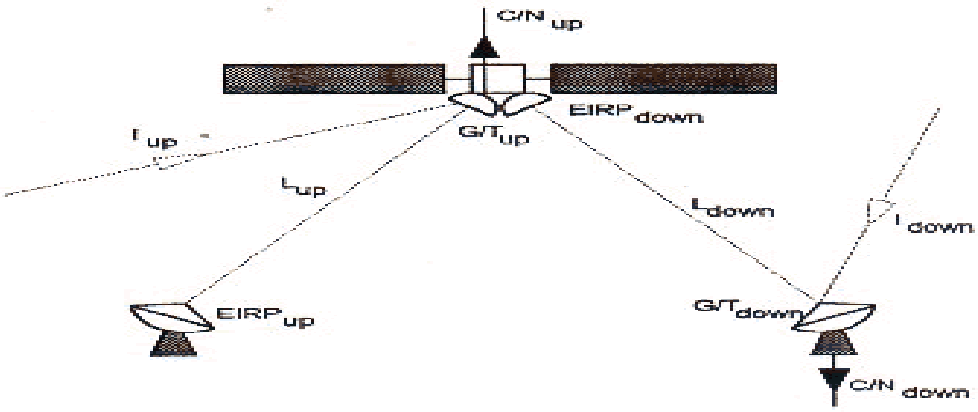

Figure (4.7): Satellite communication link budget [www.satecom.co.uk]

Similarly expression for uplink and downlink carrier to interference ratio can be derived on the overall satellite link equation to meet performance criteria can be given as:

$$\left[\frac{C}{N}\right]_{tot} = \frac{1}{\frac{1}{\left(C/N\right)_u + \left(C/I\right)_u + \left(C/I\right)_d + \left(C/N\right)_d + \left(C/N\right)_{IM}}} \quad \ldots\ldots\ldots \{20\}$$

4.3.3 Microwave Transmission Links:

Radio links are used in oil and gas industry since the beginning of Oil and Gas facilities. Even today microwave is the major transmission technology carrying most of the transmission data and voice to and from shore. The availability or reliability of end-to-end microwave transmission links can be obtained by evaluating system availability and the link budget of the point-to-point wireless link. Link budget determines the robustness of wireless link in terms of power, interference, SNR and losses etc. The system availability calculations are mainly dependent on MTTR, and MTBF as described in the previous section, while the reliability or the availability of a wireless link depends on the link budget and needs to be evaluated in order to engineer a reliable microwave LOS transmission system. The major link budget attributes affecting microwave LOS transmission links are as follows:

Free space path loss: As the signal travels along the wireless medium; it starts spreading after leaving the radiating source and gradually the signal becomes weaker as the distance increases. The FSL is independent of source and destination systems and is expressed as:

$$FSL = \left(\frac{4\pi d}{\lambda}\right)^2 \qquad \text{………………..….. \{21\}}$$

where, d=distance and λ=wavelength

Fresnel zones: The transmitted signal spreads as it travels towards the receiver. Huygens explained the propagation characteristics of electromagnetic waves and Fresnel explained the concepts of Fresnel zones. The area (around LOS microwave link) in which the signal spreads out after leaving the transmitting source is called the Fresnel zone. This spreading depends on the frequency of the signal, the lower the frequency, the higher the Fresnel zone. In order to have a clear line of sight communication; the first Fresnel zone must be clear from any obstacles in order to avoid any kind of interference.

$$Fn = \sqrt{\frac{\lambda \cdot d1 \cdot d2}{d1 + d2}} \qquad \text{…………………… \{22\}}$$

Where, Fn = Nth Fresnel Zone radius (m); λ = Wavelength of the transmitted signal (m)

d1 = Distance of P from one end (m); d2 = Distance of P from the other end (m)

Receiver sensitivity: The minimum required received signal power (in dBm) to correctly decode the transmitted signal.

Effective Isotropic Radiated Power (EIRP): The measured power in the main lobe of transmit antenna in dBm.

$$EIRP = Pt + Gt \qquad \text{……………..….... \{23\}}$$

Where, Pt = transmit power; Gt = gain of transmit antenna

Link Budget: The link budget for microwave LOS communication link is similar to satellite communication link budget. The signal to noise (SNR) is calculated based on the received signal level and the noise power. A microwave LOS is only decoded successfully if the desired SNR is achieved. A simple diagram of a microwave LOS link is shown below [25]:

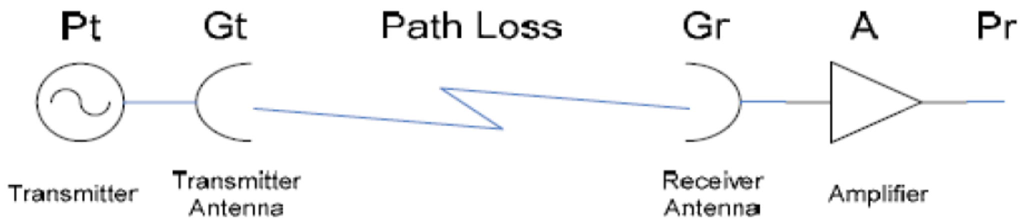

Figure (4.8): Block diagram of Microwave LOS link

Received Signal Level (RSL) is calculated by subtracting free space loss and adding receiver antenna gain and amplifier gain as expressed below in dB:

$$Rx\ signal = EIRP - FSL + Gr + A \quad \ldots\ldots\ldots\ldots\ldots \{24\}$$

And the noise power at receiver output is given as:

$$Noise\ Power = K \cdot (Ta + Te) \cdot B \quad \ldots\ldots\ldots\ldots\ldots \{25\}$$

where,

A=Amplifier gain; K=Boltzmann constant; B=Bandwidth of the system Ta=Antenna noise temperature; Te=Effective noise temperature of receiver amplifier

Finally, signal to noise ratio (SNR) can be calculated by the expression given as below in dB.

$$SNR = Rx\ signal - Noise\ power \quad \ldots\ldots\ldots\ldots\ldots \{26\}$$

In practice system availability and link availability are calculated separately. Link availability is often predetermined and remains consistent throughout the overall network life while the system availability has greater importance with respect to the performance of the network.

Section 4.3 discussed availability of optical, microwave LOS and satellite communication technologies. This was done in order to lay down the groundwork for subsequent comparison of these transmission technologies in normal and catastrophic conditions. This also reveals certain limitations and advantages of these technologies. This can be of great help in designing a robust and cost effective transmission network which is sustainable and reduces repair and replacement time which is further discussed in detail in part two of section 4.4.

4.4 Repair and replacement time and costs:

In this section, repair and replacement time and costs are discussed assuming manmade and natural catastrophic events. oil and gas facilities suffer production losses if the communication services are not restored immediately following the catastrophic damages. Oil and gas facilities can be of different types and sizes. Some facilities only produce gas or oil while some produce both, so the restoration process of communication services must be cost effective.

4.4.1 Time to Repair

Time to repair approximated as mean time to repair (MTTR) is used for calculating different attributes of robustness. MTTR is always varying according to the service level agreement (SLA) between the operator and vendor as there are no such regulations and standards. Depending on the type of the technology and the available resources i.e. transportation, technicians and tools etc, different service providers define mean time to repair. In literature, MTTR is used for calculating the availability/reliability of an entity, a link or a network. For natural or manmade catastrophic calamities this time can vary from few hours to days, weeks and months. In Chapters 2, 3 and 4, it was learned from different real world catastrophe events that the communication technologies must be robust against catastrophic events.

There are many factors which affect the repair time i.e. distance of the field, type of damage, and availability of transportation, equipment, accessories, spare parts, tools and technical staff. Satellite communication copes with these issues reasonably well since transmission medium is only unavailable during extreme weather conditions, and repair activities can be performed on platform immediately after the event, which means that the repair time for the satellite communication in catastrophic and normal situations is marginally same. Failure of optical and microwave communication networks can be disastrous, in case the transmission medium is severely damaged due an event. MTTR of optical transmission medium (optical fiber cable) in general is much higher than the transmission medium vulnerabilities of microwave and satellite communication. Table 4.4 shows MTTR for optical satellite and microwave LOS transmission links.

Table (4.4): MTTR of Oil & Gas transmission links for repair and replacement activities.

TX. Technology	Component	MTTR
OPTICAL	Transmission Medium -Optical cable [1/km]	21H
	Oil Field Station	8H
SATELLITE	Oil Field Station	8H
MICROWAVE LOS	Oil Field Station	8H

MTTR figures in Table 4.4 of offshore/onshore stations for repair or replacement activities are arbitrarily selected. In literature MTTR varies from 6-8 hours for oil and gas facilities.

4.4.2 Repair and Replacement Costs

Communication networks for the oil and gas facilities comprise of capital costs, installation costs, operating costs and maintenance and up gradation costs. Another way is to categorize the overall costs of communication networks in capital expenditures (CapEx) and operation expenditures (OpEx). Expanding or up-grading costs are included in CapEx, while the installation, operations and maintenance costs are included in OpEx. In reality there is a tradeoff between the division of OpEx and CapEx costs, some companies categorize rental and leasing as OpEx while others do not [27].

Repair and replacement costs for communication networks can be divided in three parts (Headquarter Stations, transmission network "providers" and onshore stations), which fall under operational expenditures when the damages are reparable and the network is owned by the operator. In case the transmission network is not owned (shared or leased) by the operator, the repair and replacement costs can be part of OpEx as well as CapEx depending on the service level agreement (SLA) between the operator and the service provider. Petro Energy E&P transmission network is a co-operative between Canartel, Sudatel and GNPOC. In case of any problem from the service provider the traffic can be routed to the other service provider. and is maintained by service provider for the repair and replacement costs are shared by all oil and gas operators.

Repair and replacement costs for Satellite transmission links are usually much lower than optical and microwave links, since most of the catastrophic calamities occur on earth. The cost of microwave transmission link is equal to satellite transmission link when the distance *d* between station and other station is less than 70 km and less than the repair and replacement costs for optical cable. In general for each technology (optical, fiber and microwave LOS) have fixed repair and replacement costs, while other added cost depends on the field distance are applicable such as transportation (e.g. emergency helicopter) and technical assistance . Table 4.5 compares the repair and replacement costs of transmission technologies for the damages caused by catastrophe situations.

Table (4.5): Oil & Gas Field transmission links – Repair and replacement cost matrix.

	OPTICAL	SATELLITE	MICROWAVE LOS
Oil Field	HIGH	HIGH	HIGH
Transmission Medium	HIGH	LOW	LOW if D<70 Km
			HIGH if D<70 Km
Head Quarter	LOW	LOW	LOW

Table 4.5 does not include the damages to the satellite transponder due to solar storms and charging effects as discussed in Chapter 3, since repair and replacement costs of transponder damages are part of the CapEx and managed by the satellite operator.

4.5 PETRO ENERGY- E&P (Case Study)

The major communication systems failures encountered in 2014 were collected, listed in a table then the frequency of each failure and the annual downtime were calculated then the availability of each component of the system was found out using these calculations.

Topologies of three systems in comparison (Fiber Optic, Microwave LOS and Satellite communication systems) were modeled in block diagrams to enable calculating each system's availability out of its components' availability.

As described in Chapter (3) Telecommunication infrastructure of Petro Energy E&P designed according to the requirements of Oil and Gas operators. It is a cooperative network and the infrastructure is shared by network operators. It consists of three backbone Fiber optic system which is based on Synchronous Digital Hierarchy (SDH) STM-4 (622M) is the primary telecommunication system, VSAT System is designed to be as telecommunication back-up for both data and voice communication in the case of failure of Fiber Optic main communication backbone and Microwave is also used as a redundant system for fiber optic in the upstream together with the VSAT.

In this case study, robustness and availability of the communication network for Petro Energy is evaluated in two parts. In the first part, three technologies system and transmission availability depends on the Failure Mode Evaluation and Analysis (FMEA) are discussed to improve the robustness of network for the existing network. Also the 2 scenarios for evaluation for the Overall System Availability is studied for the existing network considering backup systems in the upstream and downstream locations. In second part, the transmission technologies (Optical, Satellite and Microwave LOS) are compared based on their availability and repair time and cost in normal and catastrophic situations. Different possibilities of choosing appropriate transmission technology or combination of transmission technologies are discussed to improve the robustness of Petro Energy Network of Telecommunication.

4.5.1 Fiber Optic System

4.5.1.1 System Topology

Figure (4.9) below is showing the Fiber Optic ring structure in Petro Energy, Three Fiber optic lines are designed to form a ring structure:

- Line from upstream fields through Baleela to (PS#3).
- Shared line with Greater Nile (4 cores are specified for PE, 2 active and 2 redundant) from KT#6 to Obeid to complete the ring and work as backup.
- Line from Jake to KT#6 is leased from Sudatel as a second backup.
- From Khartoum refinery (KT#6) to HQ, 2 lines are leased from Sudatel and Canar to balance the load and being redundant for each other.

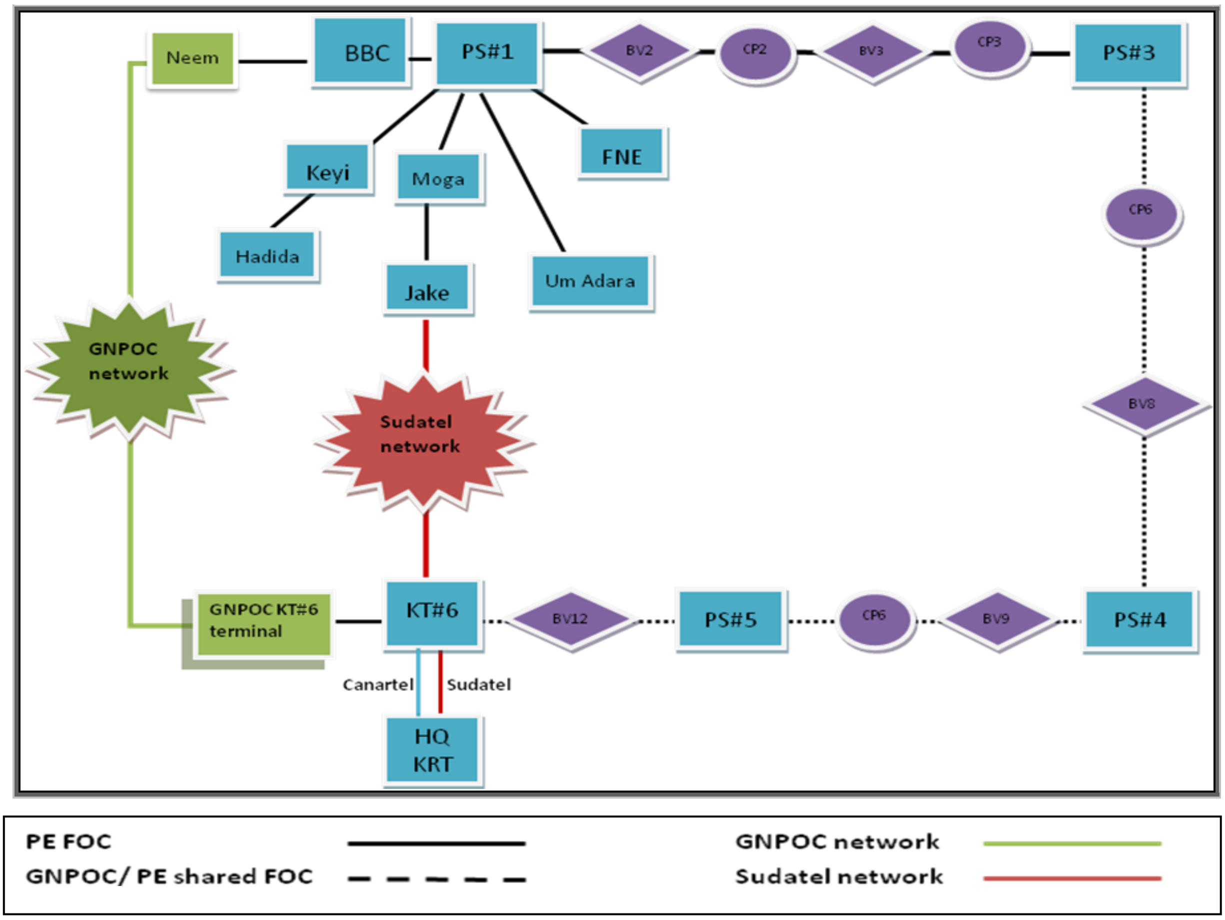

Figure (4.9): Fiber Optic System Topology

4.5.1.2 Experienced Failures in 2014

Here below is a list of the Fiber optic system failures experienced in 2014 for different reasons:

Table (4.6): Fiber Optic System Failures in 2014

No.	Location	Failure/ Behavior	Reason	Time to Repair (hrs)	Failure Annual Rate	Time between Failures (hrs)	Solution / Treatment	Remark
1	Different locations	No communication	Cable cut by different means*	24-72	10	876	Splicing after determination of the cut location by OTDR	Most of the times, the cable is erosion by floods and exposed to cut.
2	Different locations	No communication	Bad connection in the Fibers distribution frame (ODF) or disordering the color index (mostly after splicing)	3	4	2190	Re-checking and fixing	
3	Hadida field	No communication	Cable cut inside ODF by Rodents (Mice)	3	NA	NA	splicing	Incident happened only one time during system life
4	Along pipeline in KM No. 6 (KP#06)	No communication	damage of old welding inside the buried splicing box	24-72	1	8760	New splicing	
5	Remote stations	No communication	SDH power off due to low electrical supply (batteries bank efficiency degrade specially at night - Solar system)	24	6	1460	Batteries Replacement	
6	Block valve #12 (BV#12)	No communication	SDH controller damage due to repeated power instability problems.	48	1	8760	Card Replacement	Spare part was available

Cable cuts were encountered due to different reasons as shown in table (4.7):

Table (4.7): Fiber Optic Cable Cuts in 2014

No.	Date	Reason	Recovery Time
1	20-4-2014	Cut by Local people	48 hours
2	1-5-2014	site civil work	72 hours
3	22-5-2014	Cut by Local people	24 hour
4	21-06-2014	Cut by Local people	48 hours
5	24-06-2014	Cut by Local people	48 hours
6	28-06-2014	Cut by Local people	24 hour
7	27-06-2014	site civil work	24 hour
8	26-8-2014	Cut by Local people	72 hours
9	08-09-2014	Cut by Local people	48 hours
10	20-12-2014	Site excavation work (fence)	72 hours

From table (4.6), it can be seen that 43.5% of the failures were due to fiber cuts and from table (4.7) it can be seen that those cuts were by humans either intentionally by local people (70%) especially in the rainy season since it became exposed or unintentionally during construction activities (30%) even there were warning tapes and warning signs.

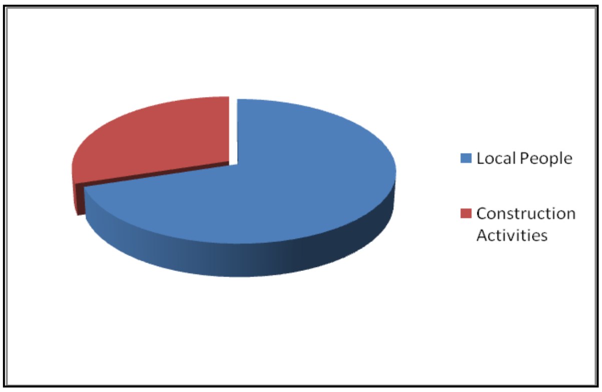

Figure (4.10): Causes of Fiber Optic Cables Cuts

4.5.1.3 System Availability

From table (4.6), we can classify all failures to cable failure or equipment failure.

- To calculate the cable availability (Cable availability can be denoted by $\mathbf{A_{VC}}$ and cable unavailability can be denoted by $\mathbf{A'_{VC}}$), from table No (4.6):

  Failure annual rate is 10, time between failures = 365*24/10 = 876 hrs.

  Time to repair is 72 hrs in worst cases.

  Since Availability = Time between failures / (Time between failures + Time to repair)

  Then $\mathbf{A_{VC}}$ = 876 / (876+72) = **0.924051**

  $\mathbf{A'_{VC}}$ = 1 – $\mathbf{A_{VC}}$ = 1 – 0.924 = **<u>0.07595</u>**

- To calculate equipment's availability (Equipment Availability can be denoted by **Aveq** and Equipment unavailability can be denoted by **A'veq**), from table No. (4.6):

  Failure annual rate is 6, time between failures = 365*24/ 6= 1460 hrs.

  Time to repair is 24 hrs in worst cases.

Since Availability = Time between failures / (Time between failures + Time to repair)

  Then **Aveq** = 1460 / (1460+24) = **0.983827**

  A'veq = 1 – Aveq = 1 – 0.983827 = **<u>0.016173</u>**

4.5.2 VSAT System

4.5.2.1 System Topology

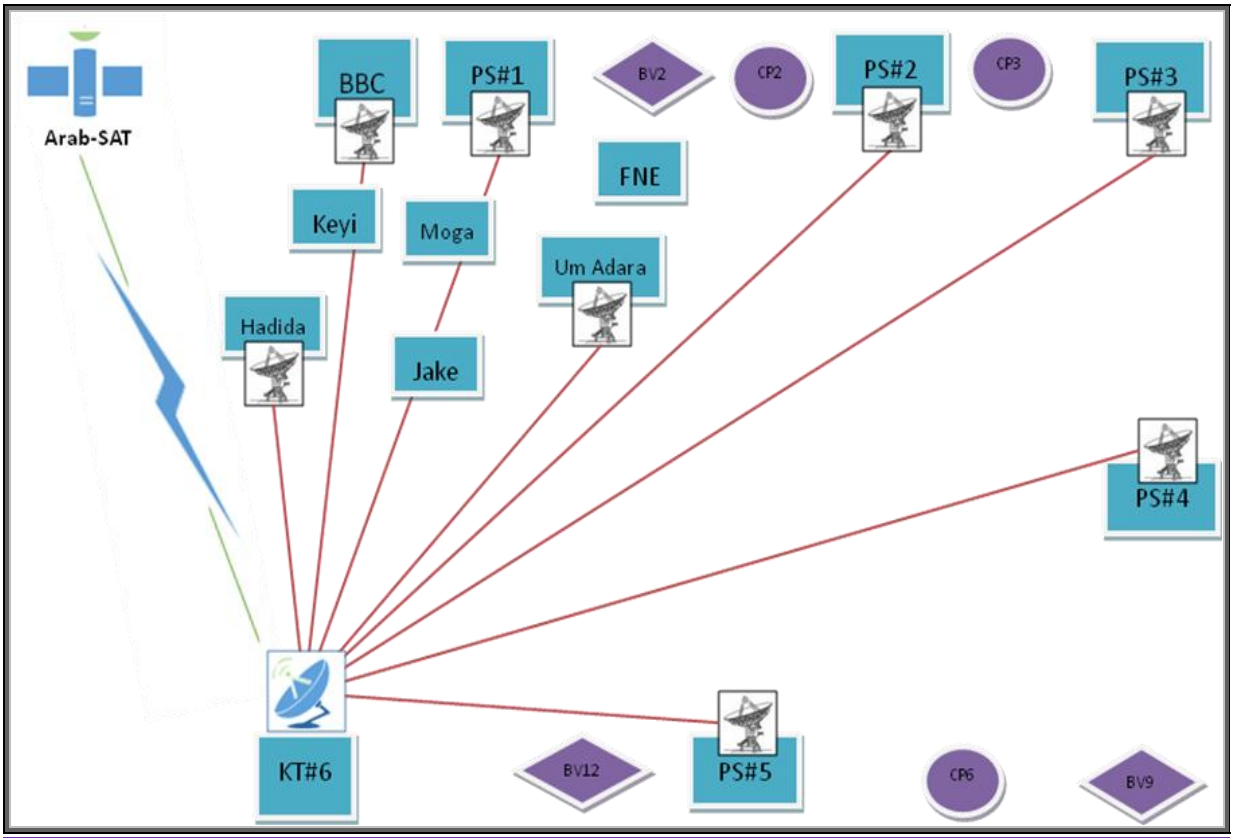

Figure (4.11): VSAT Topology

4.5.2.2 Experienced Failures in 2014

Table (4.8) VSAT System Failures in 2014

No.	Location	Failure/ Behavior	Reason	Time to Repair (hrs)	Failure Annual Rate	Time between Failures (hrs)	Solution / Treatment	Remark
1	* PS#1 * Base Camp	No communication	Feed Horn was open from above. So LNA filled with water due to rain	1	2	4380	Dry the feed horn and ensured proper fittings	
2	PS#1	No communication	Antenna's slight miss alignment due to wind	0.5	1	8760	Raise transmitted Signal power	
3	PS#5	No communication	Modem Damage (Electrical power not stable)	48	1	8760	Replacement	Spare part was available
4	PS#3	Unstable transmitted signal	Transceiver damage (lightning)	48	1	8760	Replacement + Surge Arrestor	Spare part was available
5	All locations	Outage time from Service provider (Arab-SAT Badr-6)	Eclipses	4	2	4380	No treatment	usually advanced notification is sent

4.5.2.3 System Availability

- To calculate the VSAT availability (can be denoted by $\mathbf{A_{VSAT}}$ and VSAT unavailability can be denoted by $\mathbf{A'_{VSAT}}$), from table No (4.8) and taking the worst case:

  Failure annual rate is 1, time between failures = 365*24/1 = 8760 hrs.

  Time to repair is 48 hrs in worst cases.

Since Availability = Time between failures / (Time between failures + Time to repair)

Then $\mathbf{A_{VSAT}} = 8760 / (8760+48) = \mathbf{0.99455}$

$\mathbf{A'_{VSAT}} = 1 - \mathbf{A_{VSAT}} = 1 - 0.99455 = \underline{\mathbf{0.00545}}$

4.5.3 Microwave system

4.5.3.1 System Topology

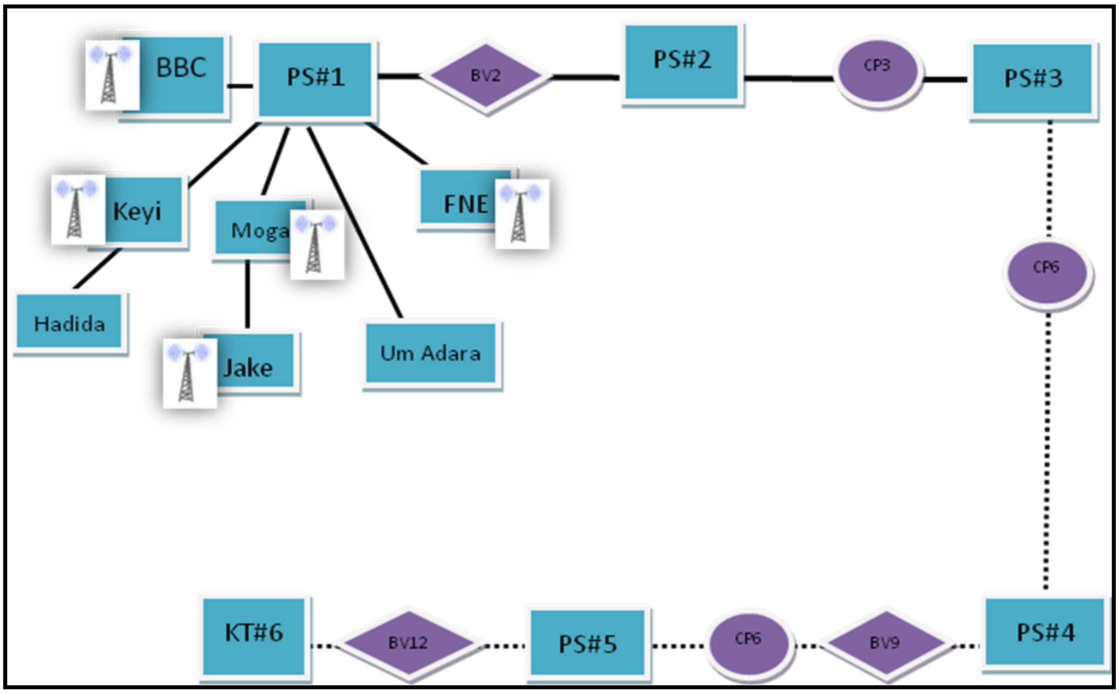

Figure (4.12): Microwave System Topology

4.5.3.2 Experienced Failures in 2014

Table (4.9) Microwave System Failures in 2014

No.	Location	Failure/ Behavior	Reason	Time to repair (hrs)	Failure Annual Rate	Time between failures (hrs)	Solution / Treatment	Remark
1	Baleela, FNE, Moga, Jake & Keyi	No communication	Miss alignment in the Antenna	3	1	8760	Re-alignment	
2	Baleela, FNE, Moga, Jake & Keyi	No communication	Damage in the CPE (customer premises equipment) due to lightning	96	2	4380	Replacement	
3	Baleela, FNE, Moga, Jake & Keyi	No communication	Damage in the CPE (customer premises equipment) due to life time expiry	96	0.5	17520	Replacement	This failure happens Every 2 years in average

4.5.3.3 System Availability

- To calculate the Microwave availability, (can be denoted by $\mathbf{A_{Mic}}$ and unavailability can be denoted by $\mathbf{A'_{Mic}}$) from table No (4.4) and taking the worst case:

  Failure annual rate is 2, time between failures = 365*24/2 = 4380 hrs.

  Time to repair is 96 hrs in worst cases.

  Since Availability = Time between failures / (Time between failures + Time to repair)

  Then $\mathbf{A_{Mic}}$ = 4380 / (4380+96) = **0.97855**

  $\mathbf{A'_{Mic}}$ = 1 – $\mathbf{A_{Mic}}$ = 1 – 0.97855 = **<u>0.02145</u>**

4.5.4 Overall System Availability

As mentioned earlier, Fiber optic system is the primary telecommunication system used and the VSAT together with the microwave are used as backup system. So, to measure the overall system availability, two scenarios for communication between any two locations had been taken one for downstream stations where only VSAT is available as backup and the other for upstream where microwave is available as well as VSAT as backup.

GNPOC and Sudatel networks are used to complete the ring. Their availability can be measured from table no. (4.10) where the failures incidents of both networks in 2014 were recorded and failure annual rate and time between failures were calculated.

Table (4.10): GNPOC and Sudatel N/Ws Failures in 2014

Location	Time to Repair (hrs)	Failure Annual Rate	Time between Failures (hrs)
GNPOC N/W	48	14	625.7
Sudatel N/W	48-72	4	2190

*Availability of GNPOC N/W (A_{VGNPOC}) can be calculated as:

Availability = Time between failures / (Time between failures + Time to repair)

(A_{VGNPOC}) = 625.7/ (625.7+48) = **<u>0.92875</u>**

*Availability of Sudatel N/W ($A_{VSudatel}$) can be calculated as:

Availability = Time between failures / (Time between failures + Time to repair)

($A_{VSudatel}$) = 2190/ (2190+72) = **0.96817**

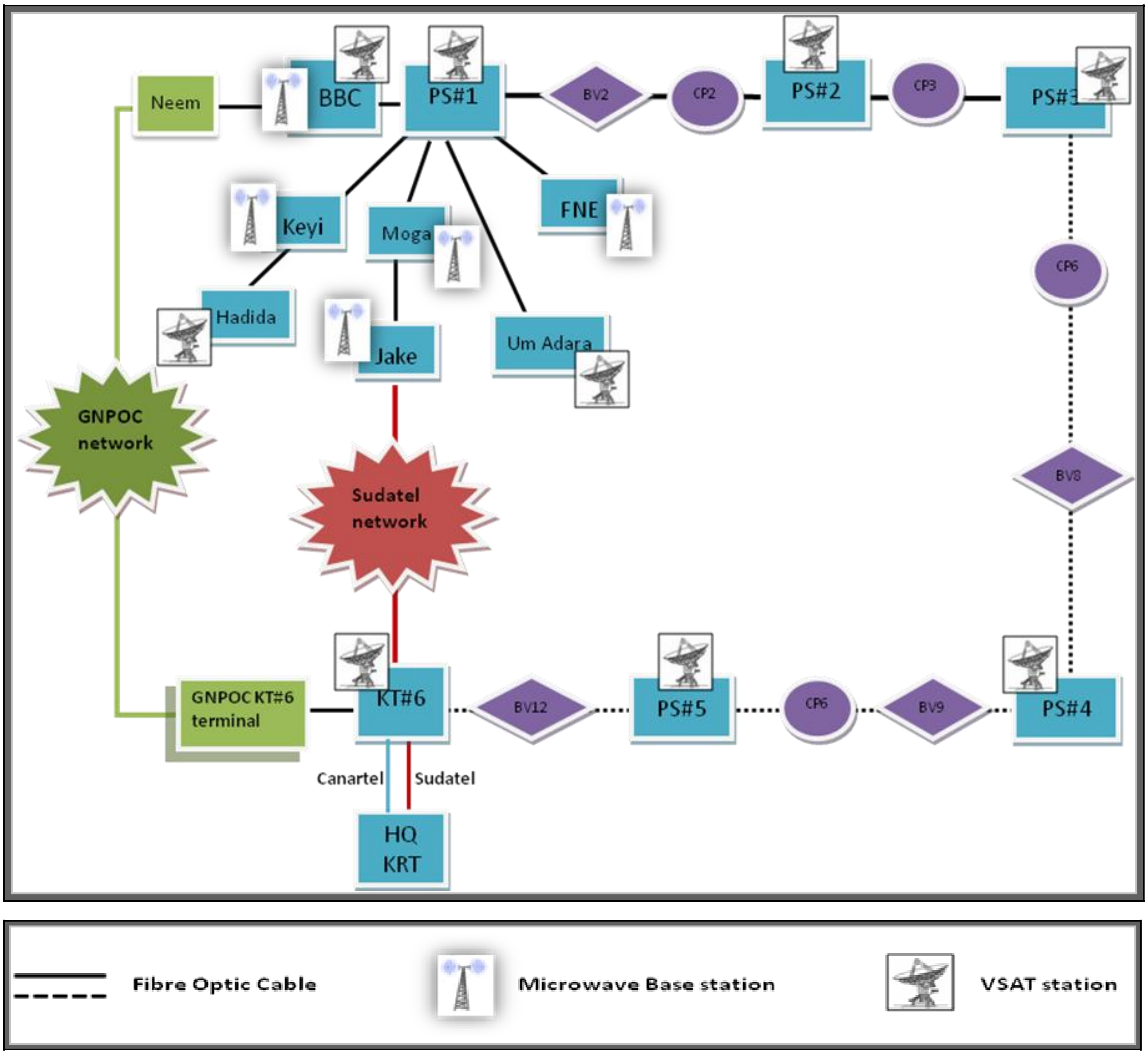

Figure (4.13): Fiber Optic, VSAT & Microwave Systems Topology

4.5.4.1 Scenario 1 (Downstream)

Suppose we want to communicate between the Initial station (PS#1) and Terminal station (KT#6) (as the first and last stations in the downstream) , the block diagram in figure (4.14) shows all the possible paths and alternative ways which will keep these two points connected:

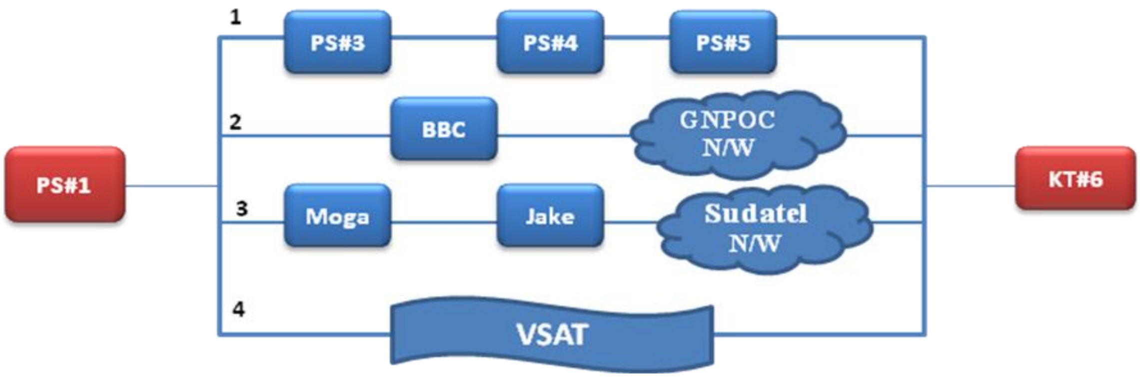

Figure (4.14): Block Diagram for the Connection between PS#1 and KT#6

Let's denote:

$\mathbf{A_1}$: Availability of the bath from PS#1, PS#3, PS#4, and PS #5 to KT#6.

$\mathbf{A_2}$: Availability of the bath from PS#1, BBC to KT#6 through GNPOC N/W.

$\mathbf{A_3}$: Availability of the bath from PS#1, Moga, Jake to KT#6 through Sudatel N/W.

$\mathbf{A_4}$: Availability of the bath from PS#1 to KT#6 via VSAT.

$\mathbf{A_{VSYS}}$: Overall system availability.

$\mathbf{A_{V}'_{SYS}}$: Overall system unavailability.

$$\mathbf{A_{V}'_{SYS}} = (1 - \mathbf{A_1})(1 - \mathbf{A_2})(1 - \mathbf{A_3})(1 - \mathbf{A_4})$$

$\mathbf{A_1}$ is the availability of the bath from PS#1, PS#3, PS#4, and PS #5 to KT#6 which includes the availability of both Fiber optic cable and equipments in each station in series.

$\mathbf{A_1}$ = Av_{eq} in PS#1 * A_{VC} between PS#1 and PS#3 * Av_{eq} in PS#3 * A_{VC} between PS#3 and PS#4 * Av_{eq} in PS#4 * A_{VC} between PS#4 and PS#5* Av_{eq} in PS#5 * A_{VC} between PS#5 and KT#6* Av_{eq} in KT#6

A1 = $(0.983827)^5 * (0.924051)^4$ = **<u>0.672013</u>**

Similarly:

A2 = Av_{eq} in PS#1 * A_{VC} between PS#1 and BBC * Av_{eq} in BBC * A_{VC} between BBC and GNPOC N/W * A_{VGNPOC} * A_{VC} between GNPOC N/W and KT#6* Av_{eq} in KT#6

A2 = $(0.983827)^4 * (0.924051)^3 * 0.928750$ = **0.686535**

A3 = Av_{eq} in PS#1 * A_{VC} between PS#1 and Moga * Av_{eq} in Moga * A_{VC} between Moga and Jake* Av_{eq} in Jake * $A_{VSudatel}$ * Av_{eq} in KT#6

A3 = $(0.983827)^4 * (0.924051)^2 * 0.96817$ = **0.774495**

A4 = $\mathbf{A_{VSAT}}$ = **0.99455**

Then overall system availability can be calculated by:

$\mathbf{A_V'_{SYS}} = (1 - \mathbf{A_1})(1 - \mathbf{A_2})(1 - \mathbf{A_3})(1 - \mathbf{A_4})$

= (1 – **0.672013) (**1 – **0.686535) (**1 – **0.774495**) (1 – **0.99455**) = **0.000126**

$\mathbf{A_{VSYS}} = (1 - \mathbf{A_V'_{SYS}})$ = (1 - 0.000126)

System availability = **0.999874**

4.5.4.2 Scenario 2 (Upstream & Downstream)

Suppose we want to communicate between Jake and Terminal Station (KT#6) (as an example of the longest path from upstream to downstream), the block diagram in figure (4.15) shows all the possible paths and alternative ways which will keep these two points connected:

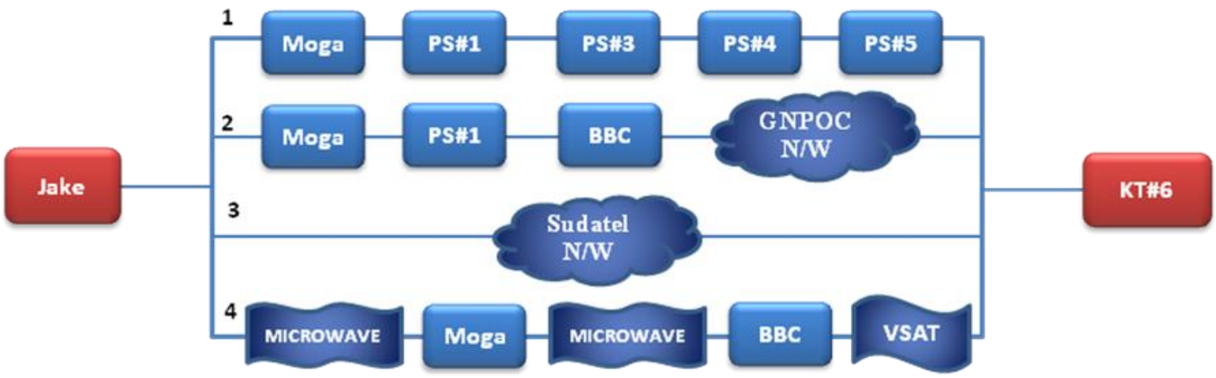

Figure (4.15): Block Diagram for the Connection between Jake and KT#6

Let's denote:

B_1: Availability of the bath from Jake, Moga, PS#1, PS#3, PS#4, and PS #5 to KT#6.

B_2: Availability of the bath from Jake, Moga, PS#1, BBC to KT#6 through GNPOC N/W.

B_3: Availability of the bath from Jake to KT#6 through Sudatel N/W.

B_4: Availability of the bath from Jake, Moga to BBC through Microwave system and from BBC to KT#6 via VSAT.

A_{VSYS}: Overall system availability.

$A_{V'SYS}$: Overall system unavailability.

$A_{V'SYS}$ $= (1 - \mathbf{B_1})\,(1 - \mathbf{B_2})\,(1 - \mathbf{B_3})\,(1 - \mathbf{B_4})$

B1 is the availability of the bath from Jake, Moga, PS#1, PS#3, PS#4, and PS #5 to KT#6 which includes the availability of both Fiber optic cable and equipments in each station in series.

i.e. B1 = Av_{eq} in Jake * A_{VC} between Jake and Moga* Av_{eq} in Moga * A_{VC} between Moga and PS#1* Av_{eq} in PS#1 * A_{VC} between PS#1 and PS#3 * Av_{eq} in PS#3 * A_{VC} between PS#3 and PS#4 * Av_{eq} in PS#4 * A_{VC} between PS#4 and PS#5* Av_{eq} in PS#5 * A_{VC} between PS#5 and KT#6* Av_{eq} in KT#6

B1 = $(0.983827)^7 * (0.924051)^6$ **= <u>0.555401</u>**

Similarly:

B2 = Av_{eq} in Jake * A_{VC} between Jake and Moga* Av_{eq} in Moga * A_{VC} between Moga and PS#1* Av_{eq} in PS#1 * A_{VC} between PS#1 and BBC * Av_{eq} in BBC * A_{VC} between BBC and GNPOC N/W * A_{VGNPOC} * A_{VC} between GNPOC N/W and KT#6* Av_{eq} in KT#6.

B2 = $(0.983827)^5 * (0.924051)^5 * 0.928752$ **= <u>0.576731</u>**

B3 = $A_{VSUDATEL}$ **= <u>0.96817</u>**

B4 = Availability of Microwave at Jake and Availability of Microwave at Moga and availability of both Microwave and VSAT at BBC

$B4 = (0.97855)^3 * 0.99455$ **= <u>0.931914</u>**

Then overall system availability can be calculated by:

$\mathbf{A_{V}'_{SYS}} = (1 - \mathbf{B_1})(1 - \mathbf{B_2})(1 - \mathbf{B_3})(1 - \mathbf{B_4})$

$= (1 - \mathbf{0.555401})(1 - \mathbf{0.576731})(1 - \mathbf{0.96817})(1 - \mathbf{0.931914}) = \underline{\mathbf{0.000408}}$

$\mathbf{A_{VSYS}} = (1 - \mathbf{A_{V}'_{SYS}}) = (1 - 0.003805)$

System availability = **<u>0.999592</u>**

Then the backbone or backup telecommunications system availability at **Petro energy** is ranging between 0.999874 as per scenario 1 and 0.999592 as per scenario 2.

4.5.5 Transmission Technologies and Catastrophic Robustness

Part one solves the one the evaluation of the availability of the microwave LOS, VSAT and optical communications system. Part two highlights the reliability/availability criteria and risks and limitations associated with each transmission technology in normal and catastrophic situations, particularly the risks related to repair and replacement time and costs. This part underlines the catastrophic robustness of transmission technologies (Optical, Microwave LOS and VSAT) and discusses the implication of such events for the existing infrastructure of Petro Energy communication network.

4.5.5.1 Catastrophic availability/reliability

Section 4.6.2, 4.6.3 and 4.6.4 showed that the availability of existing Fiber optic System is above 98.38% and Satellite VSAT is 99.45% and microwave LOS transmission network of Petro Energy is above 97.855% per year in normal situations, while these figures can vary significantly in catastrophic situations depending on the time duration of catastrophic event and the repair and replacement time (MTTR). Table 4.4 showed that the MTTR for optical cable, and optical, satellite and microwave LOS of the normal situation. Normal repair and replacement time starts once the damage has been done and calamities (manmade or natural) are over. Catastrophic repair and replacement time (CTTR) can be defined as the sum of the calamitous time duration (CT) and MTTR.

$$CTTR = CT + MTTR \quad \{27\}$$

where,

CTTR = Catastrophic time to repair; CT = Catastrophic time duration.

Catastrophic time duration is the time, a catastrophic event occurs and persists before repair and replacement activities start. CT is difficult to predict but depending on the type and magnitude of catastrophe this information can be provided by the special monitoring departments immediately before and after the event occurs. In literature, such parameters are often defined to design robust and survivable networks for emergency shutdowns and safety issues.

Transmission technologies should have certain tendencies to resist such hazards. Table 4.11 shows each transmission technology against the hazards that impact their performance. Impacts are further categorized in two parts: the Equipments part and the transmission links part. This information is based on the real time disasters and their cures mentioned earlier. Section 4.4 discussed the availability of transmission technologies which tells about the different types of hazards that can affect robustness of transmission technologies. In Table 4.11, *low* means the impacts near to the normal situations, *medium* means that the impacts are not catastrophic but the damage is predictable, while *high* means that the impacts can be catastrophic and can bring maximum damage.

Table (4.11): Impacts categories of hazards and Risk on transmission technologies

Transmission Technology		**Natural and Manmade Hazards**				
		Floods & Storms	**Earthquakes**	**Forest Fire**	**Local People/ Construction Activities**	**Fires and explosions**
Optical	Equipment	Medium	Medium	Low	Low	High
	Tx Link	High	High	High	High	High
Microwave LOS	Equipment	Medium	Medium	Medium	Medium	High
	Tx Link	High	Low	Low	Low	High
Satellite	Equipment	Medium	Medium	Medium	Low	Medium
	Tx Link	High	Low	Low	Low	High

Table 4.11 shows that the transmission technologies behave differently in different hazards. Satellite communication performs better than any other technology in calamitous situations while microwave LOS and optical technologies perform equally better than microwave LOS. Such comparisons help Oil and Gas operators in designing robust transmission network considering natural and manmade calamities by selecting appropriate transmission technology or combination of technologies based on the overall network requirements.

4.6 Risk Impact Discussion and Analysis

As from the results obtained, overall system availability was improved and found to be 0.999874 (99.987 %) with total down time of 1.04 Hours yearly in the best cases; and 0.999592 (99.96%) with total down time of 3.57 Hours yearly in the worst cases. Also the availability of each single Telecommunication Technology is very weak as described above. Considering that any failure of Telecommunication systems in the

Catastrophic situation will lead to a considerable and serious impacts from the following aspects:

4.6.1 Economical Aspect

4.6.1.1 Production Loss

- In the exploration stage and after the geological survey, rigs start drilling for seismic data acquisition. If result is satisfying and reservoir is feasible then another stage of testing, completion and work over during this stage if any catastrophic case such as Oil Spill, Leakage, explosion etc associated with case of telecommunication failure, the Production Loss will be increased before further communication with the support team for further action
- During daily operation, whenever there is a shutdown in any field, all submersible pumps inside wells had to be restarted again as soon as possible to resume production. These pumps in remote scattered wells can be restarted from field control room immediately since each well is connected with the control room via microwave and some wells with Fiber optic cable.

  In case of telecomm system failure, these wells had to be restarted manually from well location which means operators should move by cars and bring those wells back to production one by one.

  This will take at least 2 hours in best cases which mean 2 hours production loss weekly (since shut down due to power failure is experienced 4 times monthly as average).

  Moreover those wells may not be accessible due to security issues and normally if shut down took place at night, operators can't move outside camp until the next day morning which means that production loss can reach up to 15 hours.

  In rainy season also longer time is required to reach the well.
- Company is using a unified business information system for business management linking all daily operations and activities with company plans so as to monitor work progress and performance as well as controlling cost. This includes the request of materials and services purchase, materials issue out from inventories and so on.

  In case of telecommunication system failure, materials can't be issued out from inventory until system is back which means delay of all activities depending on this material or equipment which could be critical if this activity related to production.

4.6.1.2 Production Efficiency:

If the wells need to be shut down for any reason (high water content e.g.) in production, manual shut down may lead to delay in water process stoppage then more water will be injected for processing which will degrade the production efficiency.

4.6.2 Safety, Security and Environmental Aspect

4.6.2.1 Leak Detection System:

Since pipelines are important asset, it has been required by government regulations to ensure its safety and safety of population and environment where pipelines run.
Leak detection system is used to detect any leakage along pipeline and determine its location exactly to take an immediate action. Information is measured by field instruments then transferred to a central location in real time using Fiber optic cable.

In case of Fiber optic failure, leakage will not be detected immediately, unless the pressure drop down reached a considerable level in the next station, this means 3-5 hours are required to patrol the pipeline by cars and determine the leakage segment to fix it. The oil leakage or spill during this time usually not high to cause an economic loss but can lead to an environmental problem or human/animals diseases which may lead to serious legal issues since oil and gas companies are regulated by governmental obligations towards environment and local communities.

4.6.2.2 CCTV system

The CCTV system provides the life monitoring of each area in the plant and along the pipeline. Monitoring system is set up so that security and maintenance workers can get a Real-time seen of every part of the plant. The video and control signal of CCTV is transmitted to KT#06 by fiber optic telecommunication network then the KT#06 Control Center can get a Real-time seen as well.

CCTV system is also used to observe the gates and fence for plant security. Cameras are linked with monitors by coaxial cables for near areas and by Fiber optic cables for the far ones. In case of failures these areas will not be monitored lively which will be a hazard in case of emergencies like attack.

4.6.2.3 Public Address & General Alarm (PAGA)

Emergency communications is crucial to ensure safety of personnel and assets to alert on “man-down” cases, or to control emergency evacuations.

The public address and general alarm system is an application interconnected with the PABX system. PAGA system is vital for safety since any emergency is expected to drive a public reaction causing an increase in the use of the cellular network. Users communicate by voice; send pictures and messages and so-on. The cellular network will quickly become overloaded and may compromise emergency calls.

In an emergency condition, the PAGA system automatically broadcast alarm signals with different tones depending on the type of alarm. The PAGA system is also used to initiate an emergency instruction message indicating the nature of the emergency or initiate a priority emergency call received by all phones taking the highest priority and overriding all other calls ensuring an instant reaction to critical situations.

4.6.2.4 ESD (Emergency Shutdown)

Oil production is made safer and more efficient by constructing a Shutdown valve system to monitor the operation of well heads which is linked to the control room with Microwave or Fiber. In case of an emergency, the system triggers the Emergency Shutdown Device (ESD) to shut down the Processing fields and Oil & Gas wells head automatically when emergencies such as pipeline explosions or fires occur.

In case of telecommunications failure, and in case of hazard shut down should be done manually and locally. Delay in reaching the well may lead to disaster. also may lead to huge delay of information transfer for further manual shutdown actions.

4.6.2.5 Remote Rig Sites

Exploration security is always a challenge since it takes place in remote areas. They normally use VSAT, satellite Thurya and GSM (if area is covered) to communicate with outside world.

In case these systems failed due to power failure or any other reason, people on the rig will be isolated and any accident type A (life or death), major injury or attack could be vital.

4.6.3 Operational Efficiency Aspect

4.6.3.1 SCADA & DCS Network

SCADA (supervisory control and data acquisition) and DCS (Distributed Control Systems) are centralized control systems operating with coded signals over communication channels so as to provide control of remote equipments over large areas. In oil plants, they offer the advantage of linking the communications of all the plant processes for effective control, coordination between processes, and operator monitoring and reporting.

Data acquisition begins at the RTU (Remote Terminal Unit) and includes meter readings and equipment status reports, essential device data like speed, temperature, pressure, flow speed, flow density, and other statistics for analysis or alerts. Data is then compiled and formatted in such a way that a control room operator using the HMI (Human Machine Interface) can make supervisory decisions to adjust or override normal controls on real time.

Failure in communication can also impose the risk of SCADA and DCS unavailability which may lead to:

1. Loss of monitoring of the entire plant: failures will not be detected timely and the longer failures are left undetected the more damage they may leave, the more time and resources are required to fix the failure.
2. Shutdown of the plant: one of the biggest fears of plant managers is that the plant's DCS will shut down the system because of a failure at a single seemingly inconsequential point in the system. Even redundancies are there, SCADA and DCS forms a relief source for operators and managers that any threat, error or failure is detected and alarmed timely to avoid emergency shutdowns that delays the production process.
3. Loss of control of the plant: Even if the failures were detected without the SCADA/DCS it can't be controlled remotely. Control will be manual only. Failure either makes the operation difficult or makes the process out of service

4.6.3.2 Maintenance and Patrolling:

All maintenance/ emergency repair operators communicate through mobile radio system inside plant especially in risky areas or confined spaces like tanks' roof, or. In case of radio failure either operator refuses to do the job or being exposed risk.

4.7 Comparison of Technologies in Catastrophic and Risk Situation:

All three technologies can be compared in terms of availability, repair time, repair cost and impacts of natural and manmade catastrophic hazards based on sections 4.3, 4.4 and 4.5.

4.7.1 Satellite (VSAT) Technology:

Advantages:

- Best availability of 99.45%.
- Lowest repair time and cost.
- Less impacted by the natural and manmade catastrophic situation.

Disadvantages:

- High cost of CapEx and OpEx for installation
- Limited bandwidth will not meet all the requirements.

4.7.2 Optical Technology:

Advantages:

- Large bandwidth will meet all the Telecom requirements.
- Medium Equipment's availability of 98.38%.
- Less impacted by the natural catastrophic.

Disadvantages:

- High repair time and cost.
- High cost of CapEx and OpEx for installation
- Highly impacted manmade catastrophic situation.

4.7.3 Microwave LOS Technology:

Advantages:

- Medium repair time and cost.
- Medium impacted by the manmade catastrophic.
- Low cost of CapEx and OpEx for installation.

Disadvantages:

- Lowest Equipment's availability of 97.85%.
- Highly impacted natural catastrophic situations.
- Bandwidth will not meet all the requirements.

Finally from the above analysis and study, it is founded that the Satellite Communication is the best type of Telecommunication technology during the Catastrophic Risks with strong capabilities to be robust enough during this circumstances.

The Fiber Optic is the second type of Telecommunication system if the following recommendations are applied it will improve the chances of more strength during the catastrophic Risks.

The Microwave LOS is the Last type of Telecommunication and will suffer during the catastrophic risk situation

Chapter Five

Conclusion and Recommendation

5.1 Conclusion

In this thesis, The transmission networks for Oil and Gas facilities is evaluated for natural and manmade catastrophic hazards and risk analysis is carried against the availability and the repair and replacement time and costs, the evaluation is carried for the three infrastructure technologies applied in oil and gas fields, Optical, Microwave LOS and Satellite (VSAT) transmission technologies. Transmission networks for facilities have been facing several kinds of catastrophic hazards and expected risks due to the situation and locations of fields. The weakness and strength of transmission technologies against natural and manmade catastrophic hazards and the associated risks are discussed in Chapters (2), (3) and (4). It appears that each transmission technology behaves differently to different kind of hazards. One technology confronts some risks and other technology resists the same risks, while one technology have strong connotation to the certain vulnerabilities and other technology opposes the same vulnerabilities. Availability calculated and discussed in Chapter 4 using the Failure Mode and Effect Analysis (FMEA). Repair and replacement time and costs of each transmission technology in catastrophic situations differ from each other, considering Petro Energy E&P as case Study. Finally, it is shown that the These results of system unavailability were found to be serious to the industry since it may lead to revenue loss, and the Technologies shall be enhanced in order to be more strong and robust in the catastrophic hazardous and risks .

These results of system unavailability were found to be serious during the catastrophic hazards to the oil and gas industry since it may lead to revenue loss, environmental and health impacts, loss of life for the employees working at the field and nearby local people.

Some precautions had already been taken by Petro energy to guarantee the availability of the telecommunication system such as:

- Agreement with other companies in the same field to share their FOC as back up.
- Factory acceptance test for equipment and cables are done in advance to eliminate the manufacturing risk (Due to market competition normally the reliability is very high).

- Activate patrolling within site and along pipeline, transit lines, trunk lines and flow lines to review the warning signs for the fiber optic cables and discover surrounding hazards earlier if any.
- Conducting Design Review meetings, Hazards and operability studies (HAZOP) and Risk assessment and response before the construction of the fields to minimize the manmade and operation catastrophic hazards and risks.
- Spare parts stock is available and reviewed annually to check the balances .
- Long Term agreement with maintenance contractors on call basis are signed and renewed periodically to reduce the time of repair.
- Network management system linking all telecommunications systems with the main telecommunication room in Khartoum with a display screen and a specific operator is there for live monitoring.

5.2 Recommendations

Here below are some recommendations for Petro energy to enhance and increase the availability of the telecommunication system even more:

- Increase the Bandwidth for the Satellite (VSAT) to accommodate the essential Telecommunication requirements during the catastrophic hazards.
- Adopt detailed risk assessment and evaluation, risk response and implementation during the operation of the fields periodically considering the Telecommunication infrastructure technologies.
- Make a redundant for each equipment or hardware especially for those involved in the experienced failures incidents.
- Clearly state the availability and reliability requirements in contracts when implementing telecommunications projects.
- Schedule system downtimes for maintenance or other to ensure the availability of the backup and reduce the impact
- Power failure is seriously affecting the availability of the telecommunication system. So, company should work to find a solution or effective backup for that.
- To overcome the fiber optic cut problem which is the major cause of system failures:

- More protection for the cable (normally the cable is designed to be direct buried but some regions need to have ducts for more protection).
- Make awareness sessions for people resident along the FOC path to inform them about the importance of fiber optic cable to their community development)
- Consider to design deep trenches for the fiber optic cables during the design stage to avoid the heavy rain impacts.
- Carefully watch the maintenance process to ensure the new introduced components quality and the quality of the replacement process as well.
- Seek and fetch new types of more armored cables in the market to make it difficult for locals to cut it.
- Study the overhead fiber optic cables in manner of cost and associated risks for further application if suitable.

5.3 Future Work

In this thesis only the three traditional telecommunication technologies are evaluated considering the normal and catastrophic situation to avoid the associated risks and impacts for the Oil & Gas fields.

The companies are now taking advantage of the latest developments in Field Telecommunication technologies to remotely monitor and manage exploration, development and production activities at these field locations.

There have been advances in the current generation of FT technologies (e.g. "Virtual Fiber" wireless BB using WiMax, more spectrally efficient 3G technologies, WiFi speeds matching fixed BB speeds) to meet the requirements of Digital Oil Field Technology.

Further risk assessment and catastrophic hazards impacts for the above Technologies is future work.

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