



**Addis Ababa Institute of Technology**  
**School of Electrical and Computer Engineering**  
**Telecommunication Engineering Graduate Program**

**Availability and Maintainability Analysis for Mobile  
Networks in Addis Ababa**

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A Thesis Submitted to The School of Electrical and Computer Engineering in Partial Fulfillment of the Requirements for The Degree of Master of Science in Telecommunication Network Engineering (TNE Track).

**November 2018**

**Addis Ababa, Ethiopia**

**Addis Ababa Institute of Technology**  
**School of Electrical and Computer Engineering**  
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# Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been properly acknowledged.

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## **Abstract**

Modern society has a high dependence on communication technology with a wider range of applications. So, service users demand an always available network to use it whenever they wish. Thus, network operators are expected to continuously analyze the performance of their networks and take corrective actions to make them as available as possible. Reliability Engineering provides methodologies and techniques to analyze the reliability, availability, and maintainability (RAM) of systems including telecommunication networks.

The main objective of this research is to perform availability, maintainability, and downtime impact analysis as a case study of Ethio telecom (ET) mobile sites deployed in Addis Ababa, Ethiopia. Four months mobile sites outage, active 3G mobile service users and average revenue per user (ARPU) data are used for the analysis. The mean time between failures (MTBF) and the mean time to repair (MTTR) are metrics used for availability analysis while maintainability is analyzed based on the lognormal distribution of the time to repair (TTR) data.

Analysis results have shown that: (a) 91.7% of the mobile sites had an outage over four months. (b) 69% of the total mobile sites were in an outage for 114, 592 times and 25, 676.72 hours (c) The average availability of the mobile sites is 99.75% with a median, mean, and maximum maintenance times of 1.9, 3.3 & 10.4 hours respectively. (d) Longer downtimes have a significant impact on revenue, Service Level Agreement (SLA) and on customers. The results of the research can be used as an input in network maintenance policy, strategy, and resource planning to ensure high network availability. The MATLAB, Easy Fit, and MS Excel software tools are used for analysis.

**Keywords**— *Availability, Reliability, Maintainability, RAM, Mobile Networks, Network Outage*

# Acknowledgments

I would like to provide my sincere thanks to all the people who have supported me to realize my thesis work.

I am profoundly grateful to thank my advisor Dr. Yalemzewd Negash for his amazing point of views, encouragement, guidance, follow up and friendly approaches throughout the thesis work.

It is also my pleasure to heartfully thank Dr. Dereje Hailemariam and Dr. Beneyam Haile for their genuine, constructive feedbacks during the presentation phases from which I got very important ideas and useful perspectives.

I am also thankful for my coworkers and ethio telecom staffs who have supported me by providing ideas, data and covering my duty times while I was engaged on my thesis work.

I would also thank you and appreciate ethio telecom and Addis Ababa Institute of Technology (AAiT) for the opportunity to learn, for their continuous support and for the research fund they have provided me.

My deepest gratitude goes to my family, my wife Bethelehem Dejene, my daughter Delina Leake and my new baby girl Hiyab Leake (she is born on October 15, 2018). The completion of the research would have been impossible without the unreserved support of my wife who have fully dedicated to take care of the family while she was also pregnant. So, I thank you and I love you for being on my side while you were the one who deserves my support.

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# List of Acronyms

ARIMA	Autoregressive Integrated Moving Average
BS	Base Station
CDMA	Code Division Multiple Access
ET	ethio telecom
GSM	Global System for Mobile Communications
IP	Internet Protocol
KPI	Key Performance Indicator
LTE	Long Term Evolution
MTTR	Mean Time to Restore
OPEX	Operational Expense
QoE	Quality of Experience
RAM	Reliability, Availability and Maintainability
RAN	Radio Access Network
SLA	Service Level Agreement
STCO	Short-Time Cell Outage
TTs	Trouble Tickets
UMTS	Universal Mobile Telecommunication System
NOC	Network Operation center
TT	Trouble Ticket
UMTS	Universal Mobile Telecommunication System

CM	Corrective Maintenance
PM	Preventive Maintenance
TPM	Total Production Maintenance
RCM	Reliability Centered Maintenance
BCM	Business Centered maintenance
MDT	Mean Downtime

# 1.Introduction

## 1.1 Introduction

Mobile networks have been growing rapidly in the past decade to support increasing demands for mobile communications [1]. As societal dependence on mobile communications increases, users will demand high *availability* of mobile networks whenever they desired it. To improve on the satisfaction of customers, to control operation cost (OPEX), revenue loss due to service interruptions and to meet key performance indicators (KPIs) expected from regulatory bodies and SLAs, it is compulsory for telecommunication network operators to ensure network availability [4].

From the Reliability Engineering perspective, the performance of a system can be demonstrated in terms of reliability, availability, and maintainability (RAM). Reliability Engineering is a branch of system engineering which deals with the RAM characteristics of a system. Reliability is the probability of a system to perform its intended function for a given time interval and operational condition. Availability is a metric which shows the proportion of time mobile subscribers on each network have a mobile connection available to them or it is a measure of the proportion of time users have a mobile signal on a network in a case the geographical location is covered by mobile networks. While unavailability (outage) indicates that the proportion of time network users lacks mobile signal to make call or Internet surfing or whatever service being subscribed by a customer. Whereas maintainability refers to the probability of a system or a network in outage being repaired within a time  $t$  [4]. While the objective of reliability is to keep the network functioning without failure, maintainability is applied to make the maintainability of a network as quickly as possible. Whereas the objective of the availability is to increase the readiness of a network to provide the required service

when demanded by a user. Availability of a network is then a function of the reliability (the probability of occurring outages) and the maintainability (how long an outage lasts before being repaired).

From design and operational point of view, RAM can be achieved using the techniques and methodologies defined in reliability engineering which deals with RAM techniques and requirements of systems such as telecommunications [7, 8, 12, and 13].

As presented in [18], network availability and performance issues have become the leading cause of customer churn and operators are spending approximately \$20 billion a year dealing with incidents of network outages and service degradations.

Similarly, ethio telecom has large mobile infrastructure and growing customer base and faces network outage challenges. Hence, an indepth understanding of mobile networks availability and maintainability and making a scientific analysis of those performances can help operators and policymakers to work on improvement mechanisms of network performance to achieve customer satisfaction and business goals.

## **1.2 Statement of the Problem**

Globally, there are 7.8 billion mobile subscriptions (SIM connections) provided by nearly 800 operators [9]. Mobile network operators have generated 4.5% of global gross national product (GDP) and created 29 million employment opportunities as of 2017. The sector is also experiencing fast technological advancements with 4G already reached 29% of global subscription and forecasted to reach 53% by 2025 and by that time 5G is will share 14% of the global subscription.

With all the advancements in technology and subscriptions, efficiently operating of mobile network is a common challenge of all operators. According to [18], mobile operators are now reporting a higher incidence of outages and service degradations that take a long time to fix.

ET is Ethiopia's sole telecom operator which owns a huge infrastructure consisting of the global system for mobile communication (GSM), universal mobile telecommunication system (UMTS) and the long-term evolution (LTE). And its customer base is growing fast. Recently, ET became the largest mobile operator in Africa in terms of subscriptions, with 57.34 million mobile subscribers as of Nov 2017 [10, 11].

Likewise, ET uses high RAM requirements during vendor selection to deploy mobile networks [41]. Therefore, the networks are expected to perform to the level of design targets to satisfy the service availability expected by customers.

Conversely, an observation of the performance data of ET mobile networks shows that it is not up to the expectation of the design and implementation according to the study conducted during the seminar work. An observation of five months mobile networks performance analysis by ET has shown that mobile sites have around 70% share of the total network outages and above 30% of the mobile sites in outage took longer than three (3) days maintenance time. Besides, mobile sites performance analysis in ET includes availability but not reliability and maintainability. Even the availability analysis is not based on the standard metrics such as the mean time between failures (MTBF) and the mean time to repair (MTTR) set in the reliability engineering.

On top of that, mobile sites in Addis Ababa have relatively large traffic utilization compared to those in regions and remote areas. This makes intolerable for mobile sites to have frequent and long-lasting outages. Therefore, empirical data analysis is required to ensure the availability of the networks, to meet the targets on the SLA, to determine required resources for maintenance (like labor-hours, spare parts, logistics, and supplies), to reduce revenue loss and customer impact of downtimes.

## **1.3 Objective**

### **1.3.1 General Objective**

The main objective of this research is to analyze the availability and maintainability of the mobile networks (GSM, UMTS, and LTE) in Addis Ababa.

### **1.3.2 Specific Objectives**

The specific aims of the thesis are:

- To collect and process mobile sites outage and repair time data from ET's network management system in the national network operation center (NNOC).
- Perform descriptive statistics of mobile site outages
- To perform mobile sites inherent availability analysis using MTBF and MTTR metrics
- To perform mobile sites maintainability analysis using the statistical distribution of TTR data.
- To conduct mobile sites downtime impact analysis in terms of revenue loss, SLA fulfillment, and customer impact.

## **1.4 Methodology**

To accomplish this research work, relevant articles, journals, and books were reviewed. The study is an empirical research being conducted using primary data directly collected from ET's network management system. Except for the maintainability analysis, the descriptive, the availability and the network downtimes impact analysis are conducted using population data (all mobile sites in Addis Ababa were considered). While the availability analysis is conducted using the MTTR and MTBF metrics, the lognormal distribution is used for the

maintainability analysis. As a flow of work, Figure 1-1 shows the research methodology to be followed in this thesis.

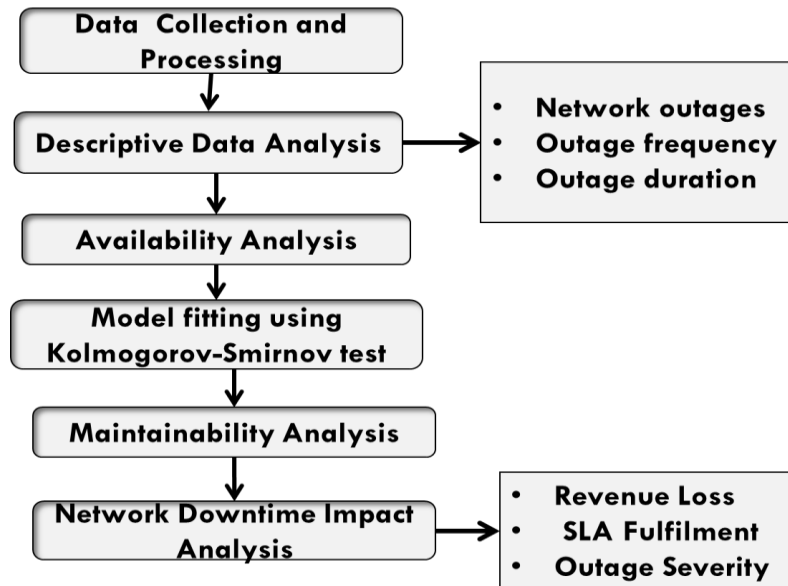


Figure 1-1 Research methodology

## 1.5 Scope and Limitations

### 1.5.1 The scope of the study

The scope of the Thesis is limited to the study of availability, maintainability of mobile sites in Addis Ababa. Besides, the impacts of network downtimes on revenue, SLA fulfillment and on customers (severity analysis) are performed. The networks are consisting of GSM, UMTS and LTE networks. There are 744 mobile access network sites, and all are considered during the observation period (February to May 2018). Mobile sites with partial as well as full outage data are considered in the study.

The descriptive, availability and downtime impact analysis were conducted using the population data. However, the maintainability analysis was conducted using a randomly selected 30 base stations. This is because the maintainability analysis is a relatively lengthy process to address all the networks in an outage. Network outage data of the mobile access

networks are used for the analysis. Although faults happening in the core or transport networks can cause network outages and can ultimately affect user services, they are beyond the scope of this study.

## **1.5.2 Limitations of the study**

Although it has effectively achieved its objectives, this Thesis is not free of limitations. Some of the limitations of the Thesis are: First, using long time data could enable to draw better conclusions about the availability and the maintainability of the networks. Second, conducting detail investigations of those networks with a higher frequency of outages and longer downtimes to determine priority areas of intervention were not done. These all limitations are occurred partly due to time constraints to go farther than the accomplished work and finishing within the schedule.

## **1.6 Contribution**

This thesis work has two main contributions. First, availability analysis of mobile network sites using MTBF and MTTR metrics and a statistical distribution-based maintainability analysis is used in the mobile sites of ET which is not done by ET as of current. Second, real network outage data are used to conduct the analysis which signifies, those methodologies can be applied for network performance analysis in terms of availability and maintainability with automation.

## **1.7 Literature Review**

In [13], the maintainability of communication networks and its impact on service downtimes was studied using network outage data and maintenance history data over a two years period. Maintenance time break down into failure to the notifying of technical engineers, time from that notification to the arrival of the engineers, and the time from arrival to the

recovery of a service was used. Besides, the impact of network downtime in service downtime was modeled by maintenance modes (remotely and on-site). The authors have concluded that networks repaired onsite have longer downtime which is obvious. It could have been better if the significance of travel time to network downtime was determined which can be minimized by operators.

In [14], unavailability evaluation for communication network management was studied using a real network fault data of Internet protocol (IP) network. Network unavailability was approximated as the sum of the value of outage time of each failure over the total of failures times averaged over the measurement period. While the time trend of unavailability is therefore evaluated over an interval of times  $T$  and  $T-1$  periods. A criterion value was defined to compare the unavailability the network at time  $T$  with that of the  $T-1$ . The evaluation criterion is determined by the distribution of unavailability in the previous period. If the calculated unavailability is greater than the criterion value in that time interval, it is considered that there is low network availability in that interval. This has enabled to analyze the trend unavailability of the IP networks over the observation period.

In [15] K. Bando et.al, have analyzed and evaluated failures of communication systems and networks by using public data from newspapers, official government information and other sources in Japan collected for a period of 14 years. They have analyzed the data using the dependability framework. Dependability refers to the ability of a system to deliver service that can justifiably be trusted [22]. Availability, reliability, safety, integrity, and maintainability are attributes of dependability. Severity is defined based on the duration of failure time and numbers of customers impacted. Four severity levels are defined namely: low, moderate, high and very high.

Accordingly, the findings of [15] are: (i) have shown severity levels of network faults by plotting fault duration against numbers of impacted customers and most faults are categorized between moderate and high severity levels. (ii), have shown trends of failure

throughout 14 years with respect to the level of impacts on telecommunication services. This could help operators to watch out the performance of their networks and to take an informed intervention.

In [16], a statistical analysis of outage of time series data collected from telecommunication network is presented. The model used by the authors is the Box-Jenkins approach and Autoregressive Integrated Moving Average (ARIMA). As a software tool, a statistical tool R was used to perform the time series data analysis. Accordingly, the outage data was plotted against time and it exhibits a highly stable pattern. Regarding the forecasting, the network outage in Ghana will have a decreasing pattern. This is a helpful finding for an operator that helps to evaluate the reliability of its networks.

In [17], a measurement of Short-Time Cell Outages (STCO) is performed in a mobile cellular network. The STCO is defined as a short-time outage of all or some base station (BS) cells (sectors) that lasts up to 30 minutes in a day. To do the analysis, seven days outage data is collected from the operator's fault management system and the authors have developed a software algorithm to filter out only STCOs out of the total network fault data. The analysis has indicated there are correlations between high network utilization and frequent occurrence of STCOs.

Authors in [21, 22, 23 & 24] have analyzed the frequency, severity and time trend of communication networks and financial information systems respectively. Failure frequency and severity are considered as parameters to measure the impact of failures on service users and network operation. Failure frequency is defined by the cumulative number of failures while failure severity is described by the product of outage times and impacted users. Besides, severity levels were defined as very high, high, moderate and low. Network outages are then categorized to respective severity level based on downtime and customer impact. The time trend of failure frequency is analyzed by plotting the time to a cumulative number of failures in a time interval. The outage frequency, severity and time trend analysis of network outages

enable to determine if most outages are tolerable, type and amount of resources required to tackle outages.

Research works in [25, 26, 27 & 28] on RAM analysis studies conducted in different systems outside of the telecommunication sectors. In [25] which is a thesis on RAM analysis of Conveyor System in Underground Coal Mine. The reliability and the maintainability analysis were done based on best fit statistical distributions of the repair time data. The subsystems did not have the same failure characteristic and have fitted to different models. Then it has managed to show the systems RAM performance. Likewise, the studies in [26, 27 & 28] had followed quite similar approaches of data analysis except that those researches were done on the robotic system, gas compression train system and on electric cable shovels respectively. All of them have applied the statistical distribution-based analysis to determine the reliability and maintainability of the respective systems.

The general approach followed by these works were first finding the statistical distribution of the failure and repair time data, and then the respective measurements of reliability and maintainability are computed and analyzed. And it is observed that statistical distribution-based reliability and maintainability analysis is both popular and effective approach but not yet applied in mobile networks.

## 1.8 Thesis Layout

The thesis document has contained four main parts.

**Part one:** is the introduction part including the statement of the problem, objectives, methodologies, and literature review.

**Part two:** is focused on the theory and analysis methodologies of the availability and maintainability of systems including telecommunication.

**Part three:** is the analysis part. It covers the data collection, processing, analysis and presentations of results.

**Part four:** is the last part of the document which has contained the conclusions, recommendations, and future works part.

# 2. System Availability and Maintainability

The reliability, availability, maintainability (RAM) of systems is studied by the reliability engineering. “The purpose of reliability engineering is to develop methods and tools to evaluate and demonstrate the RAM and safety of components, equipment, and systems, as well as to support development and production engineers in building in these characteristics” [1]. To be cost and time effective, reliability engineering must be integrated into all phases of system lifetime (design, production, installation, and operation).

In telecommunication, the RAM requirements are specified in terms of availability, rather than reliability. While availability is the end target, the reliability and the maintainability of telecommunication networks are applied in design, installation and operation phases of the networks and availability depends on the reliability and maintainability of such networks. However, availability specification is mostly used considering users perspective [1, 4, 6]. In many cases, SLAs are specified in terms of availability. To ensure the availability of the networks and to meet the targets on the SLA, empirical data analysis is required to prevent from entering into uncalculated risks on signing the contracts. Reliability engineering of systems in telecommunications serves is used to reduce such risks [1].

Historically, reliability engineering has become an important field of study following the industrial revolution [1]. Production of mechanical and electronic systems such as automobiles and telegraph have increased following the industrial revolution. Large-scale production resulted in an increased awareness of item failures, performance and its impact on business. The first formal work registered in the reliability engineering was by Walloddi Weibull during the 1930s. He has invented the well-known statistical distribution (named

after his name, the Weibull distribution) which is widely applied in reliability analysis of systems [1, 6]. Further improvement has been observed during the second world war (WWII). The advent of radar and other electronic warfare systems; and the wide usage of vacuum tubes in many electronics systems led to both poor system performance and high maintenance costs. To give focus on the reliability of electronics systems, the Institute of Electrical and Electronics Engineers (IEEE) Reliability Society was formed in 1948 [1].

Following WWII, Reliability Engineering has got an application on military and commercial systems/equipment. Space exploration programs, the establishment of NASA (National Aeronautics and Space Administration) and launching of commercial satellites further strengthened the need for reliability of products. Semiconductor development, military applications, communications systems, biomedical research, and software-based systems in the 1980s led to new work in both system design and reliability analysis [1, 2]. An increased awareness of consumers on products and services reliability have brought the advancement and application of Reliability Engineering to its current level.

## 2.1 Basic Concepts in Reliability Engineering

In this section, the basic concepts of reliability engineering are to be defined and discussed.

- **Reliability Engineering:** Reliability engineering a branch of system engineering which provides tools and techniques to be applied into a system/subsystem which enables it to function without failure for a specified time interval in a specified environment [1, 2, 3].
- **RAM in Reliability Engineering:** RAM refers to the reliability, availability, and the maintainability characteristics of a system and its operational support.
- **Reliability:** Reliability is defined as the probability of a system to perform its intended function with consideration of operating condition and time interval. This definition has the following keywords [5].
- **Probability:** occurrence of failure/outage is a stochastic phenomenon

- **Function:** the function of the product or service should be specified
- **Conditions:** the environment or condition the service is performing
- **Time:** duration of time a product/service is required to perform without failure
- **Availability:** Availability is the probability that a system is operating satisfactorily at any moment in time when used under stated conditions. [1].
- **Maintenance:** Refers to measures taken by the system users for keeping it in operational state or repairing it to operational state [7, 8].
- **Maintainability:** Maintainability is the ability of an item/system to be retained in or restored to a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair [8].
- **Outage/Failure:** In reliability engineering a failure is said to happen when a component/system is not doing its desired function and considered as being unavailable.

## 2.2 Relationship Among RAM Elements

Table 2.1 shows the relationship between the RAM which are an interrelated characteristic of a system. Availability is a function of reliability and maintainability. Keeping the reliability constant, decreasing maintainability decreases the availability of the network/any system. This is because of that longer maintenance time means longer downtime which decreases the working time of a system. On the other hand, it is also possible to increase system availability by increasing the reliability of a system while the maintainability is held constant. However, availability of a system cannot be constant, but it can either increase or decrease based on the reliability and/or the maintainability performance. For example, if a telecommunication network's availability is increasing, it is because either the occurrence of outages is rare (high reliability) or there is an efficient maintenance process.

Table 2.1 The relationship among reliability, availability, and maintainability

Reliability	Maintainability	Availability
↔ Constant	↓ Decreases	↓ Decreases
↔ Constant	↑ Increases	↑ Increases
↑ Increases	↔ Constant	↑ Increases
↓ Decreases	↔ Constant	↓ Decreases

While the choice between increasing either or both reliability and the maintainability depends on the cost-benefit analysis, the availability gets worsens when both decreases [2, 3,6]. As the focus of this research is on availability and maintainability analysis of mobile network systems, the details of reliability are not discussed in this work.

## 2.3 Availability Theory and Analysis

The concept of availability is mostly related to repairable systems. Repairable systems are those under continuous operation, the system is repaired, but not replaced after each failure [6]. Examples of repairable systems are automobiles, communication systems, aircraft, printers, medical diagnostics systems, etc. The operational status of repairable systems at any random time is either operating or failed due to an outage. And then the systems in an outage are being worked upon to restore their operation in minimum time [6, 12]. Availability can be defined in terms of reliability and maintainability, that at any given time,  $t$ , a system is either operational (not failed) or it has been restored after failure [8]. With this regard, a system has two possible states- operating or in repair. Availability is then defined as the probability that a system is operating reasonably at any random point in time  $t$ , or the system's readiness for use when there is a demand. A system is then subject to a sequence of "up" and "down" cycles which constitute an alternating renewal process as shown in Figure 2-1 below.

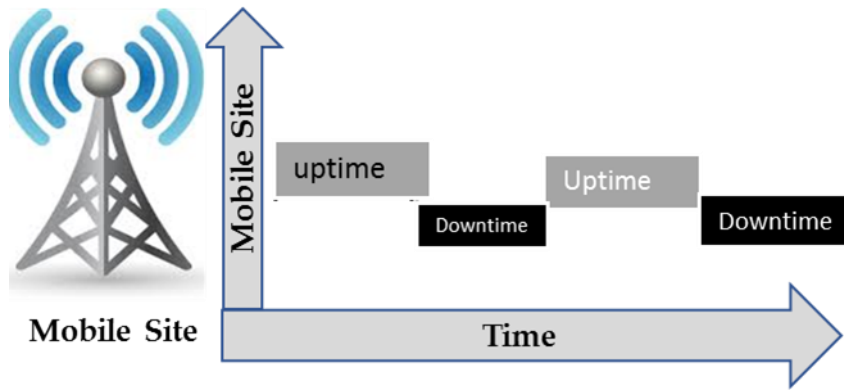


Figure 2-1. Mobile sites operational characteristics over time

Then the process is defined by a sequence of non-negative random variables which are the time to failure and the time – to – repair.

Therefore, metrics used to analyze availability are derived from the failure and repair time data. MTBF, MTTR, and the MDT are the most used measurement metrics in an availability analysis. The MTBF is defined as the average time between successive failures of a system. The MTBF is used in a system’s reliability and availability measurements and is represented as units of hours [4, 6]. The MTTR is the mean corrective maintenance time which represents the average of each repair actions and the MDT is the meantime that a system is not operational due to corrective and preventive maintenance [6].

Understanding how maintainability and reliability affect availability is key in maximizing it, and it should be done in a cost-effective manner as there is always a tradeoff between achieving target availability and the cost associated with it.

Figure 2-2 shows how the time to repair (TTR) and the time between failures (TBF) data of a hypothetical mobile site are being determined from which the MTTR and the MTBF variables are derived.

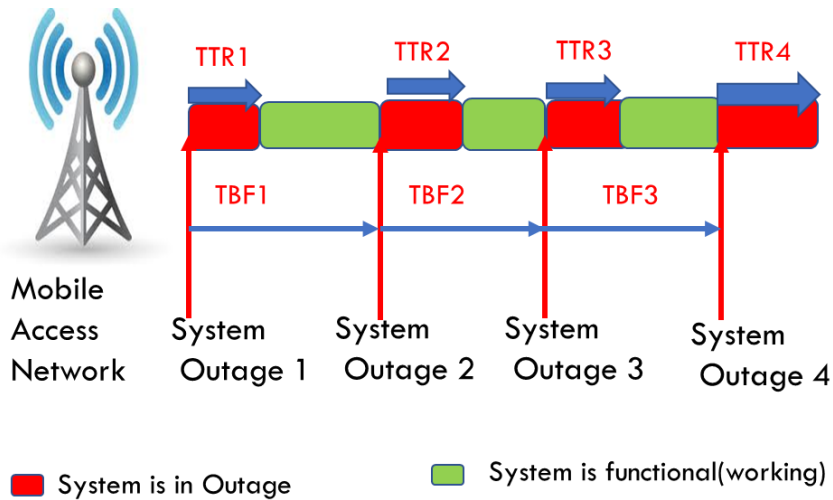


Figure 2-2 TTR and TBF data determination

$$\text{MTBF} = \frac{\text{System working times}}{\text{Number of outages}} = \frac{\text{TBF1} + \text{TBF2} + \text{TBF3}}{4} \quad (2.1)$$

$$\text{MTTR} = \frac{\text{System outage times}}{\text{Number of outages}} = \frac{\text{TTR1} + \text{TTR2} + \text{TTR3} + \text{TTR4}}{4} \quad (2.2)$$

Where TTR: time to repair

TBF: time between failures

MTBF: mean time between failures

MTTR: mean time to repair

Depending on what types of downtimes are chosen, there are different ways of analyzing system availability. These are inherent availability, achieved availability and operational availability and are explained in the following subsections.

### 2.3.1 Inherent availability

Inherent availability (IA) considers only the corrective maintenance downtime to define system availability. This is defined by the MTBF and MTTR metrics as shown in Eq (2.3).

$$I_A = \frac{MTBF}{MTBF + MTTR} \quad (2.3)$$

Where  $I_A$  = inherent availability

MTBF = mean time between failures

MTTR = mean time to repair

Inherent availability depends solely on the failure time and repair times distribution. “Inherent availability is generally derived from analysis of an engineering design and based on quantities under control of the designer” [2]. The inherent availability can be considered as a system design parameter to decide reliability-maintainability tradeoff [2, 9]. In Inherent availability calculation, preventive maintenance downtime, administrative and logistic delay downtimes are excluded.

### 2.3.2 Achieved Availability

Achieved availability (AA) calculation considers both the corrective maintenance downtime and preventive maintenance downtimes. Therefore, instead of the MTTR used in inherent availability, here the MDT is used which is the mean of the corrective and preventive maintenance times.

$$A_A = \frac{MTBF}{MTBF + MDT} \quad (2.4)$$

Where  $A_A$  = achieved availability

MTBF = mean time between failures

MDT = mean downtime

If it is performed too frequently, preventive maintenance can have a negative impact on the achieved availability even though it may increase the MTBF. Preventive maintenance intervals resulting in frequent downtimes have availability less than the inherent availability.

As the preventive maintenance interval increases, the achieved availability will reach a maximum point and then generally approach the inherent availability [2, 9, 13]. Here in achieved availability computation, the administrative delay is not considered.

### 2.3.3 Operational Availability

The operational availability (OA) computation considers all sources of downtimes, including corrective maintenance, preventive maintenance, and all administrative time delays. In general, the operational availability measures the operator's network availability performance in its customer's view [6].

$$O_A = \frac{\text{Up time}}{\text{Operating cycle}} \quad (2.5)$$

Where  $O_A$  = operational availability

Where the operating cycle is the overall time of operation being investigated and uptime is the total time the system was functioning during the operating cycle. When there is no specified logistic downtime or preventive maintenance, the above equation returns the inherent availability of the system. The operational availability is the availability that the customer experiences. In the operational availability, downtimes due to preventive maintenance, corrective maintenance, and administrative delays are considered.

While the inherent availability measures the efficiency of maintenance personnel and system design performance. The achieved availability additionally measures the effectiveness of the maintenance schedule of operators. Whereas the operational availability measures performance of operators in customers and competitors views.

Normally, the availability is expressed as the percentage of the time the network is working and usually expressed in a number of nines. For example, the five-nines refer to the percentage 99.999%, in which organizations strive to achieve in their networks to have a grade of service availability. Table 2.2 shows the relationship between percentage availability and

minutes of downtime per year. It should be noted that taking the step from four to five nines would require going from 52 to only 5 minutes of downtime per year [4, 6, 13]. Even the least availability of 99.0%, the network is not allowed to stay on an outage for more than 3 days 15h 40 min per a year operation.

**Table 2.2** Availability and network downtimes per year [6]

<b>Availability</b>	<b>Downtime per year</b>
99.9999%	32s
99.999%	5min 15s
99.99%	52min 36s
99.9%	8 h 46m
99%	3 days 15h 40 min

## 2.4 Maintainability Theory and Analysis

Maintainability is a characteristic of a system that describes the probability that its maintenance (preventive or corrective) can be performed in a specified time interval and using available procedures and resources such as skill level of personnel, spare parts, test facilities, etc. [8]. Quantitatively, maintainability is defined as the probability that a system can be retained from a failure state to operational state within a specified time  $t$ .

Maintenance involves a set of activities being performed to retain or to restore a system into the desired state. Maintenance is mainly categorized into two types known as preventive maintenance and corrective maintenance. Preventive maintenance is performed at predetermined intervals with the objective of reducing wear out failures [6, 7, 8]. Whereas corrective maintenance is performed once a system is in a failure and is recognized by the operator with the objective to get the system back into the operational state. Maintenance

involves many activities including recognition, isolation (localization & diagnosis), elimination (disassembly, replace, and reassembly), and checkout.

The need for maintainability is important due to the occurrence of very high operating and support costs of systems and equipment. For example, in the United States (USA), the cost of maintenance and operation of plants is over \$300 billion per year. While the maintenance cost of a single military jet aircraft costs \$1.6 million per year and mobile network operators worldwide spend more than \$20 billion per year to handles network outages [1, 6, 18, 19].

Maintainability engineering principles are being applied into systems with the objectives of reducing system downtime, for efficient restoration of the system, and to reduce maintenance time and costs, to determine required resources like labor-hours, spare parts and so on. Besides, the maintainability data can be used to determine the system's availability or unavailability [7].

The following are general maintainability principles being applied to systems design, production, and operations.

- Reduce life cycle maintenance costs
- Reduce the amount, frequency, and complexity of required maintenance tasks
- Reduce mean time to repair (MTTR)
- Determine the extent of preventive maintenance being performed
- Reduce the amount of supply supports required

The main purpose of maintainability is to achieve maximum operational readiness(availability) of a system. There are two ways of realizing high system availability. Either by increasing the system reliability (to operate without an outage) or by implementing speedy maintenance that even if there are outages, the networks can be repaired as quickly as possible. In such a decision, there is always a tradeoff in the cost of the realization, on the mission success of the system and the confidence of end users [ 6, 7, 9].

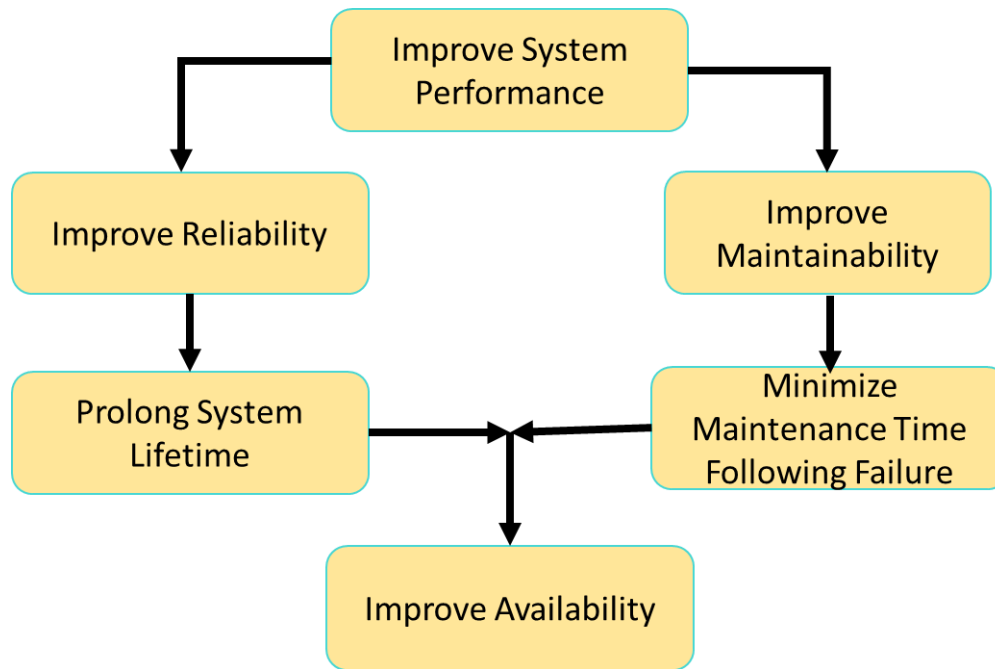


Figure 2.3. RAM relationships on system performance improvement

Figure 2.3 shows the relationship between reliability and maintainability on improving system performance. Therefore, the optimum result lies in an appropriate balancing of the reliability and maintainability of the system. Maintainability is then used to obtain maximum operational readiness in such a way that an end system can be maintained in the least time consistently, and with a minimum cost of support resources.

As already explained, the goal of improving system reliability and maintainability is to improve system availability. Then after, the system can be accessible by end users for most of the time and an operator/owner of the business can maximize the return on investment.

In the telecommunication business, maintainability considerations are related to the availability of spare parts and the reduction of turnaround time on repair services. Besides, the nature of the telecommunications business is driving demand for proactive maintenance practices. The goal is to be aware of those maintainability factors and able to compete by offering quality, reliable and low-cost services to customers.

## **2.5 Categories of Maintenance**

Maintenance can be categorized based on when or where the maintenance task is performed. Based on the when the maintenance is performed, maintenance is further categorized into preventive and corrective maintenance. While the corrective maintenance is also called reactive maintenance for the fact that it is performed in reaction to the faults or outages already happened, the preventive maintenance is also called predictive or proactive maintenance. Based on where the maintenance is performed, the maintenance is categorized into three levels of maintenance. These are organizational, field and shop or depot [7, 8].

### **2.5.1 Preventive Maintenance**

Preventive maintenance (PM) is usually voluntary downtime of a system with the intention of extending the working life of the system and keep the system safe to operate. PM is done in a predetermined interval of time while the system is operating, by making the system down or during the CM time. There are two types of PM: scheduled and condition-based [30]. A PM is scheduled maintenance when it is performed based on a specified time interval. The interval may be in terms of hours, cycles, or another measure meaningful to the way the system is operated. The actions being performed during scheduled maintenance differs from system to system, however, it may include actions cleaning, adjustments, refueling generators and so on. On the other hand, PM performed to determine the condition of a system, perceive or forecast a future failure, or performed because of such actions is referred to as condition-based PM [3, 7].

### **2.5.2 Corrective Maintenance**

Corrective maintenance (CM) is essential to repair a system in an outage to its proper operation. For restoration of a failed system/item, replacement, fixing or both can be required actions to perform. The need for CM can come from system outages or because of a condition-

based PM. When a system operation is stopped or impaired, operators get alerted via network management systems and the CM is being performed.

The formulation of maintenance strategy is used to define the proportion of time CM and PM are used. There are many factors which help to decide the ration of CM and PM. These are the cost of downtime, reliability characteristics, and redundancy among others. So, most practical maintenance programs are consisting of a combination of PM and CM. Determining what combination is required for a system is one of the objectives of the reliability centered maintenance (RCM) process [30, 31]. But, as a rule of thumb, 80/20 is used on balancing between PM and CM decided based on the cost-benefit analysis of the cases.

## **2.6 Levels of Maintenance**

Levels of maintenance are part of structuring maintenance departments and facilities and deciding where should systems/ products are being repaired. A Level of Repair Analysis (LORA) is an analytical methodology used to determine where is the better place or level of maintenance an item will be repaired, replaced, or discarded based on cost and availability requirements. Using, the LORA methodology, the objective is to determine an optimal planning and provisioning of maintenance services and facilities at a minimum possible lifetime cost. This analysis drives the maintenance support for each repairable unit analyzed. The LORA process options are being identified to decide where maintenance can be performed. It is common for systems to use 2 or 3 levels of maintenance. LORA produces a decision for each item within the system, indicating where each maintenance action for the item will be performed. Based on the LORA analysis, the maintenance levels are decided. There are generally three levels into which maintenance operations of an organization are divided: (1) organizational level maintenance, (2) intermediate level maintenance, and (3) depot level maintenance [32, 34].

## **2.6.1 Organizational Maintenance (Level 1)**

Organizational maintenance is where a day to day activity of an operator being performed in support of its own operations. Maintenance performed at this level includes both PM and CM operations performed by a maintenance organization in a company [30]. In an operating activity, organizational maintenance is performed by permanently assigned personnel.

In telecommunication, the organizational level maintenance team is organized to handle the day to day maintenance activities to be performed on the network infrastructure. Maintenance tasks are dispatched to the team in respective geographical locations. For any maintenance task beyond maintenance team level 1, there are escalation procedures to the next higher team. While in information technology (IT) systems maintenance, level 1 maintenance is related to the support provided to service users via online or telephone or using social media. Like the telecommunication case, IT maintenances have escalation paths.

## **2.6.2 Intermediate Maintenance (Level 2 )**

Intermediate maintenance is work performed in centrally located facilities for the support of operating activities within a designated geographical area, at a base or station. Technical assistance (when required) is provided by personnel of the intermediate maintenance facility to the supported operating activities [30, 31]. Most of the time, level 2 maintenance team is centrally organized and uses advanced tools and systems to provide advanced support to the level 1 team. Sometimes, field intervention might be required, and the team can travel to the place where the infrastructure to be maintained is located.

## **2.6.2 Depot Maintenance (Level 3)**

The term depot maintenance is used in the aircraft industry to refer to level 3 maintenance work that must be done in an industrial-type facility. In the case of IT and telecommunication, it is called advanced level maintenance which is performed by maintenance experts with an

advanced level of knowledge about the infrastructure design and operation. Besides, the level 3 maintenance team is equipped with tools and network management privileges required for the level of maintenance activities.

Maintenance processes and procedures are used to get access to the highest technical resources available for problem resolution or new feature creation. Level 3 technicians attempt to duplicate problems and define root causes, using product designs, code, or specifications. Once a cause is identified, the company decides whether to create a new fix, depending on what caused the problem. New fixes are documented for use by level 1 and level 2 personnel.

Sometimes, level 4 maintenance is used when external support is required. IT and telecommunication companies demand support from vendors to solve problems which are beyond the capacity of the organization.

## **2.7 Maintenance Approaches**

Maintenance is essential to ensuring that physical assets are reliable and available to deliver products or services. In large facilities, the maintenance personnel could comprise a significant number of the total workforce in the company. When considering the financial impact of maintenance, both direct costs (labor, material, spares, tools, information, and contractors) and indirect costs (lost revenue due to downtime, lost reputation, customer compensation, and penalties) should be included [30]. In this regard, following an effective maintenance approach has a profound effect on the impacts of downtime.

The most common maintenance approaches being applied by production and services organizations are the reliability-centered maintenance (RCM), the total production maintenance (TPM) and the business-centered maintenance (BCM). In general, all maintenance approaches encourage the use of preventive maintenance (PM) than the corrective maintenance (CM) while the CM is also inevitable.

## 2.7.1 The Reliability Centered Maintenance

“RCM is a logical, structured framework for determining the optimum mix of applicable and effective maintenance activities needed to sustain the operational reliability of systems and equipment while ensuring their safe and economical operation and support” [30, 32]. The emphasis of the RCM is on identifying preventive maintenance actions while corrective maintenance is also applied when the PM is not effective. The main objective of the RCM approach is to maximize the reliability of the physical asset by identifying the failure modes of the items and components of a system and ranking the consequence of each failure mode [30]. Ensuring the reliability of the system has a positive contribution to optimizing readiness, availability, and sustainment through effective and economical maintenance.

Based on the identification of the failure modes and consequences of failures of a system, subsystem or a component/s, preventive action is then performed. The output of the RCM process is used to produce a preventive maintenance plan for each component of a system. The preventive maintenance plan might include a list of preventive tasks (scheduled discard tasks, scheduled restoration tasks, or on condition tasks) for a total system.

An RCM analysis requires an extensive amount of data. The required data are failure characteristics, failure effects, costs, and maintenance capabilities and procedures. Studies in the airlines industry have shown that the effectiveness of PM for different failure data distributions. So, studying failure characteristics helps to create effective PM strategy.

The effect of failures is decided based on the cost of a failure to decide whether it is ok to let the system to fail and apply CM maintenance or to apply PM due to the cost of failure is high. While the cost data is related to the cost of the PM compared to the CM. Regarding the maintenance capabilities and procedures, the available skill levels, maintenance tools are being collected.

## **2.7.2 Total Production Maintenance**

Total production maintenance (TPM) is a maintenance system commonly practiced in the manufacturing industry. It was developed by the Japanese to solve maintenance and support problems encountered in manufacturing environments [33]. It describes a synergistic relationship among all organizational functions, but particularly between production and maintenance, for continuous improvement of product quality, operational efficiency, capacity assurance, and safety. TPM is an aggressive strategy which aims to increase the availability/effectiveness of existing equipment, the investment in human resources which results in better hardware utilization, to reduce and to control the variation in a process.

TPM implementation is based on the participation of all the employees of a company to improve production equipment's availability, performance, quality, reliability, and safety. The synergetic approach followed by the TPM methodology results in the elimination of breakdowns, reduction of unscheduled and scheduled downtime, improved utilization, higher throughput, and better product quality. Successful implementation TPM in an organization enables to achieve lower operating costs, longer equipment life and lower overall maintenance costs [33, 34].

TPM creates a synergistic relationship among all organizational functions, particularly between production and maintenance. An efficient TPM depends on both production and maintenance activities. In TPM method, it is believed that working on improving manpower skills helps in improving overall equipment productivity. Maintenance teams are organized from all organizational units consisting of top management and technicians. The goal is to have reliable and defect-free production process.

## **2.7.3 Business Centered Maintenance**

The approach to the formulation of this maintenance strategy was derived its motivation from the recognized business objective of an organization. To satisfy customers (i.e. the business

organizations and people), the support service must support the key business activities [36]. The development of the BCM was to have an efficient maintenance model or strategy. BCM is a generic approach which has a wide range of applications across various industries. It can be applied in manufacturing/production systems or service systems, power stations, fleet type systems (buses, trains), or communication networks. In the BCM approach, an emphasis is given to the alignment of the maintenance function with corporate objectives. Based on a detailed understanding of the operation of the system, a life plan is developed for the components, items, and units of the system. Then the life plan for a unit defines which maintenance procedures (condition-based maintenance, fixed time maintenance, or operate to failure) are effective, and a maintenance schedule can thus be formulated for each unit [31, 36].

## **2.8. Maintainability Analysis**

The influence of a variety of different factors on system downtime results in the fact that the time it takes to repair/restore a specific system is not generally constant. That is, the time-to-repair (TTR) is a random variable. For example, saying that it takes on average five hours to repair a network outage implies an underlying probabilistic distribution. Distributions that describe the TTR are called repair distributions (or downtime distributions) [7, 8]. Therefore, for maintainability analysis, determining the statistical distribution of the set of TTR data is required. The most commonly used statistical distribution models in maintainability analysis are the exponential distribution, the lognormal distribution, and the normal distribution functions. After determining the best fitting model of repair time data using some best fitting test model, the maintainability measurements are determined.

## **2.9 Maintainability Measurements**

The measurements of maintainability to be computed based on the best fitting statistical distribution are the MTTR, the median time to repair(M50%), the maximum time to repair

( $M_{\max}\%$ ) and the maintainability function,  $M(t)$ . The MTTR refers to the mean time required to accomplish a maintenance task. The median time to repair refers to the time used to complete 50% of maintenance actions. While the maximum time to repair is expressed as the time taken to complete 90% and 95% of the maintenance action and the latter is more popular. And the  $M(t)$  defines the probability that the maintenance of a system can be completed within a specified time  $t$ . The computation of those measurements depends on the type of statistical distribution fitting the TTR data. The variable is always the time to repair data of the networks/mobile sites.

## 2.10 Statistical Distributions for Maintainability

### Analysis

The most commonly used statistical distributions used in RAM analysis are the exponential, the lognormal and normal distributions.

#### 2.10.1 Exponential Distribution

The exponential distribution is simple and straightforward to handle and is quite useful to represent repair times [8]. Its probability density function of the maintainability with respect to repair times is defined by:

$$f(t) = \mu e^{-\mu t} \text{ for } 0 \leq t < \infty \quad (2.6)$$

Where  $f(t)$  is the repair time probability density function (pdf),  $\mu$  the constant repair rate and  $t$  is the repair time. Accordingly, the cumulative distribution function (CDF) is given by:

$$M(t) = \int_0^t f(t) dt = \int_0^t \mu e^{-\mu t} dt = 1 - e^{-\mu t} \quad (2.7)$$

Where  $M(t)$  is the maintainability function of the exponential distribution function.  $M(t)$  is the probability that a given maintenance action will be completed in the time interval  $[0, t]$ .

Since the mean repair rate is the reciprocal of the mean repair time (MTTR), i.e,  $\mu = 1/\text{MTTR}$ , the  $M(t)$  function can be modified as follows.

$$M(t) = 1 - e^{-\left(\frac{1}{\text{MTTR}}\right)t} \quad (2.8)$$

Assuming the exponential distribution of the TTR data, the system maintainability measurements such as the MTTR, the median and maximum time to repair can be computed as follows [ 7, 25].

$$\text{MTTR} = \frac{1}{\mu} = \frac{\sum ti}{N} \quad (2.9)$$

If the maintainability function,  $M(t)$ , is known, the MTTR can also be obtained from

$$\text{MTTR} = \frac{-t}{\ln(1-M(t))} \quad (2.10)$$

This is a function of the repair time  $t$ .

The median time to repair ( $M_d$ ) is obtained as

$$M_d = 0.69\mu \quad (2.11)$$

The maximum time to repair is given by

$$M_{\max\%} = K_e\mu \quad (2.12)$$

Where  $\alpha$  = the target maximum maintainability function in a time  $t$ .

$k_e$  = value of corrective maintenance time or/MTTR at the specified percentage point  $\alpha$  on the exponential function at which Max% is defined. Values of  $k_e$  are:

Table 2.3 Commonly used  $K_e$  values in the exponential distribution [ 8]

$\alpha$	$K_e$
95%	3.00
90%	2.31
85%	1.90
80%	1.61

## 2.10.2 Normal Distribution

The normal distribution is one of the most well-known probability distributions and it can also be used to represent failed equipment repair times. Its probability density function with respect to repair times is expressed by

$$f(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left[-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2\right]} \quad (2.13)$$

where  $f(t)$  is the repair time probability density function,  $t$  is the variable repair time,  $\mu$  is the mean of repair times, and  $\sigma$  is the standard deviation of the variable repair time  $t$  around the mean value of  $\mu$  [8]. Accordingly, the maintainability function of the repair time assuming it is normally distributed is:

$$M(t) = \frac{1}{\sigma\sqrt{2\pi}} \int_0^t e^{\left[-\frac{1}{2}\left(\frac{t-\mu}{\sigma}\right)^2\right]} dt \quad (2.14)$$

where  $M(t)$  is the maintainability function for normal distribution. The mean of repair times is given by

$$\mu = \sum_{i=1}^n \frac{t_i}{n} \quad (2.15)$$

where  $n$  is the number of repair times and  $t_i$  is the repair time  $i$  for  $i = 1, 2, 3, \dots, n$ .

The standard deviation is given by

$$\sigma = \left[ \sum_{i=1}^n \frac{(t_i - \mu)^2}{(n-1)} \right]^{\frac{1}{2}} \quad (2.16)$$

Assuming the repair time data is normally distributed with a mean,  $\mu$  and  $\sigma$  standard deviations, the MTTR, the median time and the maximum maintenance times are determined as:

$$MTTR = \frac{\sum t_i}{N} \quad (2.17)$$

The median time to repair is determined as

$$\mathbf{M}_d = \frac{\sum ti}{N} \quad (2.18)$$

which is equal to the mean time to repair because of the symmetry of the normal distribution.

The maximum time to repair is given by

$$\mathbf{M}_{\max\%} = \mu + \Phi\sigma \quad (2.19)$$

where  $\Phi=Z(t1-\alpha)$  is the value from the normal distribution function corresponding to the percentage point  $(1-\alpha)$  which is the same to the exponential distribution case.

### 2.10.3 Lognormal Distribution

The lognormal distribution is probably the most widely used probability distribution in maintainability analysis [7, 8]. Its probability density function with respect to repair times is defined by:

$$\mathbf{f}(t) = \frac{1}{t\sigma\sqrt{2\pi}} e^{\left[-\frac{1}{2}\left(\frac{\ln ti - \beta}{\sigma}\right)^2\right]} \quad (2.20)$$

where  $f(t)$  is the probability density function of the repair times,  $t$  is the variable repair time,  $\beta$  is the mean of the natural logarithms of the repair times, and  $\sigma$  is the standard deviation with which the natural logarithm of the repair times is spread around the mean  $\beta$ . Then the maintainability function is given by:

$$\mathbf{M}(t) = \frac{1}{(t)\sigma\sqrt{2\pi}} \int_0^t e^{\left[-\frac{1}{2}\left(\frac{\ln ti - \beta}{\sigma}\right)^2\right]} dt \quad (2.21)$$

where  $M(t)$  is the maintainability function for the lognormal distribution. The following relationship defines the mean:

$$\beta = \frac{[\ln t_1 + \ln t_2 + \ln t_3 + \ln t_k]}{k} \quad (2.20)$$

Where  $k$  is the total number of repair times and  $t_i$  is the repair time  $i$  for  $i = 1, 2, 3, \dots, k$ .

The standard deviation,  $\sigma$ , is expressed by

$$\sigma = \left[ \sum_{i=1}^k \frac{(\ln t_i - \beta)^2}{(k-1)} \right]^{\frac{1}{2}} \quad (2.21)$$

Assuming the repair time data are lognormally distributed [7, 8, 25], The mean time to repair (MTTR) is defined by

$$\mathbf{MTTR} = e^{[\beta + 1/2(\sigma)^2]} \quad (2.22)$$

Where  $\beta$  and  $\sigma$  are the mean and the standard deviations of the natural logarithm of the repair time data respectively. The Median time to repair is:

$$\mathbf{M}_d = e^{\beta} \quad (2.23)$$

The maximum time to repair is given by

$$\mathbf{M}_{\max\%} = \mathbf{t}_{\max\%} = e^{(\beta + Z(1-\alpha)\sigma)} \quad (2.24)$$

Table 2.4. Commonly used  $z(t1-\alpha)$  values

$1-\alpha$	$\Phi$ or $Z(t1-\alpha)$
0.80	0.8416
0.85	1.036
0.90	1.282
0.95	1.645
0.99	2.326

where  $\Phi=Z(t1-\alpha)$  is the value from the normal distribution function corresponding to the percentage point  $(1-\alpha)$  on the maintainability function for which  $M_{\max\%}$  is defined.

While  $M_{\max} X\%$  refers to the maximum time required to complete  $X\%$  of the corrective maintenance. The most commonly used values of  $\Phi$  or  $Z(t1-\alpha)$  are given in Table 2.4 above.

## 2.11 Network Outage Causes and Consequences

A network outage is the loss of network resources, including routers, switches, and transport facilities [31]. An outage can happen to a network due to hardware failures, power outages, scheduled maintenance, operational errors such as configurations and due to natural disasters. Each network outage can be broadly categorized as either planned or unplanned. An unplanned outage is any interruption in the operation of the network which is not scheduled. Planned outages are interruptions prearranged on relatively short notice or regular schedule.

Research works in [ 18, 19, 31] have identified the causes, the frequency, outage durations and consequences of network outages. All have followed an online survey-based methodology to collect required data from telecommunication and IT professionals all over the world.

In [18, 19] the study was conducted in 2013 and 2016 respectively with the same objectives. In those studies, it was reported that mobile operators worldwide have continued to suffer network outages at least once a month. Mobile network operators are classified as the most successful and least successful in terms of outages frequencies. While the most successful once have managed to limit network outages to be one to three times in a year; the least successful face network outages of at least 15 times per year. In the same studies, the outage frequency ranges can be summarized in terms of occurrences in mobile networks. On average, 30% of the operators had major network outages of one to three times per year, 50% of them had 3 to 20 times per year and 20% of them had more than 20 times per year. While in [31], most of the operators (74%) have reported that network outages occur daily, several times a week, several times per month and several times a year.

In terms of outage duration, the findings on [18, 19] have shown that network stays in an outage state until it gets maintained for a duration of 2 to 48 hours. And in [31], 42% of the

operators have responded as it took them one to five hours to repair once an outage has occurred. In [19, 31], outages which last for less than two hours are studied as short time outages. The network outage times were classified in a range of less than 15 minutes, 15 to 30 minutes, 30 minutes to one hour and one to two hours to study the downtime duration of outages. Accordingly, 51% of the network outages have an outage duration of fewer than 15 minutes while 30.5 % of the outages last for a time range of one to two hours. In [31], 35% of the outages took less than an hour to fix them.

Although it is both difficult or very costly if it is even possible, for network operators to have outage-free network infrastructure, the capability of easily identifying causes of network outages and be able to repair them easily are also performance issues to increase the availability of the networks for end users use. With this regard, the finding in [18, 19] shows that on average 25%, 45.5% and 22% of the operators are rated as excellent, good and fair respectively in terms capability of easily tracing outages. While in [31], the findings show that only 1% of the operators believe that they can identify all causes of network outages via their network monitoring systems, 33% of them believed that 50 to 90% causes of network outages are identifiable through the network monitoring systems, while 61% of the operators can discover 1 to 25% the network outages and 5% of them had no monitoring systems.

The main factors for network outages are busy hour traffic and a network upgrade in [18, 19] while in [31] human error and network changes are reported as the frequent causes of network outages. In mobile network domains, the radio access network (RAN), the transport network, the routing and the mobile core are consisting of the 37, 23, 18, 17 percent of the network outages respectively.

Different studies have shown that the impacts of network outages are both financial and non-financial. The direct impact on the carrier or service provider ranges from lost profits and lost customers, to damaged credibility, employee overtime and penalties for not meeting SLAs [23]. In the case of the financial loss, it is consisting of the opportunity cost and cost of

maintenance. The costs incurred by mobile network operators to deal with network outages are also studied in [18, 19]. Worldwide, the cost of dealing with network outage has increased from \$15 billion to \$20 billion from 2013 to 2016 respectively. Summarizing the detail results, 28% of the operators believe that network outages cost two to five percent of their total annual revenue, while 54.5% of them had reported that one to two percent of their annual revenue is a cost of managing network outages.

In the case of enterprise networks and applications, network outages cost differs based on industry and size of the businesses. However, financial services, telecommunications, manufacturing, and energy lead the list of industries with a high rate of revenue loss which ranges to as high as \$11,000 per minute per server during IT downtime [20].

From the above reviews, it is understood that network outages are common challenges for telecommunication network operators with different degree of frequency, outage duration. Similarly, network outages have huge financial and non-financial impacts which need to be minimized to increase revenue, retain customers and stay competitive in the market.

Therefore, it is worth doing to conduct performance analysis of telecommunication networks to handle network outages beforehand. RAM analysis is the most important network performance analysis tools to know, improve and follow the performance of using the tools provided by the reliability engineering knowledge.

# 3. Data Collection and Analysis

## 3.1. Data Sources and Description

In conducting empirical research, the first step is data collection. The outage and repair time data of the mobile networks are continuously recorded in the national network operation center (NNOC); which is the network operation management system. In general, operators recognize network outages(faults) in two ways. One is via customer complain and the other is via the network management system. In this research, the system managed data (from the network operation management system) is used. This study covers mobile access networks for all deployed in Addis Ababa. The networks are GSM, UMTS, and LTE technologies. There are a total 744 mobile network sites deployed in Addis Ababa at the time this research was conducted.

The operation of the networks is centrally managed by a network management system called NNOC. The system identifies the outage data in the form of alarms. Each alarm has a criticality classification as a warning, minor, major and critical based on the impact on the network. Alarms popped up in the form of warning have no effect on the network as well as service but requires attention as they could be a source of upcoming outages. Minor alarms have minor impacts whereas major alarms have a significant impact on network performance like degradation or stoppage of some services. The critical alarms cause a complete outage of a network that no service can be provided. To conduct this study, the TTR of the critical and major outages are used.

The main objective of collecting mobile network sites outage data is to analyze the availability and maintainability of the mobile networks. Besides, severity analysis is conducted to show the impact of network downtimes on revenue, customers and SLA fulfillment. Additional data used for impact analysis are active mobile service users and average revenue per user

(ARPU) per hour over the observation period which are collected from ethio telecom's Marketing department.

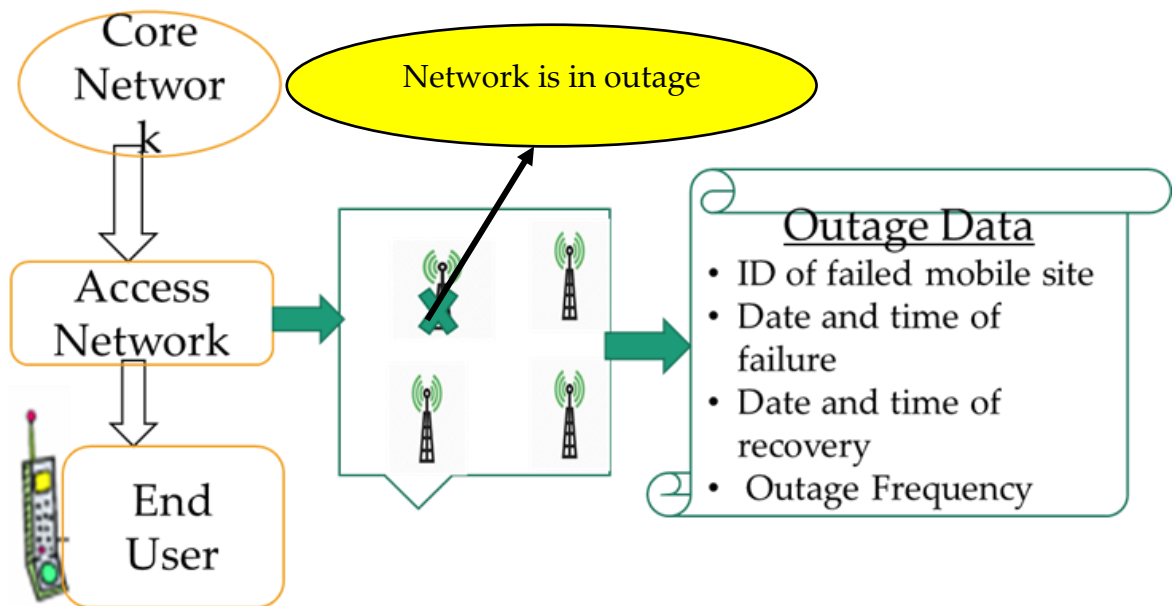


Figure 3-1 Model of cellular network and outages

For the analysis, TTR data are derived from the outage and repair time of the mobile sites which were in an outage for at least once during the observation time. The data is quantitative and based on raw data collected over a period of four months (Feb to May 2018). After collection, the processing (sorting, filtering, and classification) of raw data is performed to make the data in a format that is usable for statistical analysis.

Figure 3-1 shows the model of cellular networks and outages in the mobile access network. It also shows the outage data being used in this research. A network is in outage when it faces major degradation or complete stoppage of all functionalities or services. I.e., an end user services are degraded or totally interrupted due to the faults in the access networks.

## 3.2. Descriptive Data Analysis

During the measurement period (four months), 682 mobile access networks get into an outage state with different frequency and durations. Figure 3-2 shows the number of network outages per month.

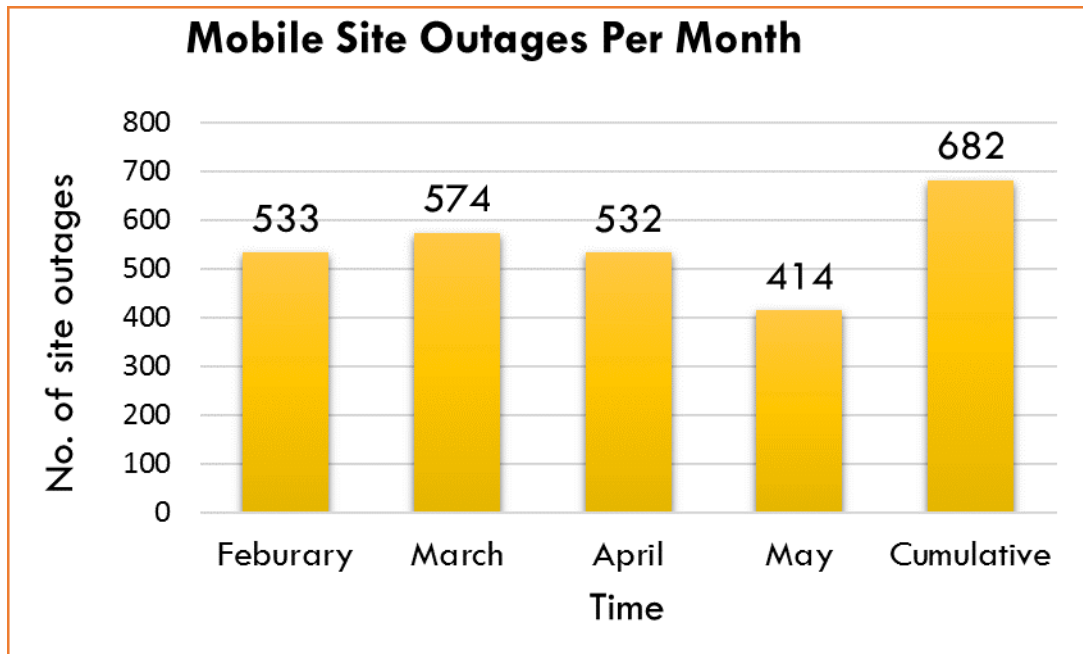


Figure 3-2 Number of mobile site outages per month

The mobile site outages pattern is almost constant in the first three months; however, it has decreased in May. Despite decreasing number of outages and the frequency, all the outages data used in May were critical. During May, reported network outage data were consisting of a minor, normal and critical but there was no major alarm.

On average, above 500 (69% of the total) mobile sites get an outage per month. In cumulative, 682 (91.7% of the total) unique mobile sites experienced an outage over the four months. Such a significant number of network outages are indications of unstable networks to mean networks face the difficulty of consistently providing services as per the user's demand. This could be due to poor design, installation, inefficient optimization, power outages, and

inefficient maintenance practices. In line with this, the impact of the outages farther lies on the frequency and the duration of downtime. Because frequent and long-lasting outages directly impact the availability and the maintainability of the networks.

To show the pattern of network outages in relation to the outage frequency and downtime, Figure 3-3 shows the trend of these variables. The number of mobile site outages is almost constant during February, March, and April with a slight increase in March, but it has decreased during May. The network outage frequency has clearly shown a decreasing pattern which is good for the operator. Regarding outage durations/downtimes measured in hours, it shows a fluctuating pattern but very much increased in May. The case in May that downtime increase while outage frequency decreases might be an indication of poor maintenance tasks management resulting in delayed response for maintenance.

In May the number of mobile sites in outage were fewer however, they were in repair for a longer time (44, 894.41 hours) as shown in Figure 3-3. The sites in outage had an average downtime of 108.44 hours per network over the observation time. While the operation time of each network is 2880 hours. On average, the number of outages per month were 513 with an average outage frequency and the outage durations of 14, 592 times and 25, 676.72 hours respectively.

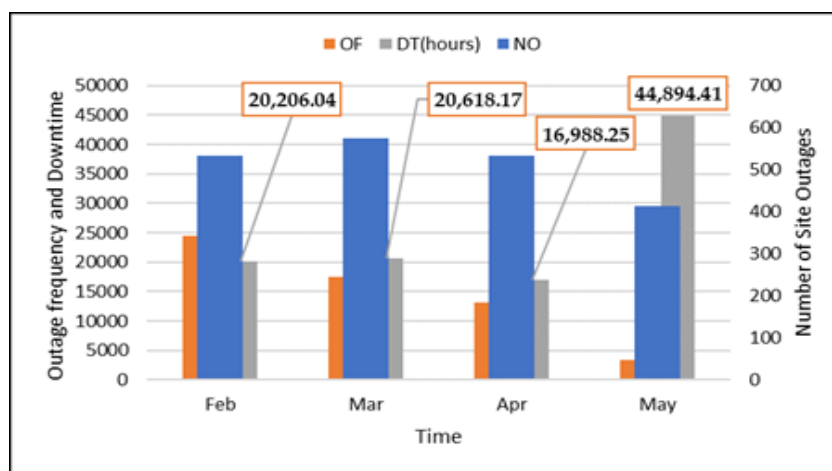


Figure 3-3 Site outages, frequency, and downtime

To farther clarify the cases, networks are classified by outage frequency ranges. The corresponding average number of sites in an outage (NO) and downtime (DT) per site is also determined for each category as stated in Table 3.1. Then, most of the mobile sites (387 of the total) have outage frequency (OF) range of 1 to 40 times. In this category, each site was in an outage 9 times with a DT of 35.1 hours. Out of the total (682 networks), 101 (or 14.8%) of them had greater than 120 times OF range. Here, each network had an average OF and DT of 378 times and DT of 211.7 hours respectively.

Having those information (outage frequencies and durations) so far, the question is can the networks be considered as performing good or bad, of course, it is not good.

Table 3.1 Outage frequency ranges, site outages and DT per site

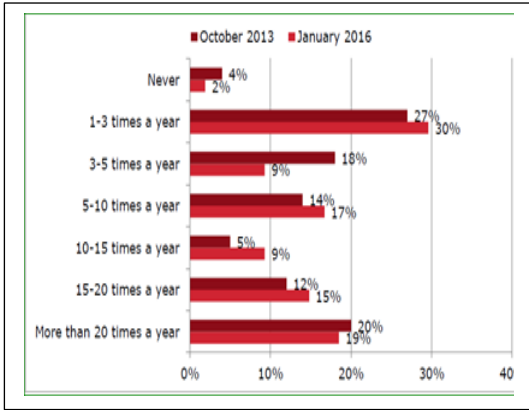
Outage frequency range	1 to 40	40 to 80	80 to 120	>120
NO	387	132	62	101
Average outage per Network	9	60	97	378
DT, hours	35.1	92.5	131.9	211.66

Where OF = outage frequency

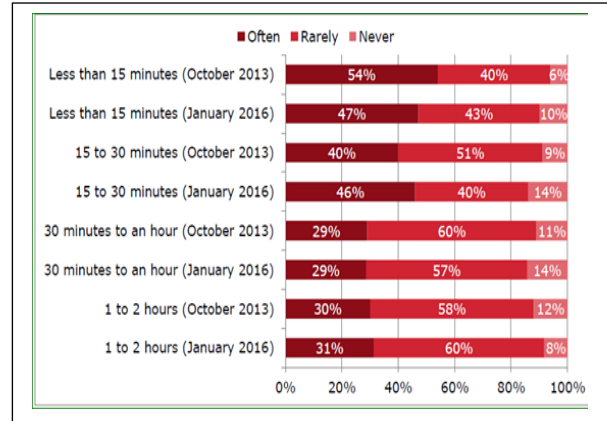
NO = number of network outages

DT = downtime

However, providing a comparative analysis can help to give better conclusions. Therefore, a study by [18] shows the network outage frequency and duration of the other operators' networks. Figure 3-4a & b shows the outage frequencies and downtimes of networks respectively.



(a)



(b)

Figure 3-4 Mobile network outages frequency and downtime per year [16]

Based on the yearly measurement, a study conducted in 2013 and 2016 has revealed that 19.7% and 18.7% of the operators have reported a network outage frequency of 1 – 10 times respectively while 12.3% and 14.3% of the operators have reported that there was network outage frequency of 10 – 20 times for the same time respectively.

Likewise, network outage durations were reported as shown in Figure 3-4b. Accordingly, considering only those occurs often, on average, 47% of the operators have reported network outages took 15 – 30 minutes DT in 2013 while 46.5% of them have reported the same in 2016. For network outages which last for 30 minutes to 2 hours, the percentage of the operators were 29.5% and 30% for the years 2013 and 2016 respectively.

Therefore, it is possible to conclude that ET's networks are performing badly. Because, during the observation period, 91.7% of the total mobile access networks have experienced an outage. And the per month evaluation of the performance of the mobile sites had 14, 592 times of outage frequency with downtime of 25, 676.72 hours. It is not even comparable. To achieve the vision of becoming an international service provider, ET or any other operator with similar performance needs more effort on improving operational performance otherwise achieving such a vision could be very challenging.

So, ET's mobile networks require extra effort being applied to minimize the outage frequency and downtime and then ultimately increase the availability of the networks.

One way, to improve the network performance could be working on the networks with the frequent and long-lasting outages, for example, in this study an emphasis can be give to the networks with an OF range of >120 times and 211.7 average DT. By doing so, it is possible to bring a performance improvement into the overall network. This can be achieved either by reducing the number of networks in an outage or the average downtime per network. To observe the effect on the total downtime, the reduction of the average downtime per network by 20, 40, 60 & 80 percent are shown in Figure 3.5.

Figure 3-5 shows the impact of reducing the average downtime per network. From Table 3.1, it is shown that 101 of the networks have 378 times and 211.7-hours average outage frequency and downtime respectively. Those networks cover 14.8 % and 20.8% of the total networks in outage and the total DT respectively. Notice that from Figure 3-3, the networks were in an outage for a total of 102, 706.87 hours over four months. Therefore, Figure 3-5 is intended to show the effect of progressively reducing the DT per network by some percentage value on reducing the total downtimes of the networks.

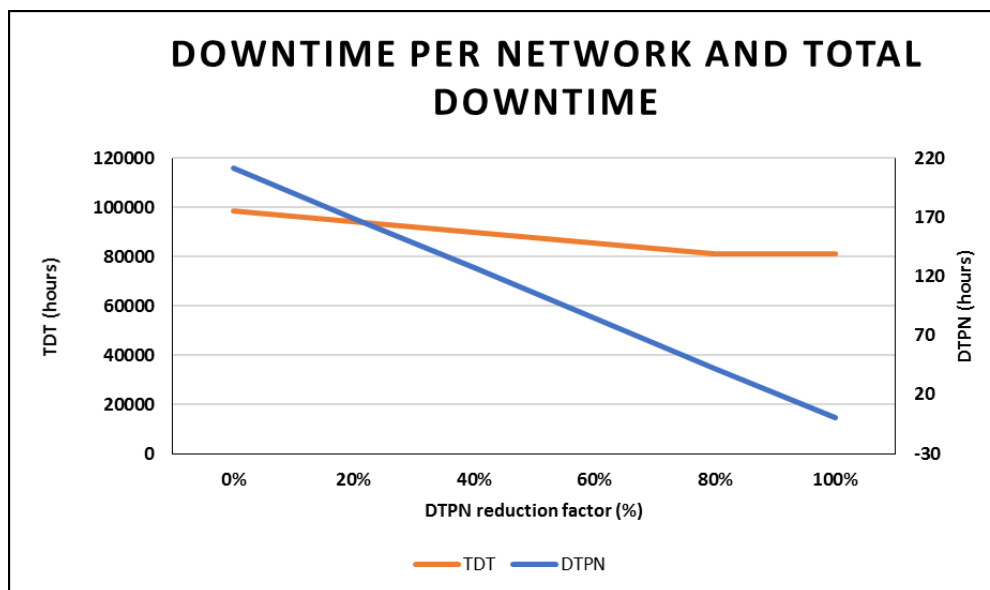


Figure 3-5 Impact of reducing average downtime on total downtime

Where TDT = total downtime of all networks in an outage

DTPN = downtime per network/site of the target networks

Therefore, it is observable that the more the DTPN of the target networks is reduced, the TDT decreases significantly. Reducing the DTPN of the target networks by 20%, 40%, 60% & 80% has enabled a reduction of the TDT by 4.20, 8.33, 12.50 and 16.70 percent respectively. Considering the 20% and 80% reduction as a pessimistic and optimistic scenario respectively, it is possible to save 4, 276.34 and 85, 601.51 hours of downtime respectively. If a 60% reduction of DTPN is considered as an attainable target, it is possible to save up to 12, 829.02 hours of downtime per four months or three times of that per year. Reducing downtimes implies in increasing network availability, revenue generation and reducing customer complaints.

Therefore, reducing DTPN have a positive impact on reducing the total downtime of the networks. Hence, DT reduction mechanisms and strategies are required. This can happen by increasing the reliability of the networks or network facilities such as the power system (for example using redundancy) or via increasing maintenance efficiency to make it as quick as possible among other possible ways.

### **3.3. Short Time and Long-Time Network Outages**

Analyzing network outages as short-time outages (STOs) and long-time outages (LTOs) gives an information if most outages are impactful and should the operator worry or tolerate such outages. Network outages are classified into STO and LTO based on their DT duration. Different researchers have used a different definition to determine downtimes as STO or LTO. For example, in [17], downtime duration of less than or equal to 30 minutes per day is considered as short time outages while in [18 &19], it is less than two hours per year.

In this research, as the observation period was for four months, the latter case is followed. I.e. a network outage which lasts for less than or equal to two hours is considered as short time outage while greater than two hours is considered as longtime network outages.

Table 3.2 A short time and longtime network outages

Valuables	Mean	Median	Mode	Standard Deviation	Range	Minimum	Maximum	Count
LTO (hours)	166.4	83.52	13.38	237.05	1922.1	2.00	1924.13	602
STO (hours)	0.44	0.34	0.55	0.32	1.58	0.01	1.58	80

Where LTOs = longtime outages

STOs = short time outages

Out of the total mobile sites in an outage (682), 88.3% of them had LTO with a mean downtime of 166.4 hours and with high variability indicated by the standard deviation of 237.05 hours. Majority of the networks have 13.38 hours DT ranging to a maximum of 1924.13 hours. While the mean downtime of the STOs is 0.44 hours with a maximum downtime of 1.58 hours. So, it is possible to conclude that the networks are characterized by LTOs

Following the STOs and LTOs analysis, it could have more sense to perform analysis of mobile sites outage frequency and downtime daily. While the outage frequency per day can indicate the stability of the network and the engagement of maintenance staffs on outage handling activities, downtime per day is an indication of the proportion of time the mobile sites were ready to give services.

A scatter plot of the mobile sites' downtime per day in Figure 3-6 shows the distribution the downtimes mobile sites per day. Accordingly, the downtime is sparsely distributed without a clear pattern with a mean downtime of 11 hours and ranges from a minimum of 0.2 hours to 23.5 hours per day.

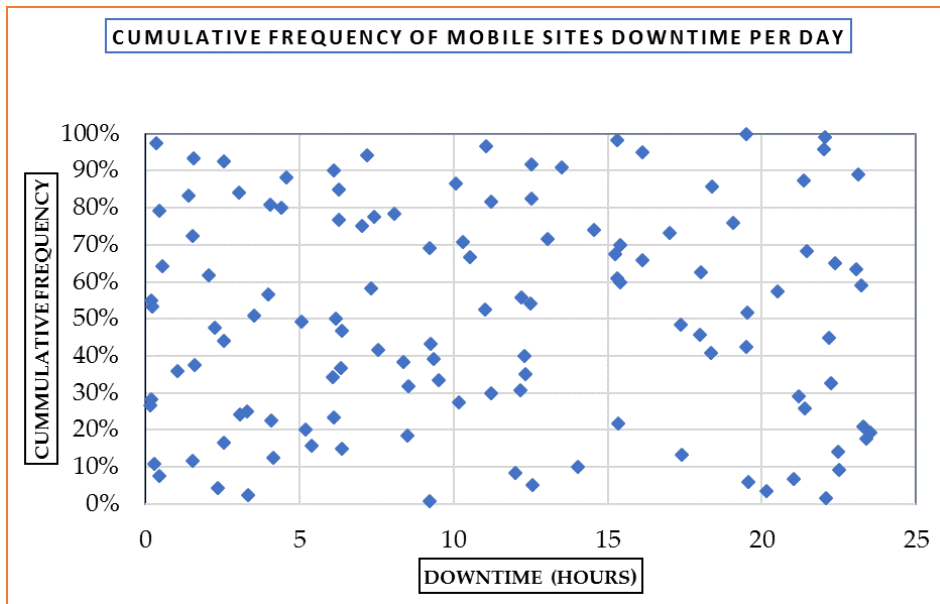


Figure 3-6 Mobile sites' downtime per day

Similarly, mobile sites daily outage frequency is presented in Figure 3-7. Based on daily analysis of mobile site outages, the CDF plot shows an increasing pattern. For 120 days (4 months), the outage frequency was less than or equal to 500 times for 50% of the time. The mean outage frequency is 697 times with a standard deviation of 700. The daily outage frequency has less variability. Because the mean and the standard deviation of the outage frequency are approximately the same (697 and 700) respectively.

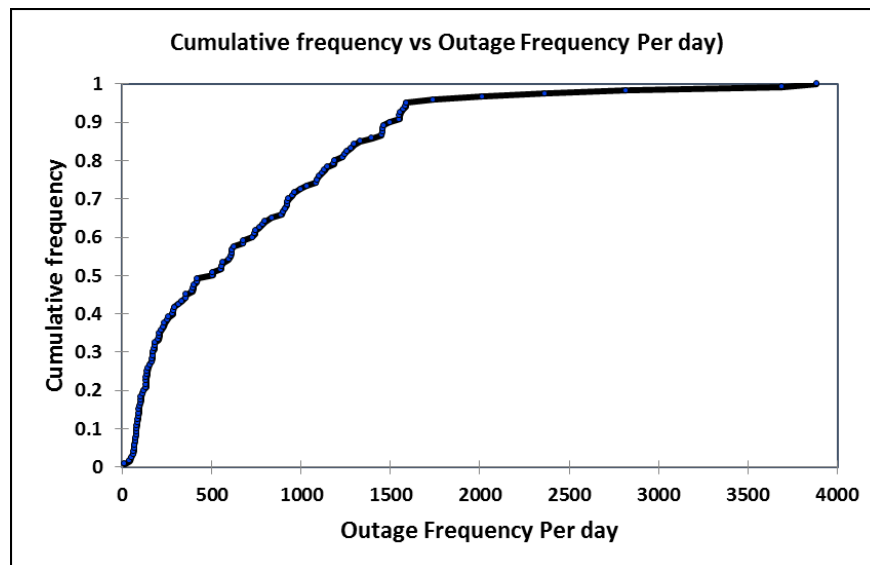


Figure 3-7 Mobile sites' outage frequency per day

In general, the mobile network sites in Addis Ababa are characterized by frequent and long-lasting outages which directly impacts the availability and the maintainability of the mobile sites, the revenue generation of the company, the customers and the creativity of the maintenance personnel. Comparing to the other operators' practices (for example as presented in [18]), ET's networks can be judged as unstable.

Table 3.3 shows the summary statistics for mobile sites outage frequency and downtime. 50% of the mobile sites' outage frequency occurred during the observation period (120 days) have outage frequency of 13 to 500 times per day.

Table 3.3 Summary of mobile sites' outage frequency and downtime per day

Summary statistics					
Variable	N	Minimum	Maximum	Mean	Std. deviation
Outage Frequency Per day	120	13.0	3885.0	696.7	700.1
Downtime (hours)	120	0.2	23.5	11.0	7.4

### 3.4. Network Availability Analysis

As explained in section (2.3.1) of this document, there are three types of availability based on the type of downtime being considered on the computation. These are the inherent, achieved and the operational availabilities. The inherent availability considers only the CM downtime while the achieved availability uses both CM and PM downtimes. whereas the operational availability includes the downtime due to administrative delays in addition to the maintenance downtimes.

ET follows both CM and PM policy to keep the network as available as possible with the required quality of services (QoS). However, no downtime is induced on the network due to PM activities. Activities of PM are mostly cleaning and refueling of generators. Therefore, in

this special case, the inherent availability and the achieved availability are equal. In the case of the operational availability, it is not known how much of the downtime is induced due to administrative delays.

Due to all the above reasons, the focus of this research is on computing and analyzing the inherent availability of the networks. It measures the efficiency of the maintenance department or personnel. It solely depends on the design and installation quality of the network. Using Eq (2.3.1), the availabilities of the 682 mobile sites are computed and summarized in Table 3.4. To recap with the equations used for the availability calculations,

$$I_A = \frac{MTBF}{MTBF+MTTR}, MTBF = \frac{UT}{OF} \text{ and } MTTR = \frac{CMDT}{OF}$$

Where IA = inherent availability

MTBF = mean time between failures

MTTR = mean time to repair

UT = the network uptime or operational time

OF = outage frequency of each mobile site

CMDT = corrective maintenance downtime

There are six ranges of availabilities starting from less than two nines (97.5%) to six nines (99.9999). Networks with higher availability have fewer outage frequency while those with low availability are characterized by higher frequency outages and longer downtimes. As the availability of the network increases, ADT and TDT decrease, and vice versa. Table 3.4 shows the availability of mobile sites and respective downtimes.

Table 0.1 Availability of mobile networks (# of nines)

Availability (No. of nines)	Availability (%)	No. of Sites, A	ADT (hours), B	TDT (hours) per four months (A*B)	TDT (hours) per year (A*B*3)
< two nines	97.5	26	72	1872	5616
Two nines	99.0	307	28.8	8841.6	26524.8
Three nines	99.9	228	2.8	638.4	1915.2
Four nines	99.99	69	0.288	19.872	59.616
Five nines	99.999	45	0.03	1.35	4.05
Six nines	99.9999	7	0.003	0.021	0.063
Total		682	103.921	11373.24	34119.72

Where ADT = average downtime

TDT = total downtime

The proportion of mobile sites in each availability category are analyzed as shown in Figure 3-8. Therefore, it is observed that most of the sites (45%) have an availability of 99.0% while 33% of them have an availability of three nines (99.9%). The combined share of mobile sites having four nines and above is only 17%. And 4% of them have an availability of 97.5% that makes each site to be in an outage state for 72 hours over the observation period. Assuming no change on the network outages status, each mobile site could be in an outage for 216, 86.4, 8.4 hours for availability levels of less than two nines, two nines, and three nines respectively. While the average availability of the networks is 99.75. Many of the networks (333) have an availability of two nines and below while 33.4% of them have 99.9% availability.

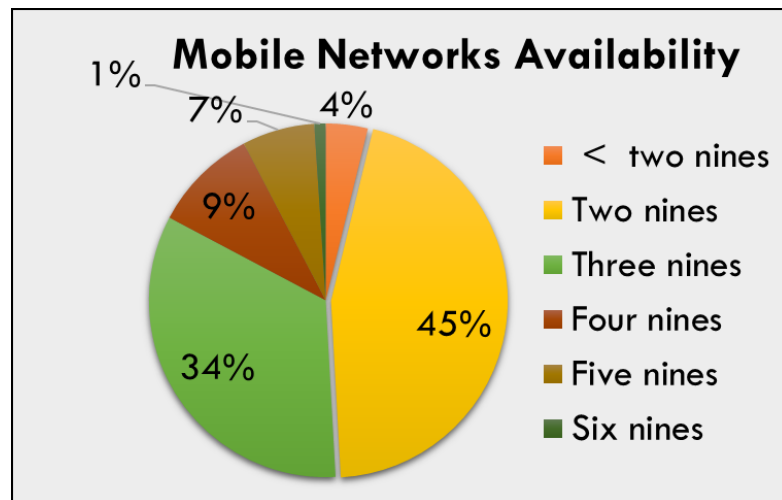


Figure 0-1 Mobile sites availability levels

As presented in Table 2.2, the grade of service availability requirement of communication service providers is in five nines (99.999%). With such levels of availability, a network can be in a downtime for only 5min & 15s per years. Whereas the networks in this study get down on average of 21.6 hours each per year. However, if only the LTOs are considered, the average availability of the networks is 98.4%.

Having the average availability of 99.75% for the mobile sites in Addis Ababa, the question is it a good performance to achieve required business objectives while also satisfying customers? This can be answered by putting the case into a perspective. For example, from service users' and operator perspectives. While it could be satisfactory or good for residential users it might not be acceptable for those business users especially if their business is highly dependent on communication. And from the operator's perspective, if the availability performance of the mobile sites is not good for the business customers, it directly affects the revenue generation capacity of the operator.

### 3.5. Network Outage Frequency, Duration, and Availability

Network availability is determined by the frequency of failures and the speed of maintenance (downtime) durations. Figure 3-9 shows the relationships between network downtime, outage frequency, and availability.

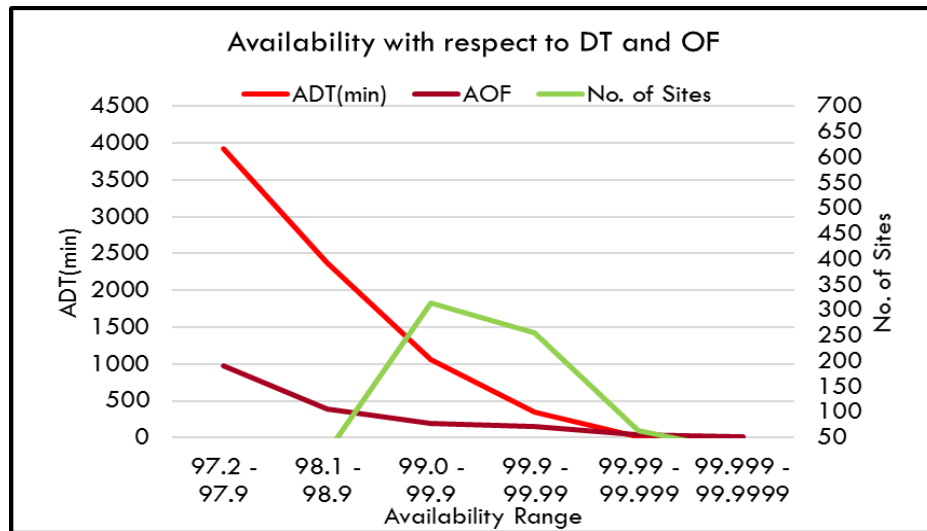


Figure 0-2. Downtime, outage frequency, and availability

Where DT = downtime

OF = outage frequency

ADT = average downtime

The higher the DT, the less is the network availability. Similarly, increasing OF have a negative impact on the network availability. However, DT has a higher impact on network availability than the OF. Because the network availability is basically defined in terms of the proportion of time a network is being functional.

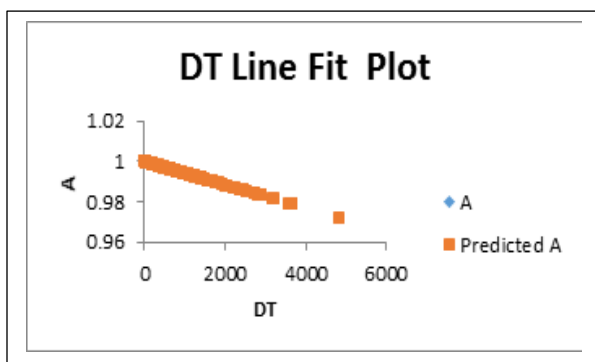
To statistically signify the relationship among the variables (availability, DT and OF), a correlation analysis is performed to determine the statistical relationship among the variables

using the data analysis tool of Microsoft Excel. A regression analysis was also performed to test the significance of the relationships. Accordingly, the results are shown in Table 3.5. Therefore, availability and downtime have a perfect negative correlation with a correlation coefficient of -1. Likewise, availability and outage frequency is negatively correlated with a correlation coefficient of -0.41. In both cases,  $p < 0.05$  that is  $p = 0.00$  and  $p = 1.95E-28$  for (availability and downtime) and (availability and outage frequency) respectively.

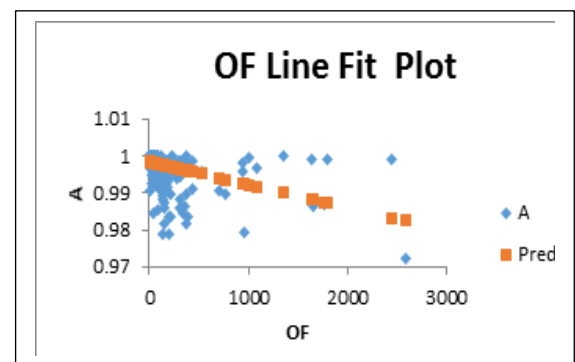
Table 0.2 Correlation between A, DT, and OF

	<i>A</i>	<i>DT</i>	<i>OF</i>
<i>A</i>	1	-	-
<i>DT</i>	-1	1	-
<i>OF</i>	-0.4081	0.40808	1

This implies that the correlation coefficients are statistically significant. Therefore, as downtime increases, availability decreases by the same proportion while the decrement of availability due to outage frequency is 41% for every unit increment of outage frequency. In line with the above explanations Figures 3-10 a & b shows the line fit plots of A & DT, and A & OF respectively.



(a)



(b)

Figure 0-3. Correlation between availability, DT and OF

A line of best fit (or "trend" line) is a straight line that best represents the data on a scatter plot. Then, in Figure 3-10a, the line has passed through all the points in the opposite direction

which is an indication of perfect negative correlation. And in Figure 3-10b, the line passes through some of the points showing some correlation.

Increasing or decreasing network availability has implications for network operators and service users. For the operator, lesser the network availability, higher will be the revenue loss from service interruption and it can significantly increase the operational cost (OPEX). Besides, it negatively impacts company image (brand) as service users will not be happy with frequent and long-lasting interruptions or degradations of services.

### 3.6. Maintainability Analysis

Maintainability refers to the speed and economy of maintenance time. Maintainability analysis is used to find efficiency and weaknesses in maintenance and take corrective actions.

The objective here is to analyze the corrective maintenance times. To do so, 30 mobile sites are randomly selected for maintainability analysis. The TTR data are determined from the failure and repair time data of the mobile networks. Besides, only TTR data of greater than or equal to 30 minutes are considered.

To be able to analyze the maintainability of the networks, the statistical distribution of the time to repair (TTR) data should be determined. A goodness of fit test is used to identify the best-fit probability distribution. Based on the best fitting distribution, the parameters of the distribution are being computed. The maintainability measurement metrics are then calculated based on the best fitting model. The maintainability metrics to be computed are:

- **Median time to repair:** time required to complete 50% corrective maintenance of a network.
- **Meantime to repair:** average time to complete a corrective maintenance action.
- **Maximum maintenance time:** time required to complete 95% of the corrective maintenance actions.
- **Maintainability:** the probability of completing a maintenance action in time  $t$ .

### **3.6.1. Goodness-of-Fit Test**

The goodness of fit test is performed by selecting a proper test for the data at hand among many alternatives. The most widely used tests in RAM analysis are the Chi-squared test, the p-value test, Anderson-Darling test and Kolmogorov-Smirnov test [18]. The principle behind goodness-of-fit tests is to see how far the chosen distribution represents the actual dataset, or how well the chosen distribution agrees with the observed distribution. Next to distribution fitting is the maintainability variables estimation. In this study, the Kolmogorov -Smirnov test is used for the goodness of fit test.

The K-S test is most popular in the reliability and maintainability analysis of systems. It is a non-parametric test that does not require the data to follow a normality test. The K-S test is based on the empirical distribution function (ECDF). It is done by plotting the ECDF and with the CDF for a given distribution. The K-S test is then based on the maximum distance between these two curves. The K-S test is selected because it is suitable for continuous random variables test, it does not depend on the underlying cumulative distribution function being tested. Another advantage is that it is an exact test despite the sample size.

### **3.6.2. Determining TTR of Mobile Networks**

The TTR data is used for maintainability analysis. The TTR for each network is derived from the outage and recovery times, i.e. TTR is a downtime which covers the time duration from the moment the network was in an outage to the time the network was maintained and return to normal operation is confirmed. The TTR data is measured in hours. As an illustration, Table 6.1 in Annex 1 shows the summary of TTR data of BTS\_111001. The TTRs of all the sample mobile sites are also determined in a similar fashion.

### 3.6.3. The Statistical Distribution of TTR Results

The Kolmogorov-Smirnov (K-S) test is used to determine the best fitting model. The model with smaller K – S statistics is considered as the best fitting model. The statistical distribution of the sample networks is determined along with respective parameters. Then, the statistical distributions of the sample networks are summarized as shown in Table 6.2 of Annex I. Accordingly, the TTR data of 83.33% of the sites are Lognormally distributed, while 10% and 6.67% of them are fitted into Exponential and Normal distributions respectively. Therefore, maintainability measurements computations are being done assuming maintenance time data are lognormally distributed.

The TTR data in Table 6.1 in Annex 1 is used for the illustration of the statistical distributions of TTR data. Figures 3-11 and 3-12 are the pdf and the CDF of the mobile site **BTS\_111011** respectively.

Where  $g(t)$  is the probability density function (pdf). From the pdf graph, it is observed that 50% the maintenance actions for this network can be accomplished in less than 0.54 hours or within 32.4 minutes. The mode time to repair which is the time where the pdf curve gets its maximum is 0.88 hours. Within the mode time, 78% of the maintenance actions can be completed.

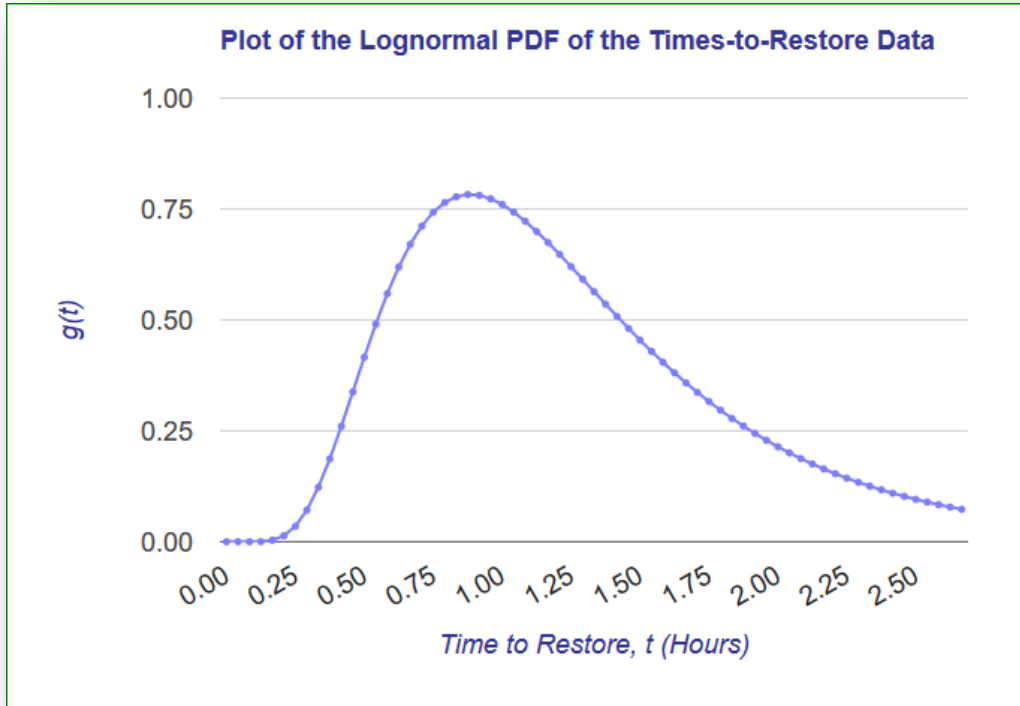


Figure 0-4 Pdf of the TTR of BTS\_111011

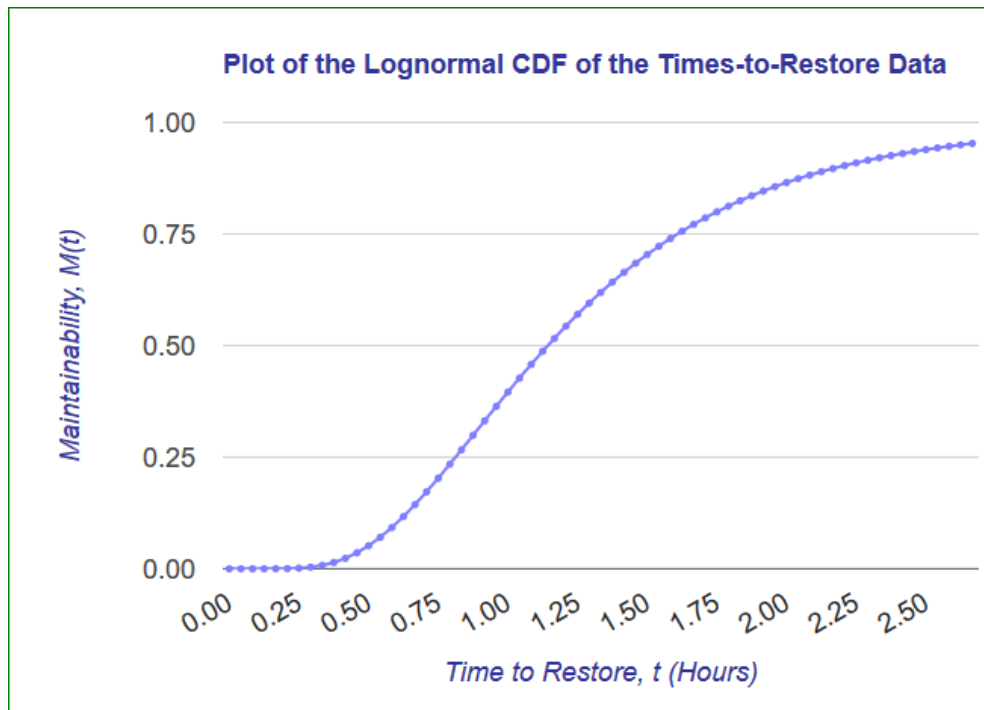


Figure 0-5 CDF of the TTR of BTS\_111011

Likewise, Figure 3-12 is the CDF of the TTR data. From the CDF of the TTR data, it is possible to figure out the median time to repair, the MTTR and the maximum time to repair (95%). Accordingly, the median time to repair, the MTTR and the 95% maintenance time are 1.14 hours, 1.30 hours and 2.63 hours respectively.

### **3.6.4. Maintainability Analysis Results**

The maintenance measurement results are also presented in Table 3.6 computed using the proposed methodology (the lognormal distribution) and using the equations in section (2.7.2) of this document. Then the average values of the median time, the MTTR, M90%, and M95% are 1.9, 3.3, 7.0 and 10.4 hours respectively. These figures tell that, on average, 50% of a site's maintenance task can be completed within 1.9 hours. While the mean time to complete a maintenance of a site is 3.3 hours. The maximum time required to complete 95% of a site outage maintenance reaches as high as 10.4 hours.

Whereas the maintainability measurements are assumed to be completed within the average values, some networks took longer times to complete. For example, in Table 3.1.10, mobile sites (BTSs) in number 1, 4, 6, 9, 15 and 18 have maintenance times of longer than the average values. Those networks need special attention as longer downtimes are problematic for the operator as well as the subscribers.

Using the average median time approximated into 2 hours and using the average mean and standard deviations values (0.50 and 0.98) respectively which are derived from Table 3.6, the maintainability of the mobile sites can be computed for a permissible range of times. To do so, Eq (2.19) which is the maintainability function,  $M(t)$  of the lognormal distribution is used. Accordingly, the maintainability of the mobile networks is computed for the maintenance times of (2, 4, 6, 8, 10 & 12 hours) as shown in Table 3.7.

Table 0.3 Maintainability Analysis results

No.	BTS_ID	Median T	MTTR	M90%	M95%	Mean	Std
1	112150	3.62	5.74	12.38	17.54	1.29	0.96
2	112242	2.08	3.08	6.49	8.96	0.73	0.89
3	112099	1.53	2.30	4.87	6.75	0.42	0.90
4	111102	2.11	7.77	16.72	30.05	0.75	1.62
5	111173	1.02	1.13	1.84	2.17	0.02	0.46
6	111638	5.21	8.23	17.75	25.12	1.65	0.96
7	111144	1.27	1.69	3.34	4.40	0.24	0.76
8	112224	1.20	1.92	4.16	5.90	0.18	0.97
9	112105	2.27	5.06	11.50	18.20	0.82	1.26
10	112149	1.32	3.51	7.94	13.18	0.28	1.40
11	111642	1.74	3.11	6.92	10.23	0.55	1.08
12	111045	2.10	3.96	8.90	13.39	0.74	1.13
13	111432	0.91	1.37	2.91	4.04	-0.09	0.90
14	111002	0.98	1.39	2.87	3.89	-0.02	0.84
15	112059	5.22	7.72	16.23	22.37	1.65	0.88
16	112083	1.88	5.17	11.65	19.51	0.63	1.42
17	111651	2.04	3.06	6.46	8.95	0.71	0.90
18	111866	2.76	6.09	13.85	21.88	1.01	1.26
19	111999	2.80	4.47	9.67	13.74	1.03	0.97
20	112030	1.69	2.36	4.84	6.52	0.52	0.82
21	112216	1.33	1.86	3.80	5.12	0.28	0.82
22	112215	1.83	2.82	6.03	8.46	0.60	0.93
23	111670	1.02	1.77	3.92	5.74	0.02	1.05
24	111809	0.98	1.73	3.84	5.65	-0.02	1.06
25	111019	0.92	1.52	3.32	4.78	-0.09	1.00
26	111663	1.09	1.81	3.96	5.69	0.09	1.00
27	111404	2.02	2.59	4.99	6.45	0.70	0.71
28	112184	1.07	1.69	3.63	5.14	0.07	0.96
29	111743	1.70	2.34	4.73	6.33	0.53	0.80
30	111547	0.66	0.87	1.70	2.22	-0.47	0.73

Increasing maintainability means as the maintenance time increases the probability of completing the maintenance activities within that specific time increases with an increasing trend. While decreasing maintainability implies the increment of maintainability is at a

decreasing rate. Figure 3-13 indicates the maintainability of the networks (in %) for each time,  $t$ , and the trend of the maintainability as the time increases.

Table 0.4. Maintainability of the networks

#	Time(hrs), $t$	$\ln(t)$	$m$	$s$	$Z$	$M(t)$
1	2.00	0.69	0.5	0.98	0.18	57.14%
2	4.00	1.39	0.5	0.98	0.88	81.10%
3	6.00	1.79	0.5	0.98	1.28	89.97%
4	8.00	2.08	0.5	0.98	1.57	94.18%
5	10.00	2.30	0.5	0.98	1.79	96.33%
6	12.00	2.48	0.5	0.98	1.97	97.60%

Where  $m$  = mean of the logarithm of the TTR data

$s$  = standard deviation the logarithm of the TTR data

$Z$  = is the value from the normal distribution function corresponding to the percentage point  $(1-\alpha)$  on the maintainability function.

Therefore, the maintainability of the networks has increased for the times of 2, 4 and 6 hours while it has decreased for the times from 6 hours to 8 hours and very much decreased for the time beyond 8 hours. In general maintenance actions taking greater than 6 hours results in decreasing of maintainability. From the Figure, it is observable that the maintainability of the network decreases and reaches as high as 12.5 hours to complete 100% of the maintenance.

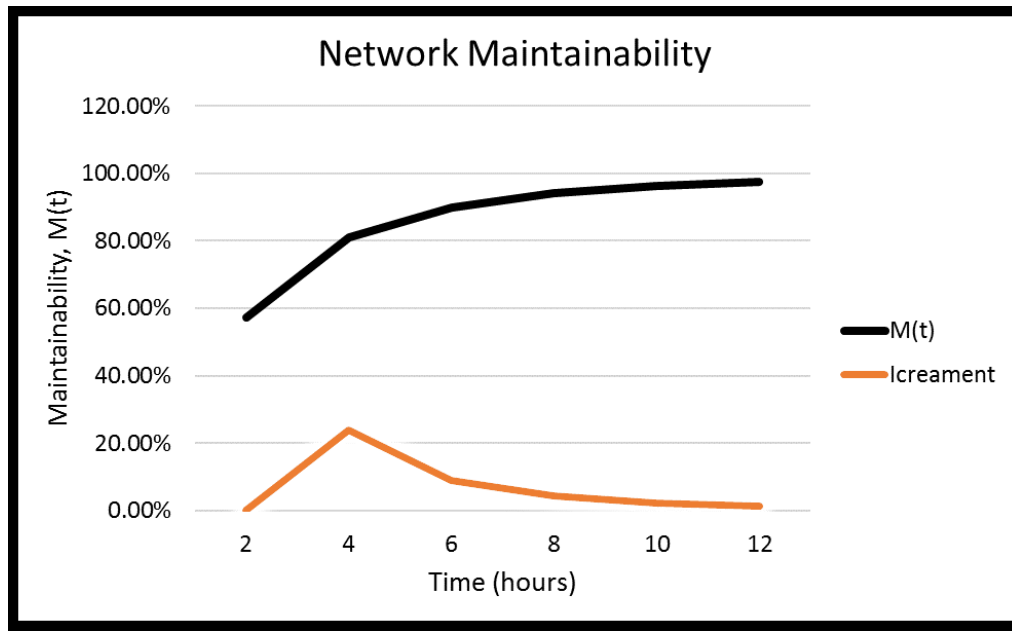


Figure 0-6. Network Maintainability.

Thus, there should be a mechanism to complete maintenance of a network within a time range of less than or equal to 6 hours and at most within 8 hours otherwise it will not be economical. This could be due to either of or the combinations of insufficient skill maintenance personnel, poor network design and installation, lack of spare parts or poor logistics management (insufficient car supply).

## 3.7. Network Downtime Impact Analysis

### 3.7.1. Revenue Loss

Impact of network downtimes is analyzed in terms of revenue loss, customer impact (severity analysis) and SLA penalty. As an illustration, four months (Feb-May 2018) data of active 3G mobile services (internet, voice, and SMS) users and revenue generated from those services during that time were collected. From those data, active mobile service users and the average revenue per user (ARPU) per hour was generated to align them with the DT data units of

measurement (in hours). Having these data, the DT, active mobile service users and the ARPU, the revenue loss analysis was performed using Equation 5.1 as follows. As a result, there were of 21,691 active 3G mobile services users with an ARPU of Birr 0.40 per hour. However, taking the same data of all services (2G, 3G, and 4G) could give a different result probably larger figure.

$$\mathbf{RL = ARPU * AU * TDT} \quad \mathbf{(5.1)}$$

Where RL = revenue loss

ARPU = average revenue per user per hour

AU = active users per hour

TDT = total downtimes

The TDT is determined based on the availability of the networks. As both the ARPU and the AU are assumed to constant, only the TDT determines the amount of the revenue loss. The lower the network availability, the higher is the downtime and hence the higher is the revenue loss.

From Figure 3-14, it is observed that there are 26 mobile access networks with an average availability of 97.5%. Those networks have induced a revenue loss of greater than Birr 1.6 million within four months which is more than 4.87 million per years. Working on those networks and making them to have at least two nines availability will help to save that much money per year.

A performance improvement program to make the networks to have availability of 99.9%, farther helps to save a significant amount of money. Per the measurement period, it is possible to save above Birr 79, 586, 881.9 and three times of that (238, 760, 645.76) per year. This is a significant amount of money for the operator to decide to take appropriate intervention mechanisms to minimize the loss. Improving network availability will have benefits beyond

the revenue. Because the higher the network availability, the happier will be the customer and the operator will have a competitive advantage over others (if any).

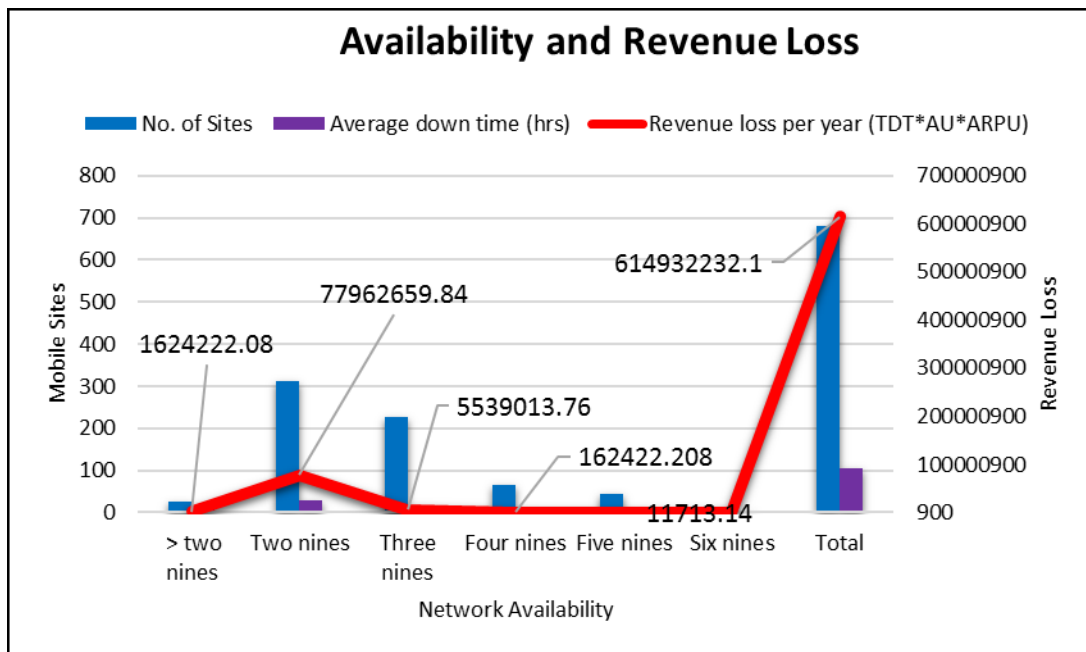


Figure 0-7 Network downtime and revenue loss

### 3.7.2. Customer Impact (Severity Analysis)

The severity analysis of network downtimes is performed to quantify the impact of network outages on mobile communication services users. The propose of network outage severity analysis is to give an input for the facilitation of the operation and management of carrier-grade mobile communication networks.

To perform network outages severity analysis, methodologies in [20, 23, 24] are adopted. Severity levels are defined based on the DT duration of network outages as the magnitude of impacted customers depends on the duration of DT. Four severity levels are then defined as Severity 1: very high impact, Severity 2: high impact, Severity 3: moderate impact, Severity 4: low impact. The network DT data are categorized into respective severity levels and the corresponding affected customers are computed by taking only the networks with LTOs. Table 3.8 shows network outage severity levels and respective range of downtimes.

Table 0.5 Network outage severity levels

Severity Levels	Severity 4-Low	Severity3-Moderate	Severity2-high	Severity1_very high
Time (hours)	2<t<=16	16<t<=32	32<t<=64	t>64

In the severity analysis, the network downtimes are measured in hours. Therefore, active 3G mobile service users per hour are calculated. There were 21,691 active mobile services users per hour. The number of affected users is then determined by the product of the downtime and the number of active mobile users per hour using Equation 5.2.

$$\text{Affected users} = \text{AU} * \text{DT} \quad (5.2)$$

Where AU = refers to the active mobile service users per hour

DT = the downtime per network during the observation time in hours.

Severity analysis results are presented in Figure 3-15. Network DT data are plotted with the number of impacted users and it has shown that as the DT increases, so does the impacted customers. This signifies that an operator who needs to run customer centric business (who provides more use value to the customers for what they pay) needs to work out on keeping the network outages and respective downtimes as minimum as possible.

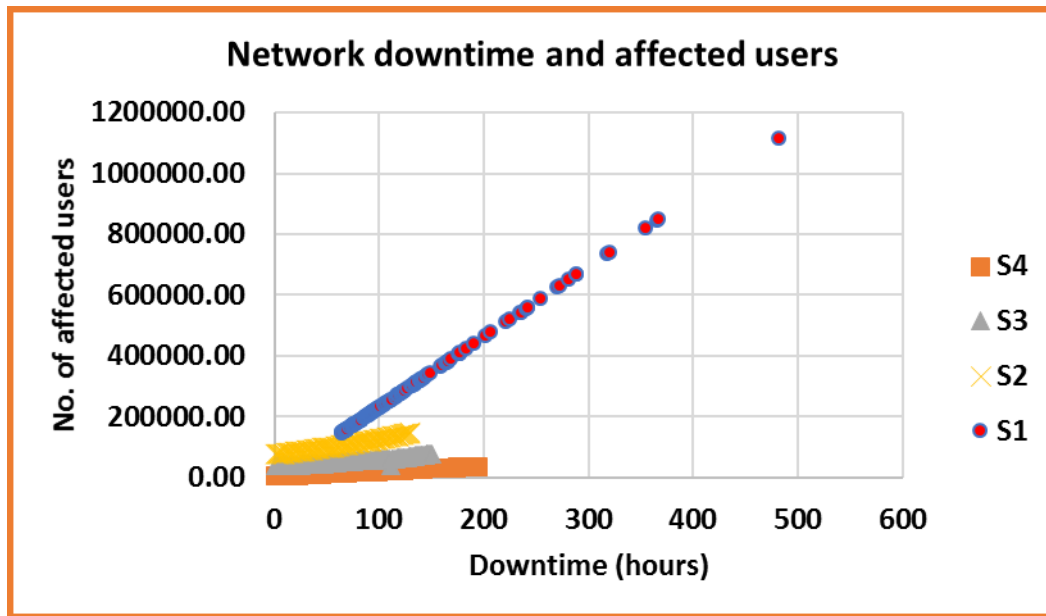


Figure 0-8 Network downtime and affected users

From Figure 3-15 and Table 3.9, it is shown most of the site outages are in severity levels S4 and S3. But, the number of site outages in S1 are also significant. The combined share of the long-time outages distributed in S1 and S2 is 42.9%.

Table 0.6 Network downtimes and affected users by severity level

Variable	S4	S3	S2	S1
MDT	8.7	23.3	46.5	135.2
MIU	188,712	498,893	1,008,631	2,932,623
MaxDT	15.4	33.1	63.4	481.0
MaxIU	334,041	717,972	1,375,209	10,433,371
NO	194	150	130	128

Where MDT = mean downtime

MIU = mean impacted number of users

MaxDT = maximum DT in a respective severity level

MaxIU = maximum impacted users in respective severity level

NO = number of networks in each severity level

In Table 3.9, the MDT, MIU, MaxDT, and MaxIU are presented for each severity level to show hours of DT and number of affected customers. Network outages in severity level 1 (S1) have MDT & MIU of 135.2 hours and 2,932,623 respectively per four months. The impact decreases as getting down from S1 to S4. In the same thought in the case of network availability improvement, an intervention mechanism focusing on S1 network outages could help to significantly minimize the impact of network outages on service users

From Table 3.9, it is observed that an increase in network downtime affects a significant number of service users which implies revenue generation and the business communication processes of the customers is being affected. Once again, this implies that working on reducing the network downtime should be the priority. This could be achieved either by increasing the reliability of the network infrastructure and facilities (for infrequent occurrence of network outages) or by reducing maintenance time (improving the maintenance efficiency). Which direction to follow shall be decided based on cost-benefit analysis of the methodologies and techniques being applied.

Considering the mobility feature of the mobile networks and relatively dense deployment of the networks in Addis Ababa, one can argue that the actual number of impacted users cannot be this much. Even if it is true, getting service due to the mobility feature of mobile networks has impacts on the capacity and QoS of the networks especially when outages are persistent and recurrent. Meaning that capacity problems due to high number handovers can in return result in an outage of other sites unless the frequency and downtime durations are minimized to ensure the stability of the networks.

### 3.7.3. SLA Penalty

A Service Level Agreement (SLA) is an agreement between service provider and end user which defines exactly the services being provided by a service provider and the required level or standard for those services [38]. The SLA document should contain important information such as the overall objectives, detail and clear descriptions of the services being provided, performance standards of the services (for example service availability of 99.0%), compensation/service credits being paid in case the performances are below the agreed performance standards, reporting and contract management mechanisms.

As a service provider, ethio telecom also enters into SLA agreement with its enterprise customers in three types of services. These are the guaranteed time to provide (GTTP), service availability and the guaranteed time to repair (GTR). Table 3.10 shows the SLAs of the network's availability and MTTR of ET.

**Guaranteed time to provide (GTTP)** – refers to the measurement of the total amount of time needed to provide a specific service to a customer.

**Service availability** - this will measure the total amount of time a specific service is available for a customer without disturbance or failures within a specific period (e.g. month).

**Mean time to repair (MTTR)** – measured the average time required to maintain a failed service within a specific time.

The SLA targets, as well as the SLA compensations, are described according to the priority levels. So, in the agreement, each priority level have different performance, price and penalty parameters. For each service under SLA, ET offers backup connections as a mechanism of ensuring the availability targets.

Table 3.10 SLAs of Availability and MTTR Services

Priority Level	Location	Coverage Time (hours)	Availability Target	MTTR
P0+	Head offices/Data center & disaster recovery group (HO/DC & DR)	24	99.5%	2hrs
P0	HO/DC & DR + Branches in Addis Ababa/Regional Capitals	24 /14	98%	4hrs
P1	Branches in Addis Ababa + Regional Capitals + Major Zonal Cities	14	95%	8hrs
P2	Branches in Regional Capitals + Major Zonal Cities	9	95%	12hrs
P3	Branches at Wereda level	9	90%	24%

The higher the priority, the higher is the required performance and penalty in case there is a performance gap. For example, as shown in Table 3.10, P0+ requires 24 hours SLA coverage, higher availability requirement and relatively lower MTTR time while P3 services require relatively lower commitment.

The SLA price is an extra money being paid by the customer for the extra commitments by the operator to guarantee the availability of the services either by preventing from an outage or via quick maintenance. The SLA penalty is the money being paid by the service provider to the customer as a compensation in case SLA performances are not fulfilled. As performance requirements are different across priority levels, so does the price and the penalty. Both are defined as a percentage of the monthly subscription fee or the monthly recurrent charges (MRC) of the services subscribed by the customer.

The lower the performance, the higher will be the penalty to the service provider and can reach up to 100% of the MRC. Table 3.11 shows the SLA prices and penalties of the MTTR and Availability targets for priority P0+ services.

SLA performance evaluation will be based on the availability and maintainability analysis results and the agreements of the operators. As an example, let's take the P0+ SLAs because P0+ SLAs require the most commitment from the operator and it is likely that majority of the P0+ SLA services are in Addis Ababa.

To begin with the availability and SLA performances analysis, most networks fulfill the availability requirements except those 26 mobile access networks with 97.5% availability. Besides, since the average availability of the mobile networks is 99.75%, no penalty can be induced to the operator unless the agreement is modified into higher availability requirement. However, comparing to the high dependence of businesses to communications services, the targets are loosely defined. So, customers with critical businesses might not accept it. But it could be due to the backup connection offer of ET to reduce service interruptions.

The SLA performance can also be evaluated from the maintainability analysis perspectives. As presented in Table 3.7, the probability of completing maintenance tasks within 2, 4, 6, 8 hours are 57.14%, 81.10%, 89.97%, and 94.18% respectively. Therefore, the probability of being penalized with those maintainability levels are 42.86%, 18.90%, 10.03 and 5.82% respectively. With these probabilities, the delays and associated penalty are as shown in Table 3.10. Thus, it is ideal to meet the SLA standards of the MTTR unless the customer agrees for an MTTR of 12 hours and above for P0+ SLA being completed without penalty.

Table 0.7 MTTR (guaranteed time to repair) and penalties for P0+ SLA

Priority Level	MTTR (hours)	Remedy (%MRC)	Availability	Remedy (%MRC)
P0+	$t < 2$	15%	$99.5\% > A \geq 97.5\%$	10%
	2 hours $< t \leq 4$	20%	$97.5\% > A \geq 95.5\%$	25%
	4 hours $< t \leq 6$	25%	$95.5\% > A \geq 93.5\%$	50%
	6 hours $< t \leq 10$ days	35%	$93.5\% > A \geq 91.5\%$	75%
	10 days $< t \leq 15$ days	45%	$A < 91.5\%$	100%
	$t > 15$ days	Customer pays for the available day only		

Where  $t$  = maintenance time

$A$  = availability

Therefore, according to the maintainability analysis, it is not advisable for the operator to enter into an SLA agreement especially in MTTR services unless an improvement mechanism is applied to increase the maintainability of the networks. On the other hand, signing SLAs can be a motivating factor to exert more effort to meet SLA performances and beyond.

For the sake of comparisons, SLA of other service providers in ensuring network availability and maintenance services are reviewed. The results are presented in Table 3.11 as follows.

Table 0.8 Availability and MTTR SLAs for wireless voice and Internet services

No.	Service Provider	Availability	MTTR	Penalty
1	Verizon	99.95		100% for <96.7% availability
2	COGENT	100%		1-hour credit (in service) for every 15 minutes unavailability
3	Spirit Internets future	99.95	1 day for CO and 2 days for MO	Up to 35% for more than 48 hours unavailability
4	Nextera	99.99%	4 hours	1-day MRC for every incident
5	Spectrum Internet	99.0%	2 hours	£25 credit each month for availability below the target.

Reviewing the SLA targets of five (5) wireless services providers, the availability targets are above 99.0% except for the Spectrum Internet. While Verizon and COGENT have no separate MTTR target which they might assume that assuring target availability includes quick maintenance, the other three service providers (SPs) have MTTR targets.

The Spectrum Internet has relatively lower availability target with quicker maintenance time (2 hours) while the Spirit Internets Future and the Nextera have an availability target of 99.95% and 99.99% and MTTR of 4 hours and (1 day for critical and 2 days for major outages) respectively.

This implies that SLA targets are mostly set based on the operational capability of the service provider, although it should have been set based on the agreement of the SPs and the customers. In the case of the penalty, all SPs except the Spectrum Internet uses a similar approach. It is defined as a percentage of the MRC.

# 4. Conclusion, Recommendations and Future Works

## 4.1. Conclusions

Based on the analyses, the following conclusions are drawn.

- The networks are characterized by a frequent and long-lasting outage. The operational performance of the networks is then least successful and such networks are considered unstable.
- The frequently occurring network outages lead to recurrent network outages. Such outages have an impact on the behavior of the maintenance personnel to be constrained to follow reactive maintenance behavior to meet KPIs without giving long-lasting solutions.
- Since most of the networks are characterized by long-time outages, it is an indication of weak responsiveness to network outages. This could happen due to the low skill of the maintenance personnel, lack of spare parts, an inefficient maintenance process, and/or insufficient logistic supplies.
- The average availability of the networks is 99.75% which is low to entertain business-critical applications and is not up to the standard.
- Considering the nearby location of the networks to the large maintenance facilities, it is too long to take a maintenance time of 10 hours and above to repair a network. Besides, the decreasing maintainability of the networks for a maintenance time of 6 hours and above is an indication of weakness in the maintenance practices.
- Based on the impact analysis of network downtimes, it is revealed that a significant number of the network outages have severity level 1 and 2, with a total revenue loss of

Birr more than 614 million is induced per year. Besides, the likelihood of SLA fulfilment is low.

- A scientifically selected intervention mechanism is required to improve the availability and maintainability of the networks via reducing network outage frequency and durations. Then the operator can be able to fulfil SLA targets and to save revenue loss of at least 614 million per year.

## 4.2. Recommendations

The following recommendations are provided based on the analysis result with the intention of giving ideas for improvements of the availabilities and maintainability of the networks

- As the outage frequency and outage durations are very high compared to the international practices, it is a sign of that recurrent outages are happening. Identifying and prioritizing the most root causes of the outages could help to minimize the frequency as well as longer downtimes.
- Mobile operator's profitability remains high and productivity levels improve only when their infrastructure continues to deliver at the desired efficiency. Doing so can damage the brand's reputation if the operation is inefficient. Therefore, maintenance efficiency improvement mechanisms should be applied to reduce the downtime of the networks. There could be many alternative ways to achieve it such as maintenance training and skill development of maintenance staffs, creating better organizational structure which ensures maximum support and communications, creating expertise maintenance groups which focus on identifying root cause and providing permanent solutions, automating maintenance task and so on.
- For network availability improvements, a phase by phase approach can be followed to bring the networks from one availability category into the next better availability category. In the meantime, the operator should set an availability target in which it is not acceptable

for a network to operate below that target and to be used as a starting point for improvement planning.

- As described in [15 & 16], network outages are the third causes of customer churn and operators worldwide incur significant cost to handle it. Therefore, it is a mandatory desire of the operators to minimize network outages and downtimes largely to stay competitive in the market so that the customers can be retained, and profits can be maximized. In the case of ET, although it is operating in a monopoly market, it will not be too long before competitors join the market as there is already a policy change on liberalizing the telecommunication sector. Therefore, with the current availability and maintainability performances of the networks, it could be challenging to have a significant market share. Thus, it is required to perform scientific RAM analysis to measure the performance of the networks in terms of availability, maintainability, and reliability and take improvement actions.

### **4.3. Future Works**

Based on the findings and the scope of this research, the following are suggested as future works to be addressed to add value to the current study.

- Studying on the improvement of the availability and maintainability of the mobile networks.
- studying maintenance policies, organizations, and strategies for network maintainability efficiency.
- Researching focusing on the most frequently and long-lasting mobile access networks outages for overall availability and maintainability improvements.
- Studying the traffic pattern of mobile network services could help to investigate the real impacts of downtime and to prioritize intervention mechanisms.

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# Annex

Table 0.1 TTR data determination of mobile sites

Mobile site 111011 outage and repair time data							
No	Outage Time	Repair Time	TTR (hours)	No.	Outage Time	Repair Time	TTR (hours)
1	2/8/2018 21:14	2/8/2018 22:54	1.4	30	3/5/2018 21:12	3/5/2018 23:02	1.5
2	2/11/2018 21:46	2/11/2018 22:41	0.55	31	3/6/2018 21:38	3/6/2018 22:58	1.2
3	2/13/2018 12:43	2/13/2018 13:58	1.15	32	3/7/2018 21:33	3/7/2018 22:43	1.1
4	2/13/2018 13:33	2/13/2018 14:38	1.05	33	3/8/2018 21:09	3/8/2018 22:44	1.35
5	2/13/2018 21:33	2/13/2018 22:03	0.3	34	3/9/2018 21:30	3/9/2018 22:45	1.15
6	2/13/2018 22:08	2/13/2018 23:03	0.55	35	3/11/2018 21:21	3/11/2018 22:56	1.35
7	2/14/2018 21:19	2/14/2018 22:54	1.35	36	3/12/2018 21:27	3/12/2018 22:57	1.3
8	2/15/2018 21:09	2/15/2018 22:49	1.4	37	3/13/2018 11:07	3/13/2018 12:12	1.05
9	2/16/2018 21:20	2/16/2018 23:00	1.4	38	3/13/2018 21:33	3/13/2018 22:53	1.2
10	2/17/2018 21:41	2/17/2018 22:06	0.25	39	3/14/2018 21:39	3/14/2018 22:54	1.15
11	2/17/2018 22:31	2/17/2018 23:11	0.4	40	3/15/2018 13:24	3/15/2018 13:34	0.1
12	2/18/2018 21:22	2/18/2018 22:42	1.2	41	3/15/2018 14:20	3/15/2018 14:50	0.3
13	2/19/2018 21:27	2/19/2018 22:52	1.25	42	3/15/2018 21:35	3/15/2018 22:50	1.15
14	2/20/2018 21:43	2/20/2018 22:43	1	43	3/16/2018 21:15	3/16/2018 23:00	1.45
15	2/21/2018 21:24	2/21/2018 22:54	1.3	44	3/17/2018 22:16	3/17/2018 22:56	0.4
16	2/22/2018 21:15	2/22/2018 22:40	1.25	45	3/18/2018 22:02	3/18/2018 22:42	0.4
17	2/23/2018 21:46	2/23/2018 22:51	1.05	46	3/19/2018 21:22	3/19/2018 22:32	1.1
18	2/24/2018 22:11	2/24/2018 22:36	0.25	47	3/20/2018 21:18	3/20/2018 22:53	1.35
19	2/25/2018 3:25	2/25/2018 4:13	0.48	48	3/21/2018 21:14	3/21/2018 22:49	1.35
20	2/25/2018 3:26	2/25/2018 4:14	0.48	49	3/22/2018 21:09	3/22/2018 22:59	1.5
21	2/25/2018 4:26	2/25/2018 10:46	6.2	50	3/23/2018 21:20	3/23/2018 22:55	1.35
22	2/25/2018 4:26	2/25/2018 10:46	6.2	51	3/24/2018 21:41	3/24/2018 22:31	0.5
23	2/25/2018 10:53	2/25/2018 10:57	0.03	52	3/25/2018 21:41	3/25/2018 22:51	1.1

24	2/26/2018 21:33	2/26/2018 22:48	1.15	53	3/26/2018 21:17	3/26/2018 22:52	1.35
25	2/27/2018 21:13	2/27/2018 22:43	1.3	54	3/27/2018 21:33	3/27/2018 23:13	1.4
26	2/28/2018 21:19	2/28/2018 22:44	1.25	55	3/28/2018 21:33	3/28/2018 22:53	1.2
27	3/1/2018 21:25	3/1/2018 23:00	1.35	56	3/29/2018 21:09	3/29/2018 22:49	1.4
28	3/2/2018 21:40	3/2/2018 23:00	1.2	57	3/30/2018 21:40	3/30/2018 22:55	1.15
29	3/4/2018 21:06	3/4/2018 22:51	1.45	58	4/21/2018 21:49	4/21/2018 23:04	1.15

Table 0.2. Statistical distribution of TTR data of sample mobile sites

K-S Test Best Fit Distribution								
No.	BTS_ID	Lognormal	Lognormal(3p)	Exponential	Exponential(2p)	Normal	Best Fit Model	Est. Parameters
1	112150	0.07177	0.07401	0.0962	0.09921	0.1777	Lognormal	$\mu=1.0474$ $\sigma=1.1166$
2	112242	0.08731	0.0885	0.11712	0.07739	0.16666	Exponential(2p)	$\mu=0.33486$ $\sigma=0.37$
3	112099	0.12248	0.11926	0.14276	0.16859	0.25017	Lognormal(3p)	$\mu=1.2819$ $\sigma=0.09979$ $\sigma=0.26442$
4	111102	0.1658	0.23076	0.32611	0.33829	0.35298	Lognormal	$\mu=1.5923$ $\sigma=0.95797$
5	111173	0.22999	0.35774	0.4173	0.24784	0.22277	Normal	$\mu=0.45339$ $\sigma=0.94429$
6	111638	0.1143	0.13547	0.30763	0.31046	0.39465	Lognormal	$\mu=1.2075$ $\sigma=1.1506$
7	111244	0.11367	0.15266	0.16033	0.16423	0.29695	Lognormal	$\mu=0.85157$ $\sigma=0.35246$
8	112224	0.20366	0.14819	0.27321	0.2308	0.21303	Lognormal(3p)	$\mu=0.47392$ $\sigma=0.87452$ $\sigma=-0.75198$
9	112105	0.11196	0.17005	0.43634	0.4569	0.43715	Lognormal	$\mu=1.3442$ $\sigma=0.57369$

10	112149	0.3256	0.25718	0.56584	0.60734	0.4852	Lognormal (3p)	$\mu=5.7834$ $\sigma=-1.1498$ $\sigma=0.32$
11	111642	0.21027	0.2075	0.35427	0.37856	0.43107	Lognormal (3p)	$\mu=2.0895$ $\sigma=-1.0059$ $\sigma=0.29765$
12	111045	0.20709	0.14098	0.35004	0.39104	0.35398	Lognormal (3p)	$\mu=1.6097$ $\sigma=0.03503$ $\sigma=0.2884$
13	111432	0.16638	0.1955	0.19136	0.2371	0.26385	Lognormal	$\mu=0.87035$ $\sigma=0.02914$
14	111002	0.32863	0.4358	0.47833	0.44668	0.31364	Normal	$\mu=0.19352$ $\sigma=0.5225$
15	112059	0.14105	0.1215	0.22083	0.18356	0.25225	Lognormal (3p)	$\mu=0.60215$ $\sigma=0.93817$ $\sigma=-0.28202$
16	112083	0.14346	0.16512	0.14689	0.18477	0.23082	Lognormal	$\mu=1.0674$ $\sigma=0.93094$
17	111651	0.14287	0.39629	0.21252	0.24761	0.33485	Lognormal	$\mu=0.85314$ $\sigma=-0.15431$
18	111866	0.3589	0.27037	0.55649	0.58484	0.29909	Lognormal (3p)	$\mu=3.0627$ $\sigma=-1.8681$ $\sigma=0.07999$
19	111999	0.14434	0.18679	0.16469	0.12779	0.2104	Exponential(2p)	$\mu=0.62427$ $\sigma=0.3$
20	112030	0.22051	0.26997	0.23274	0.26997	0.27519	Lognormal	$\mu=0.81092$ $\sigma=-0.19322$
21	112216	0.26215	0.15467	0.30872	0.42823	0.2763	Lognormal(3p)	$\mu=2.6311$ $\sigma=-1.515$ $\sigma=0.29983$
22	112215	0.20904	0.14833	0.25515	0.34225	0.39709	Lognormal(3p)	$\mu=1.5681$ $\sigma=-1.3465$ $\sigma=0.2932$
23	111670	0.25703	0.25649	0.35572	0.39275	0.39047	Lognormal(3p)	$\mu=1.5859$ $\sigma=-0.00139$ $\sigma=0.26564$
24	111809	0.2401	0.16317	0.36379	0.44812	0.39773	Lognormal(3p)	$\mu=2.2672$ $\sigma=-1.247$ $\sigma=0.29925$

25	111019	0.45455	0.45455	0.50049	0.50049	0.3876	Normal	$\mu=1.6745$ $\sigma=0.47818$
26	<b>111663</b>	0.17908	0.18566	0.19688	0.29829	0.29783	Lognormal	$\mu=1.0427$ $\sigma=0.08681$
27	111404	0.1879	0.16878	0.27816	0.29479	0.38014	Lognormal(3 p)	$\mu=1.327$ $\sigma=0.45785$ $\sigma=0.27921$
28	112184	0.13093	0.25323	0.20227	0.22864	0.31912	Lognormal	$\mu=1.0165$ $\sigma=0.27001$
29	111743	0.23867	0.1472	0.33624	0.23562	0.23562	Lognormal(3 p)	$\mu=1.3952$ $\sigma=1.5776$ $\sigma=0.28772$
30	111547	0.17392	0.45783	0.28896	0.2859	0.32385	Lognormal	$\mu=0.70128$ $\sigma=0.35074$