ADDIS ABABA UNIVERSITY

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AFRICAN RAILWAY CENTER OF EXCELLENCE

GSM-R Radio Network Planning and Dimensioning for ISAKA-KIGALI Railway Line

A Thesis in Traction and Train Control

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A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

The undersigned have examined the thesis entitled '**GSM-R Radio Network Planning and Dimensioning for ISAKA-KIGALI Railway Line**' presented by **Gedeon NDAYIRINGIYE**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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UNDERTAKING

I certify that research work titled "**GSM-R Radio Network Planning and Dimensioning for ISAKA-KIGALI Railway Line**" is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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Gedeon NDAYIRINGIYE

Abstract

Railway Control and Communication system is the heart of safe and reliable railway operations. From the very birth of railway operations up to now, railways have encountered challenges in operations mainly accidents due to head to head collision for trains moving in opposite directions on a same track and rear-end collision in case a train hits the one in front due to high speed and not enough breaking power as a result of lack of efficient communication and train control system. Besides this, railway capacity optimization which involves use of maximum number of trains on a track in given time period also requires efficient communication and control for train dispatching. Different means for train control and communication have been used such as Terrestrial Trunked Radio (TETRA), Global System for Mobile Communication – Railway (GSM-R), Enhanced position and location reporting system (EPLRS), inductive loop, satellite, and the current trend of Long Term Evolution – Railway (LTE-R).

This thesis project focuses on planning a GSM-R radio communication network for ISAKA-KIGALI Railway line. GSM-R has been chosen due to its several advantages such as being the first international communication network designed specifically for railways; GSM-R has been proven to maintain a reliable communication link between the train and the ground; GSM-R has a great experience of nearly 3 decades which shows its maturity as a communication and control system for trains and the last but not the least, GSM-R is at the heart of European Train Control System Level 3(ETCS-3) which implements a moving block technology. Network coverage planning and dimensioning is carried in three phases which are technical analysis of elements causing traffic on the network for network dimensioning, calculation of important parameters for Base Transceiver Station (BTS) deployment and network simulation in Atoll software to calculate the number of BTSs required providing radio coverage for the entire line. The obtained results are that a total of 92 BTSs are required to provide a fully redundant GSM-R network whereby each cell's BTS is assigned a single frequency channel except at Major station and other medium stations where more than one frequency channel is required due to high telecommunication traffics taking place there, and the network has to be able to support a total traffic intensity of **7.54Mbps** in busy hour. Coverage in tunnels is chosen to use leaky feeders connected to BTS adjacent to tunnel entry.

Keywords: GSM-R, Radio Network Planning, ISAKA-KIGALI Railway line.

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List of tables

Table of Figures

Glossary of Terms / List of Abbreviations

Term	Explanation / Meaning / Definition
AfDB	African Development Board
AIHSRN	African Integrated High Speed Railway Network
ARFCN	Absolute Radio Frequency Channel Number
AU	African Union
AuC	Authentication Centre
BCH	Broadcast Channel
BTS	Base Transceiver Station
CCTV	Closed Circuit Television
DAS	Distributed Antenna Systems
EDGE	Enhanced data for global evolution
EIRENE	European Integrated Radio Enhanced Network
EIRP	Effective Isotropic Radiated Power
EMLPP	Enhanced Multi-Level Precedence and Pre-emption
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
ETSI	European Telecommunications Standards Institute
FA	Functional Addressing
FDMA	Frequency Division Multiple Access
GMSC	Gateway Mobile Switching Centre
GMSK	Gaussian Minimum Shift Keying
GPRS	General Packet Radio Services
GPS	Global Positioning System
GSM	Global System for Mobile communication
GSM-R	Global System for Mobile communication – Railway
HLR	Home Location Register
IEEE	Institute of Electrical and Electronic Engineers
ISDN	Integrated Services Digital Network
LDA	Location Dependent Addressing
LNF	Log-Normal Fading
LOS	Line of Sight
MAHO	Mobile Assisted Handoff
MAPL	Maximum Allowable Path Loss
MRSL	Minimum Received Signal Level

Term	Explanation / Meaning / Definition
MSC	Mobile Switching Centre
NLOS	Non Line of Sight
PIDA	Programme for Infrastructure Development in Africa
PLMN	Public Land Mobile Network
PSTN	Public Switched Telephone Network
RECs	Railway Engineering Corporations
RSTT	Radio communication Systems between Train and Trackside
RTDA	Rwanda Transport Development Agency
SGR	Standard Gauge Railway
SMS	Short Message Service
SNR	Signal to Noise Ratio
STPs	Signal Transfer Points
TCH	Traffic Channel
TDMA	Time Division Multiple Access
TETRA	Terrestrial Trunked Radio
UIC	Union Internationale des Chemins de Fer
UMTS	Universal Mobile Telecommunications System
UNECA	United Nations Economic Commission for Africa
VBS	Voice Broadcast Services
VGCS	Voice Group Call Services
VLR	Visitor Location Register

CHAPTER ONE: INTRODUCTION

1.1 General background

Railway transportation is a mean of conveyance of passengers and goods. It is also commonly referred to as train transport[1]. It is one of the transportation means used on ground transportation and is the most energy efficient as compared to road transport which is its main competitor as it consumes only 1/3 as much energy as road transport for same traffic. Its advantages includes ability to transport high volumes due to its capability to join several units into trains of varying length, good energy efficiency as compared to road transportation, lower environmental pollution as Electric trains cause no pollution and Diesel electric trains generate 15 times less pollution than automobiles for the same traffic, and it is safer compared to its inland transportation means competitors.

The African Union Commission, in collaboration with the Railway Engineering Companies (RECs), African Development Bank (AfDB), United Nations Economic Commission for Africa (UNECA) and specialized institutions, is working on promoting and facilitating development of railway transport under its Program for Infrastructure Development in Africa (PIDA) focuses on promoting the development of an integrated transport network for the continent which capitalizes on the suitability of each mode of transport. In this context, railways have always been considered as the backbone of the transport networks at all levels[2].

The African Integrated High Speed Railway Network (AIHSRN) project is a flagship project of the African Union (AU) Agenda 2063. It basically aims at facilitating the achievement of the AU Vision of integrating Africa physically and economically and has a vision to provide Africa transport network with a modern high speed railway component harmoniously articulated around the main modernized conventional railway network, able to develop fast connections, smart and effective around the various development centers supported by various economic and social policies[2].

With all these above points in mind, Rwanda being a landlocked country plans to build a Standard Gauge Railway (SGR) line from Isaka (Tanzania) to Kigali (Rwanda) which will interconnect it with Tanzania hence getting access to Dar-es-Salam sea port and thereby participating in an interconnected Africa by Rail network.

Signaling and Communication systems are at the heart of railway operations to automatically control Train movements, enforcing train safety and directing train operations. Railway signals are provided mainly to ensure that there is sufficient separation between two trains on the same track so that one stops before it hits the one in front, to inform a train operator about track occupancy ahead of the train, to provide speed restrictions and to provide automatic train stopping when the driver fails to abide with a stop signal indication.

From the early years of railways development there has been a need for communication between train dispatchers and train drivers for safer operation of trains. Back in the 1830s and 40s in the very early days of railways there was no system for informing the driver of the state of the line ahead. Trains were driven "on sight"; Drivers had to keep their eyes open for any sign of a train in front so they could stop before hitting it or any sign of track damage or obstruction so that they stop before making an accident.

Various radio communication systems/technologies have been used for many years for railway operational applications to facilitate communication between train driver and train dispatchers and also to inform train drivers of the conditions of the track ahead of them. These include Terrestrial Trunked Radio (TETRA), Global System for Mobile Communication – Railway (GSM-R), Enhanced position and location reporting system (EPLRS), inductive loop, satellite, and the current trend of Long Term Evolution – Railway (LTE-R)[3]. Radio communication networks are critical to train operations including stringent requirements for reliability, availability, safety and security for these operations. In general, radio communication for railway operations are considered as “mission critical” for train operations and the management of train emergency situations. Furthermore, railway radio communication systems require the support of legacy technology and to have a long life cycle[1].

When in the nineties railways decided about which technology to best use as a basis for a globally acceptable rail telecom solution, GSM was selected thanks to its strong market presence and superior maturity of technology compared to its candidates such as . GSM-R, a wireless telecommunication system based on GSM technology that has been specified by rail operators for their rail operational voice and data demands, certainly has been one of the cornerstones for this transformation allowing railways to yet increase further efficiency of their existing rail operational infrastructure[4]. European Union (EU) has adopted GSM-R to be an integral part of the safest train control system and is included in its highest European Train Control System (ETCS) level 3.

1.2 Problem Statement

Trains on a track move with very high speed and their movement has to be controlled. The capacity of a railway line is the number of trains which run on that line per unit time. As the number of trains running on railway line increases, their efficient control is necessary to avoid collision either be rear-end collision for trains running in the same direction or head-on collision for trains running in opposite directions using a same track. For the case of ISAKA-KIGALI railway line, a single track will be used both by Freight trains and passenger trains running in both directions. As these trains have different maximum speeds, an automatic train control system, to control and protect train movements and safe passenger transfers is needed and GSM-R system can provide a solution as a bearer for Signaling systems and Automatic Train Control systems and as a standalone solution for Operations Control Systems, e.g. for emergency calls [5].

1.3 Research Objectives

The objectives of this thesis project are grouped in two main groups; General objectives and Specific objectives.

1.3.1 General objective

The general objective of this Thesis research project is to make a GSM-R Radio Network Planning and Dimensioning for ISAKA-KIGALI Railway Line to ensure safe operation of trains running on this Railway line.

1.3.2 Specific objectives

The specific objectives of this Thesis research project are the following:

- ✓ Radio network coverage planning for ISAKA – KIGALI Railway line
- ✓ ISAKA – KIGALI GSM-R Network dimension calculation
- ✓ To evaluate the performance of the planned network using computer simulation in Atoll software.

1.4 Scope

This Thesis project dealt in details with the design of a GSM-R radio network for ISAKA – KIGALI Railway line by providing detailed information about frequency band selection criteria for the line, line capacity dimensioning for both uplink and downlink bands, link budget calculation, BTS location selection and Simulation in computer software to verify if the planned network coverage will provide the required coverage for the whole railway line. All of these are grouped into two main important tasks: Radio network coverage planning and Capacity dimensioning.

1.5 Methodology

Radio network planning has two main important tasks: Network coverage planning and Network capacity dimensioning. Coverage planning deals with required standards for efficient network performance and estimates the number of sites needed, and capacity dimensioning provides the first estimate of the radio network element count as well as the capacity of those elements. The two tasks are independent from each other. This Thesis research project first dealt with radio network capacity dimensioning to estimate the total data rate capacity the network has to be able to support. After network capacity dimensioning, there came the network coverage planning whereby frequency band selection was made, then link budget calculation was done which was followed by path loss propagation model selection to be able to estimate cell radius required for BTS.

After finding cell radiuses, Handover process to be followed is analyzed followed by cell arrangement and frequency planning. To conclude with coverage planning, tunnel coverage is analyzed so that trains won’t miss radio coverage as they travels through tunnels. Finally, radio coverage is simulated in Atoll software to see if its coverage meets the required standards and if not, network coverage optimization has to be done. The below flow chart shows the methodology followed during this project[6].

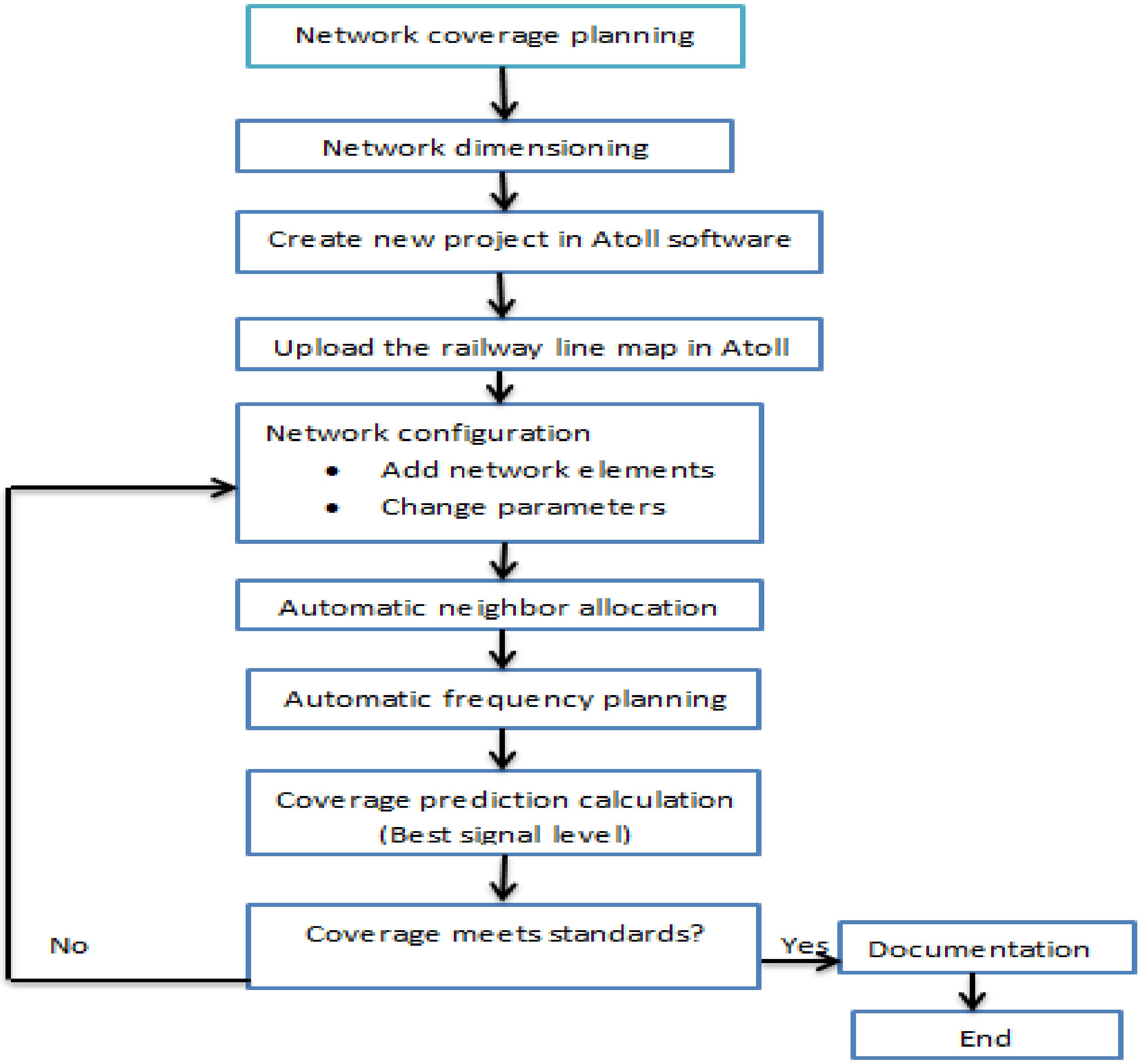

Figure 0-1: Methodology summary

1.6 Thesis report structure

The report is subdivided into six chapters: Introduction; Literature review; ISAKA-KIGALI route description; ISAKA – KIGALI Railway Line GSM-R Radio Network Planning and Dimensioning; ISAKA KIGALI Railway Line GSM-R Radio Network Simulation Results and Discussion; and finally Conclusion and Recommendations.

Chapter one gives an overview on railway communication, History behind Isaka-Kigali railway line, Problem statement, Scope of the work and Objectives both Main objective and specific objectives.

Chapter Two which covers the whole literature review, It talks about different researches that have been done regarding radio network planning in general and GSM-R radio planning specifically.

Chapter Three describes the geotechnical and topography conditions of Isaka-Kigali railway line and design standards of the line.

Chapter Four deals with general network coverage planning and dimensioning, and examines all the standards required for the network and cell radius calculations.

Chapter Five deals with simulating the GSM-R network coverage of the line using Atoll software to obtain the number of BTSs required to cover the entire line and results are examined according to best signal level.

Chapter Six gives final conclusion of the thesis with recommendations for future researches

2 CHAPTER TWO: LITERATURE REVIEW

Railway signaling and communication systems have developed significantly from the early stage of railways where trains were driven only based on sight, to trackside non-automatic mechanical signals, to automatic trackside electrical signals and nowadays are based on radio communication systems between trackside equipment and central train dispatching center to display information about the conditions of the track ahead to the driver for efficient and safe train operations. To build a reliable communication link for train operations, radio planning plays a significant role and railway radio communication planning is based on the usual general radio planning except some features added specifically for railways. Therefore, we go through the literature of general radio planning and optimization before going through railway radio planning to clearly understand how it is done.

2.1 General Radio network planning and optimization literature

The backbone task of radio network system design is to come up with an optimal radio network that gives the best feasible radio coverage for the concerned planning region. To achieve this aim, while in design process, it is required to make the best selection of base station sites and determining the basic radio frequency parameters to be used for those base stations. These parameters include base station type; inter site distance, number of sectors per site, antenna type, antenna gain, antenna height, transmission power, modulation and coding schemes, frequency reuse, azimuth angle, tilt angle etc.[7]

In the past, the major design criterion of cellular networks was the area coverage. The engineering process mainly focused on giving the best possible radio signal at every location of the concerned planning region. However, as mobile radio transits into a mass communication system where the cost of providing service is as equally important as best coverage, economic and capacity design criteria have also been considered. Hence, To design an efficient mobile radio system, it is required to consider the demand coverage as an additional and equal engineering constraint[8].

Radio network planning has different methodologies in use nowadays. However, the most conventional and commonly used methods are the Analytical Approach methods which focus on Radio Frequency (RF) issues in the first place and the capacity aspects are dealt with only in final stages of the radio network planning process. This procedure based on Analytical approach has as disadvantage to be time-consuming and to optimize the planned network it uses costly reverse-engineering procedures.

The conventional planning approach which is widely used in today's commercial cellular network planning tools is focused on the determination of the transmitter parameters to be used. In principle, the analytical approach has four phases: Radio Network Definition, Propagation Analysis, Frequency Allocation, and Radio Network Analysis that are passed in several turns iteratively[8]. Its phases are summarized in the following flowchart below.

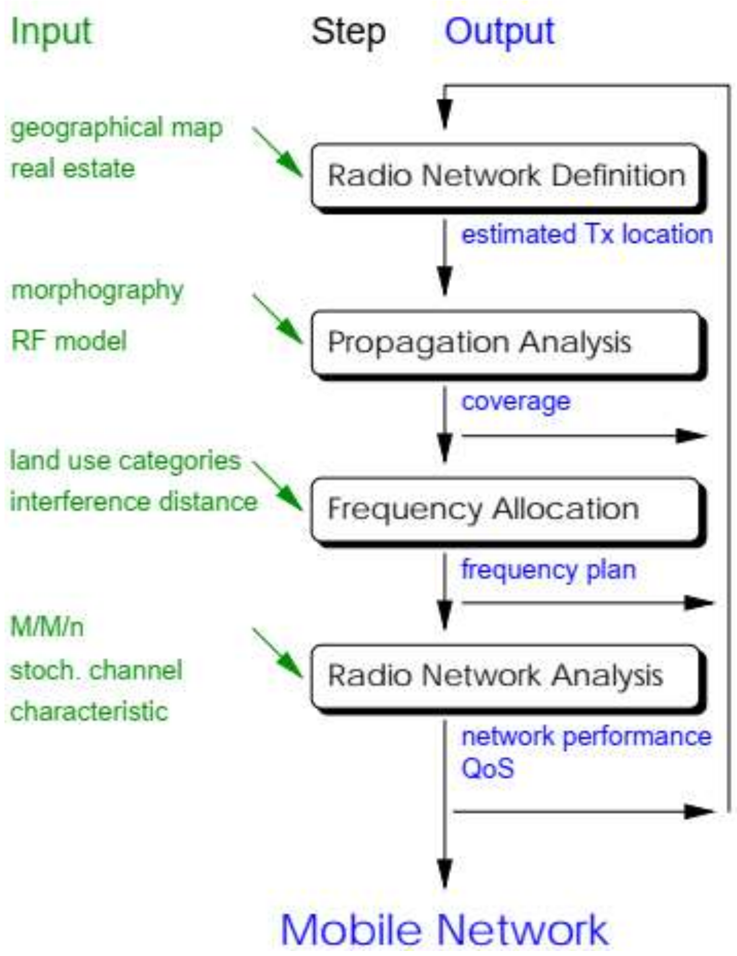

Figure 2-1: Conventional approach of cellular network planning[8]

During the Radio Network Definition phase, a planning expert selects the cell sites. The concept of hexagonal cell structures is mostly used for obtaining a regular structure. Setting transmitter configurations, the Propagation Analysis is carried based on measurements and evaluation of the area's radio coverage by signal field strength prediction methods. Here, different propagation models such as stochastic channel models, empirical models as well as more sophisticated approaches like ray tracing techniques are used. Most of the time, several field strength prediction methods are applied and the tools allow to the network planner to choose the appropriate propagation model to be used in the design. It is then up to the planning expert to decide whether the coverage is sufficient enough or not. If coverage is not sufficient, new transmitter placements have to be chosen and the propagation has to be evaluated once again[8].

In the following phase of *Frequency Allocation*, radio network capacity issues are examined. Firstly, teletraffic distribution inside the planning region is estimated based on the land use and the demographic characteristics of the area. The quality of service values of the radio network in the area are calculated with regard to call setup blocking and call handover dropping probabilities [8].

In his research about Demand-based radio network planning of cellular mobile communication systems, K. Tutschku proposed a radio network planning procedure based on a forward engineering, demand-adaptive cellular network design to overcome the disadvantages of the conventional approach. The Integrated Approach starts the network design with the analysis of the expected teletraffic and uses this information together with other objective performance values to derive in a forward reasoning step an optimized radio network configurations [8].

For emerging and future cellular systems, different planning target objectives are identified like maximization of capacity, coverage, fairness of service in the coverage area, spectral efficiency, throughput, Quality of Service (QoS) or minimization of cost, energy consumption and outage etc. All these objectives can be classified into three main categories of performance measures [7]:

1) Capacity Oriented Performance Measures: These include cellular capacity, spectral efficiency, throughput, and goodput[7].
2) QoS Oriented Performance Measures: Rate fairness and outage are well known examples of QoS measures[7].
3) Cost Oriented Performance Measures: Total cost of ownership of a cellular system over its life has three further major factors[7]:
    a) Capital Cost: cost of hardware, software and deployment labour cost.

b) Maintenance Cost: Cost of labour required for operation, optimization and maintenance of sites and the switching networks.
c) Energy Consumption: Energy consumed to keep the cellular system running is increasingly becoming a main factor of operational cost.

After the radio network has been deployed comes the stage of network optimization to ensure that Key Performance Indicators (KPIs) are met. KPIs can be considered as a tool used to evaluate network performance while different KPIs are merged together to form an overall QoS report of the network. For example, All GSM operators use KPIs to judge their network performance and evaluate the Quality of Service (QoS) regarding end user perspective[9].

Radio Frequency Optimization is a very important process in which any radio network already deployed is evaluated and monitored. This activity is carried periodically in order to maintain a good quality of service. This Optimization action helps to correct different errors made in network planning and gives benefits like improved network capacity, enhanced coverage and quality of service[10].

Two types of methods are used for network optimization, namely Counter method (CT) and Drive Test (DT) method. The counters method is based on analyzing raw data information from counters which their specific values are either incremented or decremented by network event occurrences. Such events include dropped calls, call initiation, traffic channel assignment, traffic channel release, traffic channel demand, call handover and many more which are being reported to the Base Station Controller (BSC) by BTS. Different counters (CT) are triggered against different particular events that happen[9].

The Drive Test (DT) method for radio network optimization is based on field trials and surveys to depict the radio network performance in different locations that it covers. During DT, Radio Network Optimization (RNO) teams use specific drive test equipment supported by Global Positioning System (GPS), Transmission Evaluation and Monitoring System (TEMS) investigation software (TEMS 9.0) or its equivalent, power supply unit, TEMS-enabled test mobile station with data cable and Universal Serial Bus (USB) hub, Laptop and a vehicle to drive around the concerned specific geographic area to check the network performance in that area. The test is carried by driving at very low speed in the area of interest while calls are being placed and monitored by the TEMS mobile station which is integrated with GPS for location updates[10]. Different data such as received signal quality;

received signal strength; GSM radio parameters; neighboring cell information; frequency band and best server list can be obtained with drive test, Interference on Broadcast Control Channel (BCCH) and hopping frequencies can also be monitored, and reasons for call set-up failures can equally be noted during the drive test[10].

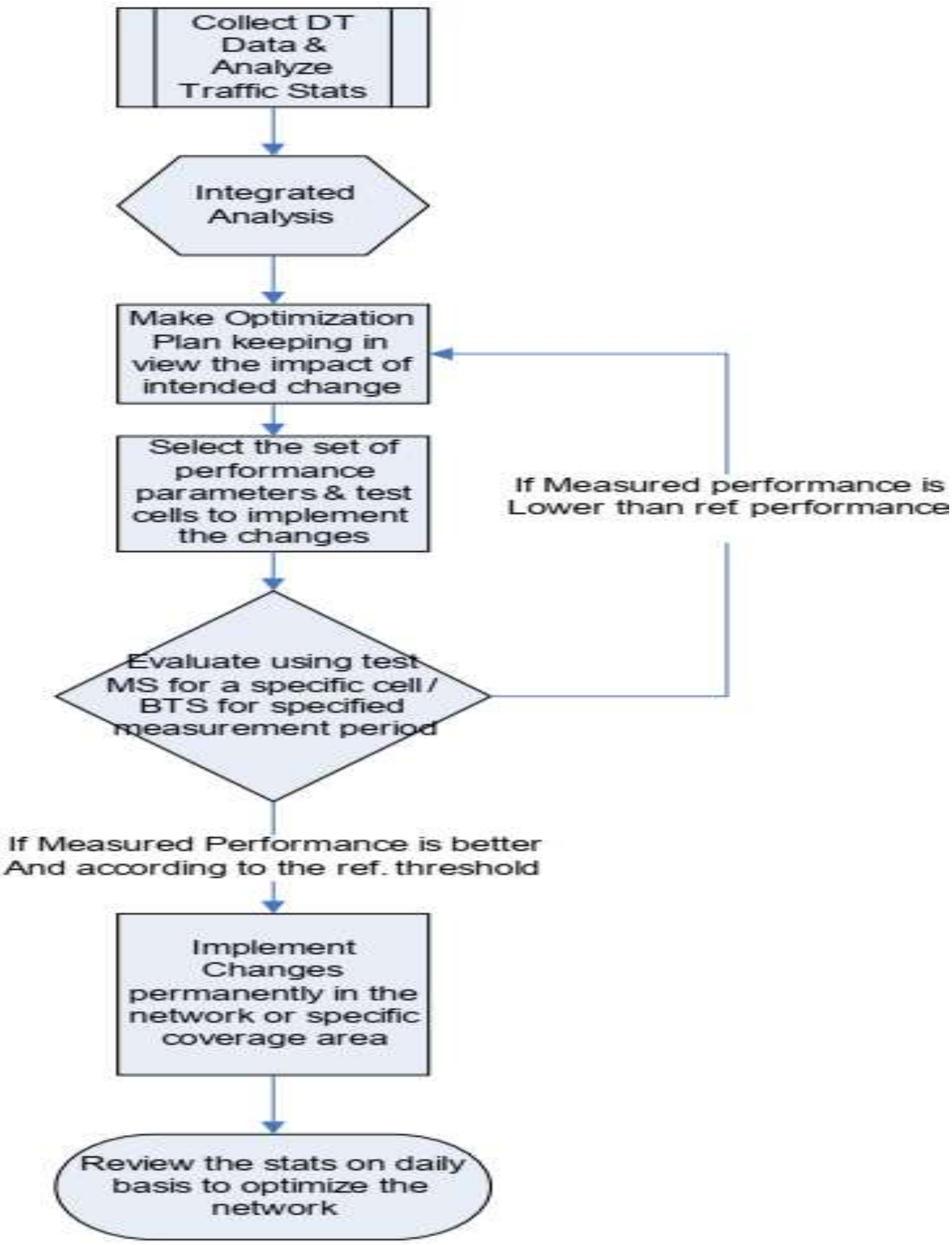

Figure 2-2: Drive Test performance evaluation flow[9].

In order to evaluate the radio network performance, traffic statistics and DT results are first of all analyzed and following that, optimization plan with all the changes to take place, parameter modification for BTS/BSC and physical optimization such as antenna tilt adjustment (both electrical and mechanical tilt angle) is prepared.

The next step after preparing the optimization is to implement it over a cluster of cells and then measure the new performance using test MS for a specific period of time. The obtained results after changes were applied are then compared with the reference threshold values and if they are found to be satisfactory, the proposed changes are approved and final implementation is done over that cluster of cells[9]. The whole process is summarized in Figure 2-2 above.

2.2 Railway radio network planning literature

Railway communication technologies undergo a revolutionary change bringing them from the analogue to the digital era. A signaling system is commonly understood to be the system that manages and safely controls train movements. In principle, train movements are managed using the signaling system as the core with many peripheral systems integrated into its functionality to truly manage and control a railway operation. Modern operations require more than just a simple, singular system that gives a train driver authority to move a train into a protected track section, hence the concept of a Rail Management and Train Control System. Modern requirements are directed towards a higher level of safe operations including the automation of certain controls in the locomotive and the provision of information for management and customers alike. This involves having a signaling system or compilation of systems, integrated through a telecommunication system with other supervisory and information management systems[11].

Today, different incompatible railway analogue radio systems, classical track-side signs and legacy in-cab signaling systems are being replaced by The European Rail Traffic Management System (ERTMS) which serves as an integrated comprehensive solution to compatibility of railway systems [12]. In order to ensure that train operation control system work efficiently, maintaining a reliable communication link between the train and the ground, dedicated mobile communications play a key role. One of such a communication system is called the global system for mobile communications for railway (GSM-R), a narrow-band communication system[13].

GSM-R is a standard communication platform for railways. It is a strategic communication system which has been established to assure the interoperability between European railway infrastructures but it has also been adopted by many other countries around the world such as china as a standard for railway communication system[14]. The history of GSM-R started in 1995 when UIC (Union Internationale des Chemins de fer / International Union of Railways) selected GSM as the most suitable platform for railway communications. Its specifications work started at that time and in 2000, EIRENE released GSM-R specifications [15]. GSM-R is derived from public GSM and is dedicated to railway application. Therefore, GSM-R has similar characteristics to those of public GSM system. GSM-R functionality is built on standards and recommendations supported by mainly two organizations, ETSI (European Telecommunications Standards Institute) and UIC [14].

GSM-R has been customized to provide different range of managerial services to meet railway needs such as Train control systems (Signaling information, ETCS level 2, Train authorities, Caution- and train orders, Support for safe working systems and data.), Passenger services (Seat reservations, Ticketing (SMS), Passenger information, Public address systems), Security surveillance services (CCTV, Local and remote monitoring, Tracing, Alarm notifications), Telemetry Services (Fleet management, Crewing, Vehicle & object tracking, Status monitoring, Accident alarming), Maintenance data services (Train status, Fault information, Diagnostics (hot wheel), Passenger counting), Trip information services (Distance / time since last overhaul, Freight status (e.g. temperature monitoring), Estimated time of arrival, Cargo tracking) and last but not least Text messages service both operational and non-operational[15].

Different functional services are available in GSM-R, to cite a few such as voice group call, Voice Broadcast Service, functional addressing, location dependent addressing, enhanced multilevel priority and pre-emption, train control safety data transmission, and dispatching non-safety data transmission service[16][17].

Some works have been published which talks about GSM-R network planning and dimensioning. Even though most of them are based on case studies, they come up with some considerations which can be applied anywhere else for Rail network design. In [18], some aspects of GSM-R Radio network planning and dimensioning have been discussed with emphasis on parameters to be taken into account for individual base stations useful range of coverage. Those parameters are: The required minimum signal level and the probability of signal coverage, the height of the suspension of the base station antenna and the antenna mobile station, Margin call transfer (handover) and power margin for dropouts, Margin of safety, Losses in the radio channel, Gain antennas and a gain resulting from the use of spatial diversity reception and polarization (diversity), The expected ranges of base stations and Planning of radio channels[18].

In network dimensioning, for the purpose of determining the volume of telecommunications traffic, they have taken into account the classification of the main sources of traffic resulting from those distinguished by EIRENE uses of GSM-R network in relation to a typical modern rail network. Those identified sources are: Control and Monitoring, Connectivity Technology, Local connectivity on the pathways and nodes, Communication Area non-operational, and Connectivity passenger in the passenger information. Finally, they determined the network capacity due to characteristics of the movement and its intensity. Various scenarios taken into considerations includes: Railway network nodes in terms of their size, Train stations, Number of shunting locomotives, the number of employees in teams maneuvering and other users in the areas of maneuvering and Railway lines of distinction on railway lines with high traffic and railway lines with little traffic[18].

Cellular network parameters and deployment technology considerably depend on area relief, foliage and building density[19]. Valentin I. Popov and Andrei J. Baranovskii summarized the stages of GSM-R Cellular communication network planning in the following ascending order: Spectrum allocation, Development of frequency reuse plan, Operational planning, Designing of even serviced radio coverage, Numerical calculation of network traffic throughput and finally come Capacity and Reliability analysis[19].

In their work, Corneliu Mihail ALEXANDRESCU and Lăcrămioara-Mihaela NEMŢOI described in detail a radio planning procedure for the design of a railway radio communications network based on GSM-R, compliant with all the mandatory requirements specified by the International Union of Railways (UIC)[20]. They provide clear information on why and how to manipulate the digital cartography dataset to accurately represent the railway infrastructure, and eventually providing all the cell and frequency planning deliverables required to dimension a GSM-R network that covers the Bucuresti – Constanţa railway corridor (225 km)[20].

In their research conducted using ICS Telecom software, the first important data which played a big role in the design is the digital cartography of the railway route. This map provides information such as Terrain elevation data, Radio clutter data which gives information about terrain occupancy and Vector data which is digitization of railway infrastructure, represented as vector lines and polygons – highly relevant in the prospective radio planning. With all this information, it was easy to determine the locations for Base Transceiver Stations (BTSs) and Terminal Stations which helped in analytical point-to-point radio propagation models to be used for the detailed radio design of the GSM-R network coverage[20].

Parameters used in the network coverage design had to comply with European Integrated Radio Enhanced Network (EIRENE) System requirements Specifications, that is to mean a coverage probability of at least 95% in each location interval (length: 100m) with a coverage level of -95dBm on lines with ETCS Levels 2/3 for speeds lower than or equal to 220Km/h, taking into consideration a maximum loss of 3dB between Transmitter antenna and receiver and an additional margin of 3 dB for other factors such as ageing. Two types of propagation models were used, namely free space attenuation and Propagation by diffraction. The design was completed with an interference analysis which found that 1.3% from the desired service area is subject to interference which is so small to be negligible and the highest interference percentage for one sector is 0.56%, again negligible from the radio planning perspective. The design wasn't meant for railways running through mountainous terrain as well as for railway tunnels environment and the future was to refine the radio planning procedures to meet the needs of those particular railway sections[20].

Radio propagation models play an important role to estimate the number of required base stations and their positions to provide coverage over the area of interest. Two types of propagation environments exist, namely indoor environment and outdoor environments. Many radio propagation models exist nowadays for indoor and outdoor environments and have been integrated in commercial radio planning tools to ease radio planning process for engineers but very few models cater for radio propagation in tunnels [21]. The indoor propagation model takes into account not only the free space propagation losses but also additional radio signal degradation caused by absorption and multipath propagation[22].

The propagation environment of tunnels is different from the outdoor environment due to its unique properties such as interior walls poor smoothness, long limited space and the bounding of tunnel walls. These characteristics cause the propagation of signals in tunnels to be quite different from those of other rail line scenarios. Besides that, railway tunnels length can be several hundreds of meters to several kilometers and have different shapes such as circular and rectangular sections[23].

Basically, two techniques can be used to calculate the propagation inside a tunnel: Modal analysis and Ray-optical modelling. Modal analysis is used in straight tunnels, and ray tracing is used only to calculate extra attenuation in curves and in the entrance and exit of the tunnel[24]. Reflections, diffractions, and scattering are the main scenarios which affects radio waves propagation inside tunnels. Radio signal propagation inside tunnel is also affected by different parameters such as internal electromagnetic (EM) properties of tunnel walls, tunnel shape, tunnel size, surface roughness, and antenna radiation and position [23]. To reduce signal attenuation, it is wise to use antennas with suitable radiation pattern at appropriate locations. Two types of antennas can be used depending on the conditions in the tunnel, and these are omnidirectional antennas which offer better signal coverage in No Line Of Sight (NLOS) tunnel regions and directional antennas which perform better in Line Of Sight (LOS) regions[21].

In their research paper, Lăcrămioara Mihaela Nemţoi and colleagues described in detail an entirely original radio design procedure suitable to calculate and optimize the radio coverage of GSM-R systems inside arbitrary shaped railway tunnels. Their findings were that a straight tunnel section of average length (around 430m) can be covered successfully with a GSM-R base station or repeater antenna, placed in the proximity of the tunnel portal. The effect of the reflections on tunnel walls was found to be negligible as the direct Line Of Sight (LOS) radio coverage is much larger than the strength of reflected signals. The situation is however different for the case of a curved tunnel section. In this case, the reflections of the radio signals on tunnel walls have a very significant effect. The radio coverage is extended beyond the direct line of sight zone along the tunnel[22].

Lei Zhang and his colleagues carried a study about Broadband Radio Communications in Subway station and Tunnels. Two different frequencies were used to measure best location for the BTS antenna in tunnels for efficient coverage, namely 1000MHz which is near to frequency band of GSM-R and 2450MHz. Their findings where that the ideal location for the Base Transceiver Station is inside the tunnel and close to the entrance of the subway station for network planning[25]. These findings can been tested to check their applicability in GSM-R radio network coverage in tunnels which most of the time uses radiating cables.

3 CHAPTER THREE: ISAKA – KIGALI ROUTE DESCRIPTION

3.1 Background

Currently, Rwanda has no railway network. However, the country is working in partnership with other countries of the region to own a railway network. The railway network will contribute in lightening the country's landlocked status, thus leading to a significant reduction of transport costs[26]. For that, Isaka-Kigali Standard Gauge Railway (SGR) aimed at reducing logistics costs, boost trade and ease the movement of people has been planned which will connect Rwanda's capital city Kigali to Dar-Es-Salaam sea port[27].

Figure 3-1: Isaka to Kigali railway - general corridor alignment

3.2 Isaka-Kigali Railway line design

The Isaka-Kigali railway line which will connect Rwanda to Tanzania is an extension of the standard gauge railway (SGR) line between Dar es Salaam and Isaka which is divided into four sections with the extension into Rwanda from Isaka seen to be section 5.

The four sections are:

- Section 1 - Dar es Salaam to Morogoro.
- Section 2 - Morogoro to Makutupora.
- Section 3 - Makutupora to Tabora.
- Section 4 - Tabora to Isaka.

This railway line design is Single line track route of 470 km from Isaka to Kigali Passenger Terminal, 35t/axle loading electrified line with 14 passing loops spaced along the single line route with an additional 55 km of track and it incorporates 14 passenger stations and 3 yards. In the 470 km long railway line, only 130 km will be built on Rwanda's territory with 340 km on Tanzania side. This single track line will be used both by passenger trains with a maximum speed of 160 km/h and freight trains with 120 km/h maximum speed. The design is that the line will be operative 24 hours per day with 20 trains running over it every day.

3.2.1 Passenger stations

The system has been designed as a single line system with infrastructure such as passing loops and passenger stations being located at major Origin-Destination points. Station platforms are designed to eliminate passenger trains occupying the main line during station stops. This design allows for free flow of freight trains without the hindrance of passenger services. Where passenger stations are separate to the freight train passing loops, the passenger train will be accommodated by a 400-m long siding with platform to suit. The line has 14 passenger stations which fall under 3 categories:

- ✓ Major stations;
- ✓ Medium stations;
- ✓ Minor stations

Major and Medium Stations will have a ticket office, waiting room and baggage service. From an operational perspective, the only difference between Major and Medium Stations will be the station size with Major stations also accommodating retail space for commercial purposes. Both will have station times in the train schedule. Unless a station track is present, passengers will entrain and detrain from a platform adjacent to the main track.

Minor Stations will have no station building or staff and passengers will entrain and detrain from a platform adjacent to the main track. The table below shows passenger stations and their types.

Table 3-1: List of Passenger Station Types

STATION NAME	TYPE	COUNTRY	LOCATION
Isaka	Medium station	Tanzania	-
Kahama	Medium station	Tanzania	KM 40 + 500
Masumbwe	Medium station	Tanzania	KM 94 + 000
Ushirombo	Minor station	Tanzania	KM 120 + 950
Runzewe	Minor station	Tanzania	KM 171 + 450
Nyakanazi	Minor station	Tanzania	KM 210 + 225
Lusahunga	Minor station	Tanzania	KM 239 + 600
Muzani	Minor station	Tanzania	KM 280 + 325
Keza	Minor station	Tanzania	KM 310 + 575
Rusumo Border Crossing	Medium station	Tanzania	KM 355 + 500
Butanga	Minor station	Rwanda	KM 399 + 175
Sake	Medium station	Rwanda	KM 428 + 890
Kigali Terminal	Major station	Rwanda	KM 470 + 040
Bugesera Airport Terminal	Medium station	Rwanda	KM 18+000 (branch)

3.2.2 Railway yards

According to Wikipedia, A **rail yard**, **railway yard** or **railroad yard** is a complex series of railroad tracks for storing, sorting, or loading and unloading, railroad cars and locomotives. Railroad yards have many tracks in parallel for keeping rolling stock stored off the mainline, so that they do not obstruct the flow of traffic. Railroad cars are moved around by specially designed yard switchers, a type of locomotive. Cars in a railroad yard may be sorted by numerous categories, including Railroad Company, loaded or unloaded, destination, car type, or whether they need repairs. Railroad yards are normally built where there is a need to store cars while they are not being loaded or unloaded, or are waiting to be assembled into trains [28]. Isaka-Kigali railway line comprises three (3) yards, namely Runzewe yard, Keza yard and Kigali breakup yard.

Runzewe yard located at Km 171 from Isaka will provide crew exchange facilities where train operating crews are relieved by another operating crew. At this facility, the crew exchange will occur on the siding line, which also acts as a passing loop to allow other trains that don't require crew changes to pass by. A small yard will be built at Keza to enable rake swops and refueling for the Kabanga and Kigali trains. Locomotives will also be exchanged between trains destined to Kigali and Kabanga mine to distribute power to mine loaded trains. In addition to the above requirements, the yard will also comprise sanding and refueling facilities for diesel mine trains.

Kigali breakup yard will be used to break-up and compile the long trains arriving and departing from Kigali Logistics Platform. It is located between KM 438 + 500 and KM 442 + 000. This area has been found to be geometrically suitable for accommodating the long freight trains, together with a small facility for rolling stock maintenance. The yard will support the movement and compilation of long trains of 2000 m clearance distance. The break-up and compilation lines will allow for mid break-up of trains and thus provides turnouts on each line to support the break-up and shunting movements of trains.

3.2.3 Railway passing loops

Passing loops are used for the passing of trains on the single line and allow a location for the longer freight trains to dwell without interfering with passenger train services. Passing loop locations tie-up with the location of passenger stations as defined in Section 3.2.1 of this chapter. However, there are a few instances where passing loops for freight trains are not linked with passenger stations. In these cases, a short siding for passenger trains will be provided independently.

3.3 Geotechnical evaluation of conditions of Isaka-Kigali Railway line

One of the most important factors to take into account while designing and planning a radio network is geotechnical conditions of the place where to deploy the radio network. This takes into account the relief, vegetation and other elements which may affect radio waves propagation. The Geotechnical conditions of Isaka-Kigali railway line are summarized in Table 3-2 and Table 3-3 below.

Table 3-2: Geotechnical evaluation of conditions in Tanzania

Topography	Geology	Soil Profile	Geotechnical Considerations
Isaka – Kahama (KM 0 to KM 41+700)			
Flat to rolling hills, deep cuts and high fills not expected. Only small watercourses in this section.	Granite, expected to vary from outcrops to deeply weathered in floodplain areas.	Topsoil, lateritic soil (residual granite), which is expected to be granular material.	• Generally shallow to moderate cut and fills with good founding conditions. • In situ soil material expected to be suitable for bulk fill and some rail layer works. • Clayey soils expected in floodplain areas, which can become soft and require replacement with granular pioneer layer. • Crossing of water courses expected possible with culverts or bridges. • Residual granite and granite bedrock are expected to be suitable sources of bulk fills and some rail layer works.
Kahama –Uyovu (KM 41+700 to KM 194+000)			
Rolling hills topography with more prominent watercourses	Granite, expected to vary from outcrops to deeply weathered in floodplain areas.	Topsoil, lateritic soil (residual granite), which is expected to be granular material.	• Generally shallow to moderate cut and fills with good founding conditions. • In situ soil material expected to be suitable for bulk fill and some rail layer works. • Clayey soils expected in floodplain areas, which can become soft and require replacement with granular pioneer layer. • Crossing of water courses expected possible with culverts or bridges. • Residual granite and granite bedrock are expected to be suitable sources of bulk fills and some rail layer works.

Uyovu – Rusumo (KM 194+000 to KM 356+500)			
Flat and rolling hills topography to KM 246+300, thereafter the topography is hilly and mountainous to KM 268+500 and between KM 286+500 and KM 356+000. Prominent watercourses are present in the mountainous areas.	Soft schistose metamorphic formations expected at an average depth of 3m. Shallow bedrock and outcrops are expected in the mountainous areas identified above. The sections between KM 246+300 and KM 268+500 as well as between KM 286+500 and KM 303+500 are in major fault zones, with expected foliated and jointed bedrock. This will hinder tunnelling operations and necessitate flatter cut angles to ensure stability of excavations.	The soil horizons are expected to comprise topsoil and lateritic soil (residual schist), which can be a predominantly cohesive (clayey) material. It is reported that the soil horizons are generally expected to a depth of 3m.	• The depth of cut and height of fills are expected to vary from shallow to deep/high. Variable founding conditions can also be expected, depending on the degree of weathering in the schist bedrock. • The schist bedrock is expected to weather to predominantly silty clayey soil horizons with high mica contents. The transported and weathered soil materials are therefore not expected to be suitable for bulk fill and rail layer works. • The topography of the section is classified as that of a young landscape with deep river valleys and narrow floodplains. • Residual schist bedrock is expected to be fine grained (silt or clay) and therefore not to be suitable sources of bulk fills and rail layer works. • Crossing of water courses expected possible with bridges. • Very deep cuttings (up to a depth of 30 m) and a potential tunnel (70 m below ground level at KM 265) are expected on the major fault zones identified between KM 246+300 and KM 268+500 as well as between KM 286+500 and KM 303+500. The expected foliated and jointed bedrock will hinder tunneling operations and necessitate flatter cut angles to ensure stability of excavations. • The potential tunnels at KM 335 (depth 72 m below ground level) and KM 353 (depth 115 m below ground level) will be constructed in schistose metamorphic formations, which will necessitate temporary support for the drill and blast operations as well as a permanent lining.

Table 3-3: Geotechnical evaluation of conditions in Rwanda

Topography	Geology	Soil Profile	Geotechnical Considerations
Rusumo - Kirehe (KM 356+000 to KM 393+500)			
The topography is hilly and mountainous with prominent watercourses.	Soft schistose metamorphic formations schist, as well as phyllite and slate capped with laterites expected at an average depth of 5m. The presence of quartzite bands is also reported in the geotechnical report. Shallow bedrock and outcrops are expected in the mountainous areas. A fault zone is indicated on the geological maps from KM383 to KM 389.	Topsoil, lateritic soil (residual schist), which can be a predominantly cohesive (clayey) material, is expected. It is reported that the soil horizons are generally expected to a depth of 5 m.	• The depth of cut and height of fills are expected to vary from shallow to deep/high. Variable founding conditions can also be expected, depending on the degree of weathering in the bedrock. • The schist bedrock is expected to weather to predominantly silty clayey soil horizons with high mica contents. The transported and weathered soil materials are therefore not expected to be suitable for bulk fill and rail layer works. • The topography of the section is classified as that of a young landscape with deep river valleys and narrow floodplains. • Crossing of water courses will require construction of high fills and bridges. • Residual schist bedrock is expected to be fine grained (silt or clay) and therefore not to be suitable sources of bulk fills and rail layer works. • Very deep cuttings (up to a depth of 30 m) are expected in the fault zones identified between KM383 to KM 389. The expected foliated and jointed bedrock will necessitate flatter cut angles to ensure stability of excavations. • The potential tunnel at KM 392 (depth 63 m below ground level) will be constructed in schistose metamorphic formations, which will necessitate temporary support for the drill and blast operations as well as a permanent lining. Difficult tunneling conditions can be expected.

Kirehe –Bugoma (KM 393+500 to KM 415+000)			
Hilly topography with prominent watercourses	Quartzite, whist is expected to vary from outcrops to deeply weathered in floodplain areas.	Topsoil, lateritic soil (residual quartzite), which is expected to be granular material.	• Generally moderate to high cut and fills with good founding conditions • In situ soil material expected to be suitable for bulk fill and some rail layer works • Major river crossings, entailing high abutment fills and bridges are expected. • Residual quartzite and quartzite bedrock are expected to be suitable sources of bulk fills and some rail layer works.
Bugoma – Sake (KM 415+000 to KM 423+000)			
The topography is flat to rolling hills.	Soft schistose metamorphic formations as well as phyllite and slate capped with laterites expected at an average depth of 5m.	Topsoil, lateritic soil (residual schist), which can be a predominantly cohesive (clayey) material, is expected. It is reported that the soil horizons are generally expected to a depth of 5 m.	• The depth of cut and height of fills are expected to vary from shallow to deep/high. Variable founding conditions can also be expected, depending on the degree of weathering in the bedrock. • The schist bedrock is expected to weather to predominantly silty clayey soil horizons with high mica contents. The transported and weathered soil materials are therefore not expected to be suitable for bulk fill and rail layer works. • Crossing of water courses will require construction of high fills and bridges. Soil replacement with a rockfill pioneer layer may be required for fills and abutments constructed on soft and saturated clayey soil at the bridges. • Residual schist bedrock is expected to be fine grained (silt or clay) and therefore not to be suitable sources of bulk fills and rail layer works.

Sake – Mugesera Lake (KM 423+000 to KM 441+700)			
Flat to rolling hills, deep cuts and high fills not expected. Only small watercourses in this section.	Granite, expected to vary from outcrops to deeply weathered close to floodplain areas.	Topsoil, lateritic soil (residual granite), which is expected to be granular material.	• Generally shallow cut and fills with good founding conditions • In situ soil material expected to be suitable for bulk fill and some rail layer works • Crossing of water courses expected possible with culverts or small bridges. • Residual granite and granite bedrock are expected to be suitable sources of bulk fills and some rail layer works.
Mugesera Lake – Kigali (KM 441+700 to KM 488+000)			
Flat and rolling hills topography with prominent watercourses.	Schistose metamorphic formations expected.	The soil horizons are expected to comprise topsoil and lateritic soil (residual schist), which can be a predominantly cohesive (clayey) material. It is reported that the soil horizons are expected to a depth of 20m.	• The depth of cut and height of fills are expected to vary from shallow to deep/high. Variable founding conditions can also be expected, depending on the degree of weathering in the schist bedrock. • The schist bedrock is expected to weather to predominantly silty clayey soil horizons with high mica contents. The transported and weathered soil materials are therefore not expected to be suitable for bulk fill and rail layer works. • Several wetlands are present, such as the main Akagera/Nyabarongo wetland. The wetland crossings vary from a few hundred meters to 2 km. Soil replacement with a rockfill pioneer layer may be required for fills and abutments constructed on soft and saturated clayey soil in the wetlands. • Crossing of water courses expected possible with bridges. • Residual schist bedrock is expected to be fine grained (silt or clay) and therefore not to be suitable sources of bulk fills and rail layer works.

4 CHAPTER FOUR: ISAKA – KIGALI RAILWAY LINE GSM-R RADIO NETWORK PLANNING AND DIMENSIONING

The objective of the radio network planning and dimensioning activity is to estimate the number of sites required to provide coverage and capacity for the target service areas and forecasted subscribers[29]. This chapter deals in detail with the GSM-R radio network planning and dimensioning for ISAKA-KIGALI railway line.

4.1 Introduction about GSM-R

Global System for Mobile communications-Railway (GSM-R) is one of the dominant railway communication systems in use today. It is the first mobile communication standard designed specifically for railways[30][31]. It has been developed based on the standard cellular communication telephone system of GSM to offer two particular types of communication in railways, namely: Train to Trackside equipment communication designed for ETCS Level 2 and ETCS Level 3 and Voice communication for the driver which incorporates features designed specifically for Railways.

Even though GSM-R was designed based on the standard GSM, it is worth noting that it doesn't provide any direct GSM service to train passengers. This means that passenger cell phones can't detect and neither connects to the GSM-R network as they don't operate in the same frequency spectrum with GSM-R.

4.1.1 Why to choose GSM-R

The choice of GSM-R to be at the heart of railway communication and control system is due to many advantages it presents. Some of the advantages available in GSM-R are listed as follows:

- Numerous applications are supported due to the Integrated Services Digital Network (ISDN) character of the network
- Interoperability between different railway networks has been achieved
- Resources such as radio frequencies, cabling and so on have been used to the maximum level.
- Procurement cost has been reduced remarkably due to the use of only one system and additional market for GSM suppliers.

- Reduction in maintenance cost due to the fact that the logistics and service organization structure is similar everywhere due to use of only one system.
- State-of-the-art for GSM-R technology is open for technical evolution.
- GSM-R has been proven to maintain a reliable communication link between the train and the ground[32].

4.1.2 GSM-R system Architecture

As it was said before, GSM-R system is built on the standard cellular communication system of GSM. That is the reason why the architecture of GSM-R looks the same with GSM architecture except spatial deployment whereby for GSM a large area has to be covered while GSM-R network is only deployed along rail tracks linearly and in some places such as stations where coverage is required as it is shown in Figure 4-1. The following elements are some of the most important elements found in GSM-R architecture:

- Base Station Subsystem composed of Mobile Stations (containing a SIM card, both handheld mobile device and train cab radio) and Base Stations for the radio interface, Base Station Controller to handle allocation of radio resources and handovers [33].
- Network Subsystem composed of Mobile Switching Centres (MSCs) to handle mobility and security, Gateway MSC (GMSC) to interface the GSM-R PLMN with external networks, location and group call registers, Equipment Identification Register and Authentication Centre (AuC) [33].
- The SS7 protocol introduces certain nodes called Signal Transfer Points (STPs) which help in call routing [33].
- Dedicated different types of terminals to fulfil railway operational requirements, e.g. locomotive voice and data cab radios, terminals for standard and specific applications like in rough environment or shunting, specific work stations for dispatcher. Specific equipment to support needed railway applications and services (VAS), e.g. VRS, OTA [33].

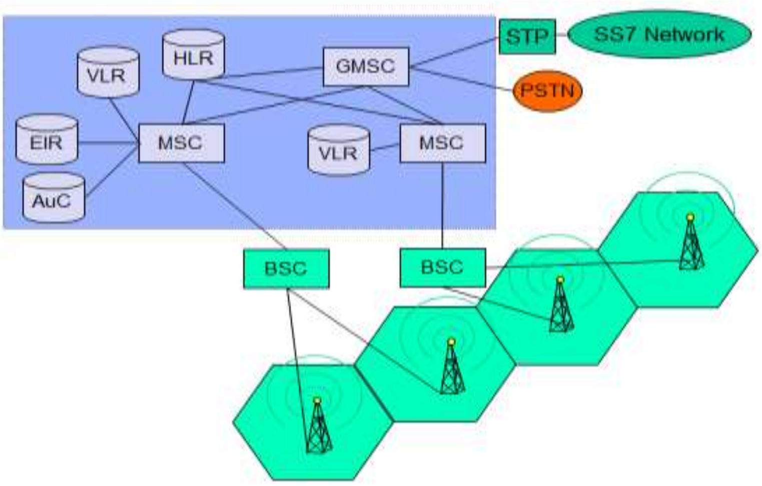

Figure 4-1: GSM-R Radio Network Architecture[33]

With this architecture, a GSM-R network is able to interact with other networks, such as private railway fixed networks, public operator networks, controller equipment, and specialized railway systems (e.g. train control systems)[5].

4.1.3 GSM-R Services

GSM-R services are of two types: Those which have been derived from the normal GSM technology and those which have been designed specifically for railway operations. The available services derived from normal GSM technology are: Voice Group Call Services (VGCS), Voice Broadcast Services (VBS) and Enhanced Multi-Level Precedence and Pre-emption (EMLPP).

Voice Group Call Services (VGCS): VGCS defines a closed user group communication service, where the right to talk can be passed along within the group during a call by using a push-to-talk mechanism as in mobile radio[34].

***Voice Broadcast Services (VBS)*:** It is a broadcast voice call to all trains in service in a pre-defined geographic area which lies wholly or partly within the regional controller's area of responsibility[35] In this service, one person can speak while others are listening.

Enhanced Multi-Level Precedence and Pre-emption (EMLPP): Multi-level Precedence and Pre-emption Service (eMPLPP) allows the priority of different calls to be set. The default level is 4, used for regular point-to-poin calls. The highest level is 0, mainly used for emergency calls. There are higher priority levels (known as A and B); these are reserved for network messages[36].

The available services which have been designed specifically for railway operations are Functional Addressing (FA) and Location Dependent Addressing (LDA).

***Functional Addressing (FA)*:** Functional Addressing is the GSM-R feature that allows calling users by their Functional Number, where Functional Numbers identify both functions and applications. This allows callers to reach the driver of a specific train, or a specific control centre, or anyone else in a specific role, without knowing who fulfils that role at the particular moment[36].

Location Dependent Addressing (LDA): Location dependent addressing (LDA) is an effective and efficient addressing method in GSM-R (GSM for railways), which needs information on the location of the mobile station in order to forward the call to the correct called party[37].

4.2 Isaka-Kigali GSM-R Radio Network Capacity Planning

Radio network capacity planning deals with calculating an estimate of telecommunication traffic that a radio network will have to carry. Telecommunication traffic intensity is expressed in Erlang (E), after the Danish mathematician who embarked on the study about how to use a limited number of servers and accommodate a large population. One Erlang denotes the amount of traffic intensity carried by a channel that is completely occupied (i.e. 1 call-hour per hour or 1 call-minute per minute) [38]. To calculate the traffic intensity generated by every user, we make the product of call request rate and the mean holding time of that call. This is expressed in the following formula:

$$A_u = \lambda \times H \qquad (4\text{-}1)$$

Where H is the average holding time of a call and λ is the average number of call request per unit of time. If the whole radio network contains N users with an unspecified number of channels, the total traffic intensity generated $\mathbf{A_t}$ is given by the following formula:

$$A_t = N \times A_u \qquad (4\text{-}2)$$

In railway radio networks, expected sources of telecommunication traffic are: Control and Monitoring systems such as Automatic Train Control (ATC) and remote control of railway elements which are all data communications and Voice communications such as Voice Group Calls (VGCs), emergency calls, etc. Total offered traffic refers to specific areas and includes traffic generated on the train as a sum of the traffic generated by staff and data transmission systems as well as the movement of the other users of the system, both stationary and mobile, defined as the number of active terminals [18]. For ISAKA-KIGALI railway line, Four particular groups of traffic will be calculated for the total offered traffic, namely Traffic generated by running trains themselves, traffic generated by employees using GSM-R for the control of trains, traffic generated by the signaling and interlocking system and finally traffic generated at major stations and medium stations.

For the entire route of a train, a continuous communication must be kept all over the train's journey for GPS positioning of the train, this means that the train reports at every second its position which makes that an occupied time-slots remains occupied for the whole travel. In the long-term planning of ISAKA-KIGALI railway line, 20 trains are envisioned to be operating on the line every day and rise to 30 in the optimistic case's year, adding extra 5 trains in case demand becomes much more than expected, making a total of 35 trains per day, a total traffic of 35 Erlangs for GPS positioning is already there, 1 Erlang/train.

In other communication events with the trains besides GPS positioning such as remote control of the trains operating, the generated traffic intensity for 35 trains is given by the following formula:

$$A\_tr\ (E) = \left(\frac{Tr\_tot\ X\ \ Call\_ph\ X\ Call\_dur}{3600}\right) \tag{4-3}$$

Where: Tr_tot is the total number of trains (35 trains)

Call_ph is call frequency per hour (35 calls)

Call_dur is the call duration in seconds (30 seconds)

Replacing the above values in equation (4-3) gives a total traffic A_tr (E) = 10.21 Erlangs

As by now the total number of people that will be employed is not known, assuming 600 employees will be employed on ISAKA-KIGALI railway line and are going to use the GSM-R network, the total traffic intensity they will generate is given by:

$$A\_Empr\ (E) = \left(\frac{(600-0)\ X\ \ Call\_ph\ X\ 25}{3600}\right) \tag{4-4}$$

Where: 25 is the average call duration per user (seconds)

0 is the blocking probability

Call_ph is the call frequency per hour = (Tr_tot/24)x(Av_speed/23) with Av_speed being the average speed of freight and passenger trains (140Km/h), Tr_tot the total number of trains per day (35), 23 being average distance between stations (Km) and 24 being 24 hours per day. Therefore, Call_ph = 9.

Replacing Call_ph by its calculated value in equation (4-4) yields a total traffic intensity of A_Empr (E) = 37.5 Erlang.

Regarding the signaling system of ISAKA-KIGALI railway line, a total of 400 objects are expected to be on the line for signaling purpose. The Total traffic intensity they will generate is given by:

$$A\_Sign\ (E) = \left(\frac{(400-0)\ X\ \ Call\_ph\ X\ 15}{3600}\right) \quad (4\text{-}5)$$

Where: 15 is the average call duration per user (seconds)

0 is the blocking probability

Call_ph is the call frequency per hour = (Tr_tot/24)x(Av_speed/23)x(Tr_tot /400) with Av_speed being the average speed of freight and passenger trains (140Km/h), Tr_tot the total number of trains per day (35), 23 being average distance between stations (Km) and 24 being 24 hours per day. Therefore, Call_ph = 1.

Therefore, A_Sign (E) = 1.67 Erlang.

The total data rate in busy hour for this ISAKA-KIGALI railway line will therefore be equal to:

$$\boldsymbol{TDR_{bh}(R)} = 37.5E\ X\ DR_{doc} + 37.5E\ X\ DR_{voi} + 1E\ X\ DR_{s\&a} + 35E\ X\ DR_{GPS} + 10.21E\ X\ DR_{t\&tss}\ [39] \quad (4\text{-}6)$$

Where:

DR_{doc} is the document transfer data rate (9.6kbps)

DRvoi is the voice communication data rate (22.8kbps full duplex)

DRs&a is the signaling and trackside equipment transfer data rate (80bps)

DRgps is the GPS location signaling transfer data rate (0.4 kbps)

DRt&tss is the total data rate of the train and trackside operational communication (373.224kbps)

Replacing all these values in equation (4-6) gives that $TDR_{bh}(R)$ = **5.04Mbps**

This data rate calculated above in equation (4-6) is the total data rate along the route in regards to efficient travel of trains on the route in the busy hour. Next is to calculate the traffic generated by the major station and medium stations. ISAKA-KIGALI Railway line has one major station (Kigali) and six medium stations (Isaka, Kahama, Masumbwe, Rusumo border crossing, Sake and Bugesera Airport Terminal). However, the number of Personnel who will be working at each station and the number of tracks at each station is not known up to now. Therefore we can't calculate the traffic intensity generated at each station and a total margin of **2.5Mbps** for all those stations (Major station and Medium stations) has been estimated, which is reasonable as GSM-R doesn't have huge data rates. From these data rates calculated above, the whole GSM-R network system has to be able to handle a total traffic intensity of **7.54Mbps** in busy hour.

4.3 Isaka-Kigali GSM-R Radio Network Coverage Planning

Radio network planning includes two main parts for it to provide efficient network. Those are Radio network coverage planning and Radio network capacity dimensioning. The main objectives of radio network planning are: To ensure appropriate coverage over the desired area with better service quality and low bit-error-rate, Delivering the desired network capacity with less service blocking, in the case of GSM-R communication, this blocking rate is fixed at 1%, providing a cost-effective network infrastructure by minimizing the number of required sites and transmitters required to satisfy coverage, quality and capacity requirements. These radio network planning objectives are fulfilled by proper selection of site locations and configuration of cell settings and parameters, including antenna models, antenna heights, azimuth and tilt angles, etc.[40]. The network planning process and design criteria vary from region to region depending upon the dominating factor, which could be capacity or coverage[41]. Coverage planning design aims to approximate which part of the area has radio network access reaching the required coverage level and the frequency reuse plan.

4.3.1 GSM-R Spectrum Allocation

GSM-R is a system relying on the definition of the GSM system, and as such, any operating band defined for GSM could also be utilized by GSM-R. GSM is a very robust standard since it is defined for very high blocking performance, and wide dynamic range. Such qualities are keys to deliver a reliable communication, especially in terms of resistance to blocking interferers, or in terms of required carrier over interference ratio which is very low and thus profitable for frequency reuse pattern. Finally GMSK modulation defined for GSM/GSM-R is very robust to system linearity and this allows wide receiver dynamic range[5].

Table 4-1 : Standardized frequency bands for GSM-R[5]

Band	**Uplink**		**Downlink**		**Bandwidth**
GSM 450	450,4 MHz	457,6 MHz	460,4 MHz	467,6 MHz	7,2 MHz
GSM 480	478,8 MHz	486 MHz	488,8 MHz	496 MHz	7,2 MHz
GSM 850	824 MHz	849 MHz	869 MHz	894 MHz	25 MHz
ER-GSM	873 MHz	915 MHz	918 MHz	960 MHz	3 MHz
R-GSM	876 MHz	915 MHz	921 MHz	960 MHz	4 MHz are reserved in Europe for Railways
GSM 900	880 MHz	915 MHz	925 MHz	960 MHz	35 MHz
DCS 1800	1 710 MHz	1 785 MHz	1 805 MHz	1 880 MHz	75 MHz
PCS 1900	1 850 MHz	1 910 MHz	1 930 MHz	1 990 MHz	60 MHz

R-GSM band is a dedicated band to railway operators used throughout Europe and some other countries, has demonstrated its high quality and very good match for railway needs. GSM 450 MHz and 480 MHz bands are not currently used for GSM systems. However such frequencies are also well matching railways needs, and total Radio Frequency (RF) bandwidth is compatible with high traffic conditions[5].

Viewing the fact that GSM 450 MHz and 480 MHz bands are not currently used in Rwanda, and the fact that no analogue systems are deployed in it, it was chosen to be used in this network planning which has advantage of immunity to interference from Public Land Mobile Network (PLMN) which operates in the 900/1800MHz bands.

Besides being less affected by interference from PLMN, The 400 MHz band in comparison with the 900 MHz, also offers the following advantages:

- ✓ There is improvement in link budget which helps in reduction of site cost as the number of required BTSs reduces. All those are a result of lower losses in RF cables;
- ✓ This frequency band has lower propagations losses which is advantageous to either improve range or to deliver a better data rate;
- ✓ Interference level is minimum due the fact that few or no communication systems are deployed in neighbor bands;
- ✓ Lower multipath effects, which provides the possibility to have lower margins for network engineering.

To enable the deployment of GSM400, there was a need also for frequency allocations around 490 MHz, Hence, ETSI has standardized 450 - 467 MHz as a primary band and 479-496 MHz as the extension of GSM400 frequency allocations. The ETSI GSM400 standard covers about 6.8 MHz uplink and 6.8 MHz downlink with 10 MHz duplex spacing in both bands[42].

This table below shows the frequency spectrum assigned to be used on the ISAKA-KIGALI Railway line.

Table 4-2: Route Frequency Band Allocation

Frequency allocation	479.0 – 483.0 MHz uplink
	489.0 – 493.0 MHz downlink
Frequency spectrum	4 MHz
Duplex separation	10 MHz
Carrier spacing	200 KHz
Number of available channels	18 communication channels + 1 guard band channel (100kHz at both ends)

As in normal GSM network, GSM-R radio network carrier frequency channel is 200 KHz. The carrier frequency is designated by its absolute radio frequency channel number (ARFCN) which is found according to the following formula:

$$\begin{cases} Fl = 479.0 + 0.2 \times (n - 306), MHz \\ Fu = Fl + 10, MHz \end{cases} \quad (4\text{-}7)$$

Whereby F_l is used to find carrier frequency in the lower band and $F_u = F_l + 10$ is the corresponding frequency value in the upper band. Here, n is an integer varying in the range $306 \leq n \leq 325$, each pair is referred to as a frequency channel. The first ARFCN is numbered 306 and the last one is numbered 324, their frequency distribution is expressed in this following figure whereby the frequency band we are operating in, which is 480MHz is shown on the right side of the figure.

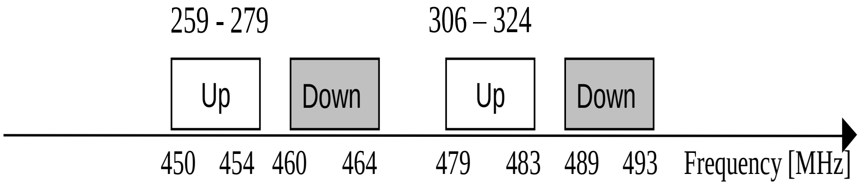

Figure 4-2: MS frequency allocations and channel numbers.

The 259 – 279 ARFCN channels range is for the 450 MHz band made available for deployment of any other railway line which might be needed to build.

4.3.2 GSM-R Multiple Access Technique

As GSM-R was designed based on the standard GSM architecture, its multiple access techniques are quite similar with those used by GSM. The channel structure is based on FDMA/TDMA and 18 channel pairs for normal communications and one guard band channel for uplink and downlink are available to be used on this GSM-R radio network. A TDMA radio carrier frequency channel supports 8 simultaneous users, with the channel data rate being equal to 270.833 kbps.

Two types of logical channels in GSM-R map onto the physical channel, and these are: Control channels used for call setup, power adjustment…etc. and Traffic channels used for voice and data transmission. One carrier frequency is divided into 8 timeslots, whereby 7 time slots are used as traffic channels (TCH) and the remaining 1 timeslot is used for control channel (CCH), and one time slot has the capacity to either transmit 13 kbps half rate and 22.8kbps full rate. This makes it available that the maximum capacity of a BTS using only one carrier frequency, with all timeslots being used at full rate is 8 x 22.8kbps which is equal to **182.4kbps**. As the data rate of a BTS using one carrier frequency channel is supposed to carry 270.833 kbps, and here we find that it can only carry 182.4 kbps with all time slots being used at full rate, this is due to the efficiency of a TDMA frame which is equal to 67.35%.

GSM-R uses a combination of both TDMA and FDMA techniques. The FDMA element involves the division by frequency of the (maximum) 4 MHz bandwidth into 19 carrier frequencies spaced 200 kHz apart as already described. The carriers are then divided in time, using a TDMA scheme. This enables different users of the single radio frequency channel to be allocated different time slots. They are then able to use the same RF channel without mutual interference.

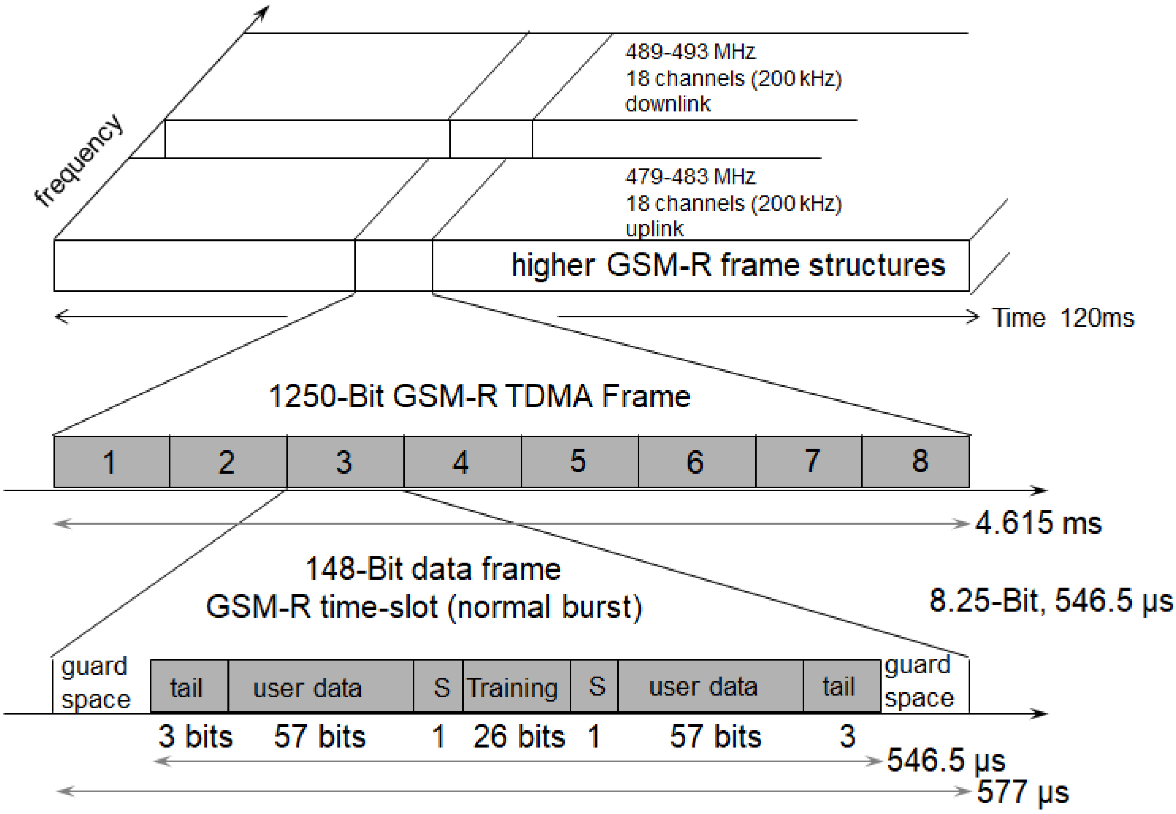

Figure 4-3: GSM-R TDMA/FDMA[43]

The slot is the time that is allocated to the particular user, and the GSM-R burst is the transmission that is made in this time. Each GSM-R slot, and hence each GSM-R burst lasts for 0.577 mS. Eight of these burst periods are grouped into what is known as a TDMA frame. This lasts for approximately 4.615 ms and it forms the basic unit for the definition of logical channels. One physical channel is one burst period allocated in each TDMA frame[44].

4.3.3 Link Budget of Uplink/Downlink Power Balance

Link budget of uplink/downlink power balance refers to estimating the system uplink/downlink coverage capability by reviewing various factors in the path for system uplink/downlink signal propagation, and getting the maximum path loss allowed by the link under the precondition that a certain quality is ensured[45]. Link budget is calculation of all the gains and losses in a transmission system taking into account all the elements that will determine the signal strength arriving at the receiver. Link budget calculations are used for calculating power levels required for radio communication systems, and for investigating the base station coverage[46]. Link budget calculations estimate the maximum allowed signal attenuation, called path loss, between the mobile and the base station antenna. The maximum path loss allows the maximum cell range to be estimated with a suitable propagation model, such as Okumura–Hata[47].

We respectively assess the maximum path losses allowed by uplinks/downlinks, and adopt the lower one as the final maximum path loss, and take this as the path loss in estimating coverage radius. In order to calculate the required link budget, it is necessary to first of all calculate the receiver sensitivity which is the lowest signal strength level which can be detected by the receiver and decoded for normal communication. Receiver sensitivity can be calculated using this formula[45]:

*Sin (dBm) = hot noise power + system noise coeffi*cient + signal to noise ratio (4-8)

Where,

Sin (dBm) is receiver sensitivity

The formula for calculating hot noise power is: 10 x *Log {K*T*(BRF)} (dBm).* (4-9)

● K is Boltzmann constant (W/Hz/K) and it is equal to 1.381 x 10-23 W/Hz/K.

● T is temperature (K). Room temperature is 290K.

● BRF is RF carrier bandwidth (Hz), which is 200,000Hz.

Hot noise power = 10 x log (1.381 x 10^{-23} W/Hz/K x 290K x 200000Hz x 1000mW/W)

= **-121 dBm**

System noise coefficient (NF): When the signal passes the receiver, the receiver adds noise to the signal, and noise coefficient is a method for measuring the added noise. In value, it is equal to input signal to noise ratio divided by output signal to noise ratio. The formula to find the system noise coefficient is:

$$NF = \frac{SNRinput}{SNRoutput} \tag{4-10}$$

It characterizes the degradation degree of the signal to noise ratio (SNR) after signal passes the system, the ideal scenario is the system has no additional noise, and it only amplifies input signal and noise at the same time, and at this time, NF＝1. A value of NF (dB) = 2, is used for the purpose of this project in order to increase the system's internal noise performance.

Signal to Noise ratio $Eb/_{No}$ *(dB)* is the Minimum signal to noise ratio required in demodulation, which characterize the intrinsic characteristic of the modulator. For GMSK modulation used in GSM-R, a signal to noise ratio for BTS should not exceed 9dB, and a value of 9dB has been chosen in this project.

Therefore, the BTS Receiver sensitivity will be equal to: -121+2+9 = -110dB

Table 4-3: ISAKA - KIGALI Railway line GSM-R Link Budget[48]

S/N	Parameter	Uplink	Downlink	Calculation
A	Transmitter power (dBm)	39	45	-
B	Duplexer loss(dB)	0	-1	-
C	Internal jumper loss(dB)	0	-1	-
D	Transmitter filter loss(dB)	0	-1	-
E	Total Transmitter feeder loss (dB)	-2	-3	-
F	Transmitter power splitter loss(dB)	0	-3	-
G	Transmitter antenna gain (dB)	0	17	-
H	**Effective Isotropic Radiated Power (EIRP) (dBm)**	**37**	**53**	A+B+C+D+E+F+G
I	Receiver sensitivity (dBm)	-110	-104	-
J	Total Receiver feeder loss (dB)	-3	-2	-
K	Receiver Duplexer loss (dB)	-3	0	-
L	Receiver antenna gain (dBi)	17	0	-
M	Fade margin (dB)	-3	-3	-
N	Receiver Antenna height (m)	35	4.5	-
O	Minimum permissible received signal level (dBm)	-118	-99	I-(J+K+L+M)
P	**Maximum Allowable Path Loss (dB)**	**155**	**152**	H-O

To obtain the Mobile station (Cab radio / handheld device) receiver sensitivity, the formula used is the same as for BTS and the difference is only on the Signal to noise ratio whereby for the Mobile station, at least 12dB is required. Choosing the signal to noise ratio value of 15dB which is above the minimum required level, the MS receiver sensitivity will be equal to: -121+2+15 = -104dB.

Table 4-3 above is used to calculate the maximum allowable path loss (MAPL) for ISAKA-KIGALI railway line link budget. The Maximum Allowable Path Loss (MAPL) for this line is therefore chosen to be equal to 152 dB from the downlink channel. This means that the BTS range is lesser than the train's cab radio range, therefore no coverage problem is found from train to BTS.

4.3.4 Coverage Level Requirement and Coverage Probability

In order to make efficient radio network coverage planning, coverage level and coverage probability must be defined for the entire or particular part of the network. In Railway networks, coverage level is the measured field signal strength at the antenna on the roof of a train. The antenna height is assumed to be 4m above the track. The train antenna used is an isotropic antenna which means that it radiates and receives signal evenly in all directions and the gain of the train's antenna is set to 0dBi.

4.3.4.1 Minimum Required Coverage Level

The minimum coverage level needs to satisfy Cab radio receiving sensitivity, and usually in the network design it is also necessary to reserve certain margin to offset (compensate) Rayleigh Fading, interference and body loss (In case of the handheld device) in wireless environment. The receiving end needs to reach the minimum level requirement, that is, the minimum level requirement necessary for maintaining normal conversation in a real case[45]. Normally, the minimum required coverage signal level in outdoor environment can be calculated by the following formula:

$$SSmin\_req = MSsen + RFmarg + IFmarg + BL, dB \qquad (4\text{-}11)$$

Where

SSmin_req is the Minimum required Signal level
MSsen is the MS (either be the cab radio or handheld device) receiving sensitivity

RFmarg is the Rayleigh Fast fading margin

IFmarg is the interference margin

BL is the Body loss (0dB for cab radio and 3dB for handheld device)

UIC has set minimum standards to be met by each and every railway company using GSM-R as its basis for communication and train control, whereby for lines using ETCS levels 2/3 must abide with the following minimum standards: a coverage probability of 95% with a coverage level of -95dBm for all trains moving with speeds less than or equal to 220Km/h.

According to the design of ISAKA-KIGALI railway line, Passenger trains will be moving at 160Km/h and freight trains will be moving at 120Km/h, which falls within the above ETCS level 2/3 speed requirements for the specified standards. Hence, the above minimum requirements are to be respected in this design.

4.3.4.2 Design Coverage Level

Besides the various above-mentioned margins, it is also necessary to add additional margins on *SSmin_req* to process the impact of slow fading on coverage probability. In planning, it is necessary to consider these factors and consider coverage level and coverage probability. We call the level value at this time design level, *SSdesign*. The formula to calculate design level in outdoor environment is[45]:

$$SS\ design\ (outdoor) = SSmin\_req(outdoor) + LNFmarg \qquad (4\text{-}12)$$

Where *LNFmarg* is the Log-Normal Fading margin also known as the slow fading margin, *SSdesign* is design signal strength and *SSmin_req* is the minimum signal strength required.

Using this formula to find the designed coverage level, considering a maximum slow fading margin (LNF) loss of 3dB between the BTS antenna and the receiver antenna with also an additional margin of 3dB which represents other factors such ageing of equipment, we find that *SS design (outdoor) = -95dBm +6dB=-89dBm.* The coverage design level for ISAKA-KIGALI Railway line is set to be equal to -89dBm, a signal level below which handover to another cell will be initiated in normal operations if the signal strength from that cell exceeds -89dBm.

4.3.5 Propagation Models

Whenever radio signals are transmitted in space, they are attenuated due to phenomena such as reflection, diffraction, scattering and absorption encountered due to the nature of transmission environment. Propagation models are used extensively in network planning, particularly for conducting feasibility studies and during initial deployment. They are also very useful for performing interference studies as the deployment proceeds[49]. The path-loss prediction models can be roughly divided into three categories. These are the empirical, theoretical, and site-specific models[50].

Different models to estimate path loss have been put in place such as Free-Space Path Loss model which assumes no obstruction between the Transmitter and receiver so that the only attenuation possible is due to free space, which in practical radio transmission rarely happens, Ray-Tracing models which takes into account reflected, diffracted and scattered wave components to estimate the path loss and Empirical Path Loss Models which are usually a set of equations derived from extensive field measurements used to calculate path loss in complex propagation environments that cannot be accurately modeled by free-space-path loss or ray tracing[51].

Empirical models can be split into two subcategories namely, time dispersive and non-time dispersive[52]. The former type is designed to provide information relating to the time dispersive characteristics of the channel i.e., the multipath delay spread of the channel [53]. An example of this type is the Stanford University Interim (SUI) channel models developed under the Institute of Electrical and Electronic Engineers (IEEE) 802.16 working group. Examples of non-time dispersive empirical models are Hata [54] and the COST-231 Hata model. All these models predict mean path loss as a function of various parameters, for example distance, antenna heights etc.

Different empirical path loss models are used nowadays, and the most widely used in radio network coverage planning are OKUMURA Model, HATA Model and COST 231 Extension to Hata Model.

4.3.5.1 The Okumura Model

Okumura carried out extensive drive test measurements with range of clutter type, frequency, transmitter height, and transmitter power[55]. The Okumura model is an empirical model which works at several frequencies having the range of 150 MHz to 1920 MHz. It is the most broadly used model in large urban macro cell for signal prediction over distances of 1 km to 100 km and it is extended up to 3000 MHz. The Okumura model takes into account some of the propagation parameters such as the type of environment and the terrain irregularity. The range of base station antenna heights is 30 m to1000 m and a mobile antenna height of 5 m [50]. The basic prediction formula is as follows:

$$L50(dB) = L_{free} + Amu\ (f,d) - G(hte) - G(hre) - Garea \qquad (4\text{-}13)$$

Where L50 is the 50th percentile (i.e., median) value of propagation path loss, L_{free} is the free space propagation loss, Amu is the median attenuation relative to free space, G(hte) is the base station antenna height gain factor, G(hre) is the mobile antenna height gain factor, and *Garea* is the gain due to the type of environment.

For free Space, Path Loss becomes $PL\ (dB) = Gt - Gr + 32.44 + 20\log d + 20\log (f) \qquad (4\text{-}14)$

With Gt being the transmitter antenna gain (17dB), Gr being the receiver antenna gain (0dB), d being the distance between Transmitter and receiver and f is the operating frequency (479 – 493 MHz).

Okumura found that G(hte) varies at a rate of 20 dB/decade and G(hre) varies at a rate of 10 dB/decade for heights less than 3 m[38].

$$G(hte) = 20\log\left(\frac{Hte}{200}\right) \qquad 1000\ m > h_{te} > 30\ m \qquad (4\text{-}15)$$

$$G(hre) = 10\log\left(\frac{hre}{3}\right) \qquad hre < 3m \qquad (4\text{-}16)$$

$$G(hre) = 20\log\left(\frac{hre}{3}\right) \qquad 10\ m > hre > 3m \qquad (4\text{-}17)$$

As the BTS height is equal to 35m, G(hte) = $20\log\left(\frac{30}{200}\right)$ = -16.48dB and for Receiver antenna (Cab radio) being equal to 4.5m, G(hre) is equal to G(hre) = $20\log\left(\frac{4.5}{3}\right)$ = 3.52dB

4.3.5.2 Okumura-Hata Model

Hata's propagation model is the basis for several widely used propagation models in the cellular industry. The main attraction of Hata's model is its simplicity with reasonable accuracy, and its main drawback is its constraints on the ranges of some parameters. Hata's basic model includes path loss for an urban environment and provides correction factors for other environments, such as suburban and open areas. Caution should be exercised while using Hata's model because it is valid only for specific cases. Hata's model makes the following assumptions: path loss is between isotropic antennas and the terrain is quasi-smooth and regular[56]. The median propagation path loss in an urban area is given by:

$$Lp(urban) = 69.55 + 26.16\log_{10} fc - 13.82\log_{10} hb - a(hm) + (44.9 - 6.55\log_{10} hb)\log_{10} R \quad (4\text{-}18)$$

Where *Lp* is the propagation path loss in decibels, *fc* is the carrier frequency in megahertz in the range of 150-1500 MHz, *hb* is the BS effective antenna height in meters in the range of 30-200 m, *R* is the distance between the transmitter and the receiver in kilometers in the range of 1-20 km, the height of mobile antenna (hm) ranges from 1 m to 10 m and *a(hm)* is a correction factor for the mobile station (Cab radio) antenna height based on the size of the coverage area[46], [57].

For a *medium-small city, a(hm)* is given by the following formula:

$$a(hm) = (1.1\log_{10} fc - 0.7)hm - (1.56\log_{10} fc - 0.8) \quad (4\text{-}19)$$

For *fc* in 150-1500 MHz range.

For a *large city*, a(hm) is given by

$$a(hm) = 8.29(\log_{10}(1.54\ hm))^2 - 1.10 \quad \text{for } fc < 200 \text{ MHz} \quad (4\text{-}20)$$

$$a(hm) = 3.2(\log_{10}(11.75\ hm))^2 - 4.97 \quad \text{for } fc > 400 \text{ MHz.} \quad (4\text{-}21)$$

Equations (4-19) to (4-21) can be used to estimate the path loss in an urban environment containing large, medium, or small cities for the parameter ranges specified above.

The path loss in a suburban environment is given by:

$$Lp\ (suburban) = Lp(urban) - Kr \quad \text{with} \quad Kr = 2\,[\log_{10} (f_c/28)]^2 + 5.4 \quad (4\text{-}22)$$

In Equation *(4-22)*, *Kr* is the correction factor for the suburban environment relative to the urban environment and *fc* is the carrier frequency expressed in megahertz.

The path loss for rural flat open areas is given by:

$$Lp\ (Open) = Lp(urban) - Qr \quad (4\text{-}23)$$

$$\text{With } Qr = 4.78\,[\log_{10} (f_c)]^2 - 18.33\,\log10(f_c) + 40.94 \quad (4\text{-}24)$$

In Eq. (4-23) Qr is the correction factor for the rural flat open areas relative to the urban environment and fc is the carrier frequency expressed in megahertz. *For rural semi-flat and open areas*, $Qr = 4.78\,[\log_{10}(f_c)]^2 - 18.33\log10(f_c) + 35.94$ *(4-25)*

Hata model is not suitable for micro-cell planning where antenna is below roof height and its maximum carrier frequency is 1500MHz. It is not valid for 1800 MHz and 1900 MHz systems[58].

4.3.5.3 COST 231 Model

The COST 231 model, sometimes called the Hata model PCS extension, is an enhanced version of the Hata model that includes 1800–1900MHz. While the Okumura model extends to 1920MHz, the Hata model is only valid from 150 to 1500MHz. The COST 231 model is valid between 1500 and 2000MHz. The coverage for the COST 231 model is [59]:

Frequency: 1500–2000MHz
Transmitter (base station) effective antenna height, *hte*: 30–200m
Receiver (mobile) effective antenna height, *hre*: 1–10m
Link distance, *d*: 1–20km

The COST 231 median path loss is given by:

$$L_{50}(dB) = 46.3 + 33.9\log(f_c) - 13.82\log(h_t) - a(h_r) + [44.9 - 6.55\log(h_t)]\log(d) + C \quad (4\text{-}26)$$

where
fc is the frequency in MHz
ht is the base station height in meters
hr is the mobile station height in meters
a(*hr*) is the mobile antenna height correction factor defined earlier
d is the link distance in km
C = 0dB for medium cities or suburban centers with medium tree density
C = 3dB for metropolitan centers

The COST 231 model is restricted to applications where the base station antenna is above the adjacent roof tops. Hata and COST 231 are central to most commercial RF planning tools for mobile telephony[59].

4.3.6 Propagation Model Selection

The propagation path loss model selection plays a very important role in radio network planning as it is used to estimate up to which distance the transmitter can provide radio coverage meeting the required signal strength level. Comparing the output of simulation of path loss of the above three discussed empirical path loss models; it is observed that Okumura-Hata models is the one with high path loss level as seen in Figure 4-4 below.

A propagation model with lowest path loss results in longer distance signal coverage from the transmitter while the propagation model with highest path loss results in shorter distance signal coverage.

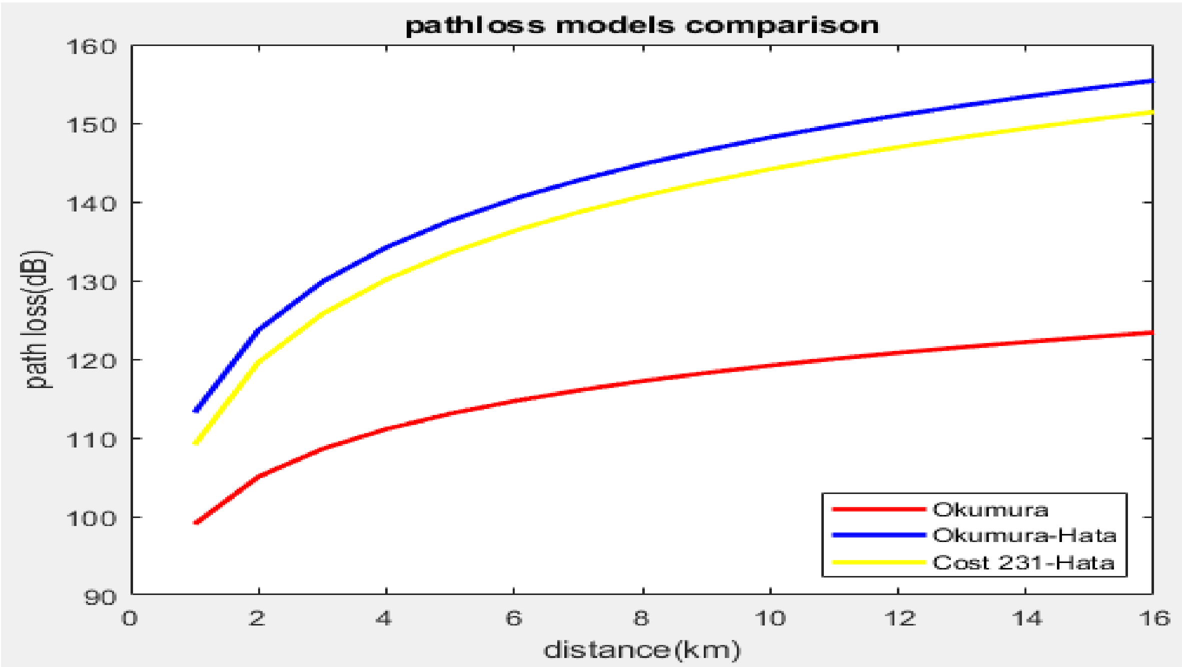

Figure 4-4: Path loss models comparison

In this project, Okumura-Hata model has been chosen to be used even though it provides shorter distance coverage (Cell radius) because when you are planning cellular coverage, it is better to consider the worst case scenario of coverage instead of contenting yourself with the propagation model with lowest path loss estimated while it may lead to insufficient coverage which is very bad in railway communication systems as it might endanger the life of the personnel onboard when an accident happens due to poor coverage.

4.3.7 Cell Radius Calculation

After finding the Maximum Allowable Path loss and selecting an appropriate propagation model to be adopted, the next step is calculating the estimated cell radius. Having the cell radius allows us to estimate the number of Base stations required to cover the entire railway line as well as planning handover distances between adjacent cells. Cell radius can be deducted from the following formula:

$$MAPL = C_1 + C_2 logd + C_3 Hm + C_4 logHm + C_5 logHb + C_6 logHbLogd + C_7 * diffraction + clutterLoss \quad (4\text{-}27)$$

Whereby Cs represent different parameters of the selected path loss model. Hm is the mobile station height and Hb is the base station antenna height. To find the radius of the cell, we simply do an inverse calculation of d which is the estimated distance between the transmitter and the moving train, as MAPL is already known and Cs parameters known. However, when we apply equation (4-27), we find the maximum distance from base station whereby the signal is too weak below the Minimum permissible received signal level for the Mobile station (Cab radio / handheld devices) which is far below the minimum standard required coverage signal level. Therefore, we will define cell radius based on the standard minimum required signal coverage level (-95dBm) and hence define cell radius as the distance from base station where the path loss equals the minimum received signal level (MRSL)[60].

In this project, Okumura-Hata propagation model has been selected and from it we will deduce the cell radius for ISAKA-KIGALI Railway line. Looking on the route of ISAKA-KIGALI railway line, suburban, rural, hilly, semi-hilly and flat topographical areas have been identified along the route. This route has been classified into three distinctive geographic coverage areas: Suburban areas, rural semi-flat and open areas and rural open areas.

The maximum radius distance of a BTS according to the required minimum received signal strength (MRSL) by UIC is given by the following formulas:

$$MRSL = EIRP - \{69.55 + 26.16\log_{10} fc - 13.82\log_{10}hb - a(hm) + (44.9 - 6.55\log_{10}hb)\log_{10}\mathbf{Rsu} - 2\,[\log_{10}(f_c/28)]^2 - 5.4\} \quad (4\text{-}28)$$

$$MRSL = EIRP - \{69.55 + 26.16\log_{10} fc - 13.82\log_{10}hb - a(hm) + (44.9 - 6.55\log_{10}hb)\log_{10}\mathbf{Rrso} - 4.78\,[\log_{10}(f_c)]^2 + 18.33\,\log10(f_c) - 35.94\} \quad (4\text{-}29)$$

$$MRSL = EIRP - \{69.55 + 26.16\log_{10} fc - 13.82\log_{10}hb - a(hm) + (44.9 - 6.55\log_{10}hb)\log_{10}\mathbf{Rro} - 4.78 [\log_{10} (f_c)]^2 + 18.33 \log10(f_c) - 40.94\} \quad (4\text{-}30)$$

With $a(hm) = 3.2(\log_{10}(11.75\ hm))^2 - 4.97$ for $fc > 400$ MHz. (4-31)

MRSL: Minimum Received Signal Level according to the standard -95dBm

EIRP: Effective Isotropic Radiated Power (37dBm of Uplink as the link budget is uplink limited)

Hb: Base station antenna height (35m)

Rsu: Suburban cell radius distance (Km)

Rrso: rural semi-flat and open areas cell radius distance (Km)

Rro: rural flat open areas cell radius distance (Km)

Taking $fc = 479MHz$

$a(hm) = 3.2(\log_{10}(11.75X4.5))^2 - 4.97 = 4.53$

From equations *(4-28)*, (4-29), (4-30) and (4-31) we can deduce that:

Suburban cell radius distance **(Rsu)** is equal to **5.75Km**

Rural semi-flat and open areas cell radius distance **(Rrso)** is equal to **13.5Km**

Rural flat open areas cell radius distance **(Rro)** is equal to **18.6Km**

Here below is a table showing the classification of regions falling under Suburban, Rural semi-flat and open areas, and Rural flat open areas.

Table 4-4: Region classification according to BTS cell radius

Suburban region	**Rural semi-flat and open areas**	**Rural flat open areas**
Isaka (Km 0 – Km 6+000)	Bukombe kombe –Sake (Km 133+500 – Km 424+500)	Isaka –Kahama (Km 6 – Km 37+500)
Kahama (Km 37+500 to Km 42+000)	Sake-Gitaraga (Km 432+500 – Km 464+500)	Kahama – Marongwe (Km 42+500 – Km 91+000)
Marongwe (Km 91+500 – Km 97+000)	-	Marongwe – Bukombe kombe(Km 97+000 – Km 128+500)
Bukombe kombe (Km 128+500 – Km 133+500)	-	Sake (Km 424+500 – Km 432+500)
Gitaraga – Kigali (Km 464+500 – Km 470+968)	-	-

4.3.8 BTS Number Estimation

One of the most important cellular network planning activities is to select the best site locations that form the basis of a network that must satisfy certain network requirements such as high area coverage and high traffic capacity but that minimize infrastructure cost[61].

As we come to obtain different cell radiuses depending on the population and geography of the location where the railway line passes, the next step would be estimating the number of base transceiver stations (BTS) required to cover the entire line. However, GSM-R cell planning in railway line is a bit complicated compared to normal GSM. With normal GSM, to estimate the coverage of BTSs, having its radius, we can calculate the coverage area of one BTS and knowing the total area to be covered, dividing it with the coverage of one BTS, the total number of BTSs is obtained. This is not the case with Railways as coverage is only along a line following the tracks. However, as the total data rate capacity is already obtained from section 4.2 of this chapter where total data rate capacity was obtained to be equal to 7.54 Mbps, and also knowing the total data rate of a BTS running with all timeslots occupied at full rate which is equal to 182.4 Kbps, we can find the minimum number of BTSs required to carry the 7.54 Mbps by dividing this total data rate of the whole line with the data rate of one BTS, which gives us that the minimum number of BTS required is 41BTSs. The maximum number of BTSs required providing coverage meeting required standards and the best location for BTSs can only be obtained after network coverage simulation in software tool which will be done when the simulation of network coverage is done in the next chapter and it is where the maximum number of BTSs will be obtained.

4.3.9 Handover process for Isaka-Kigali GSM-R radio network

When a train is running on the rail, the received signal strength from the serving base station of the cell in which it is starts decreasing according to the distance traveled away from the base station. As soon as the train starts approaching the next cell, the received signal from that cell starts increasing and becomes greater than the previous signal. When the signal from the preceding cell reaches a set threshold signal strength value where it is required to switch to the signal from the next cell when it is above that threshold value, the process through which that transfer is done is what is known as Handover. Generally, handover is triggered at the overlapping region between two neighboring cell[62].

Handover process must be done in a way that it is imperceptible to the user and be achieved successfully, especially in GSM-R a handover failure resulting in dropped connection to the train may be catastrophic to cause accident. In order for handover to be efficiently performed, the designer of the radio network has to set the minimum usable signal level that is acceptable for both data and voice transmission between the train and the serving BTS. However, handover is not set to be done at that minimum usable signal level as it might result in dropped connection. Therefore, a threshold signal level slightly above the minimum usable signal level must be defined upon which level a handover process is initiated. A margin Δ separating the threshold signal level at which handover is carried and minimum usable signal level which is given by:

$$\Delta = P_{r\ handoff} - P_{r\ minimum\ usable} \qquad (4\text{-}32)$$

This Δ must not be set too high in order to avoid unnecessary handover and must also not be set too low in order to avoid a lost connection scenario.

According to UIC standard for railways using ETCS Level 2/3, -95dBm with vehicles running at speeds less than 220Km/h has been set to be the minimum usable signal level coverage along the entire railway line so the same standard has been respected in this design and a margin of 6dB has been used which gives that the threshold signal strength level from which handover is initiated is -89dBm.

Isaka-Kigali railway GSM-R radio network has been designed as a double coverage network which has advantage of providing fully redundant network coverage as seen in figure 4-5 and figure 4-6 on the next page.

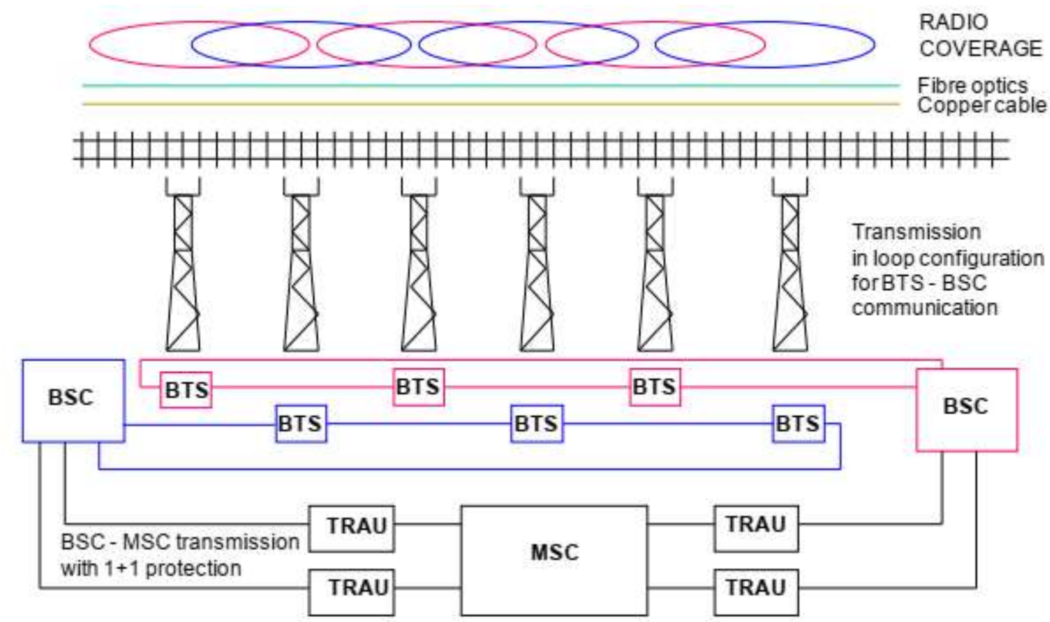

Figure 4-5: Double network coverage for the entire line for system redundancy[63]

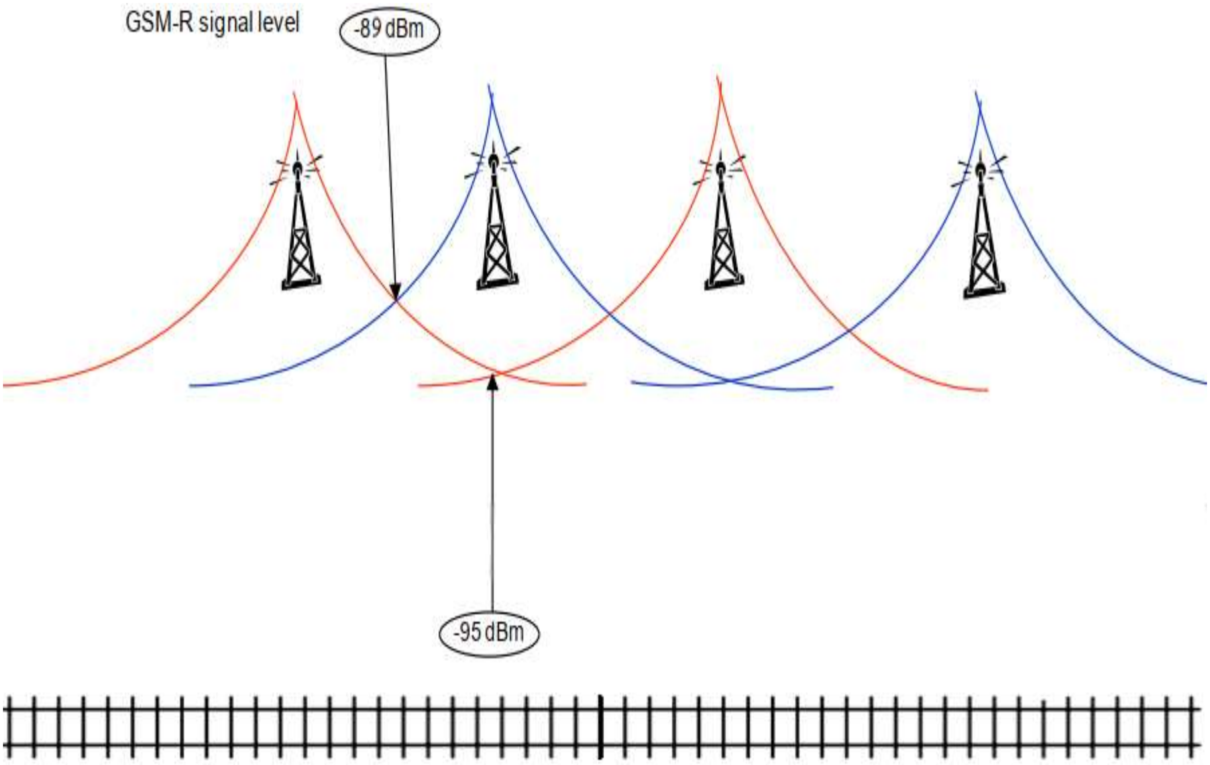

Figure 4-6: Handover signal strength [63]

Even if one BTS might fail as seen in figure 4-7, still the minimum required signal level of -95dBm will still be available as the minimum required signal level is still met at the point where the BTS failed. It is worth noting that in GSM-R network, a signal to noise ratio better than 12dB must be assured for the entire line. That is what is shown in figure 4-7 between the received signal and noise signals.

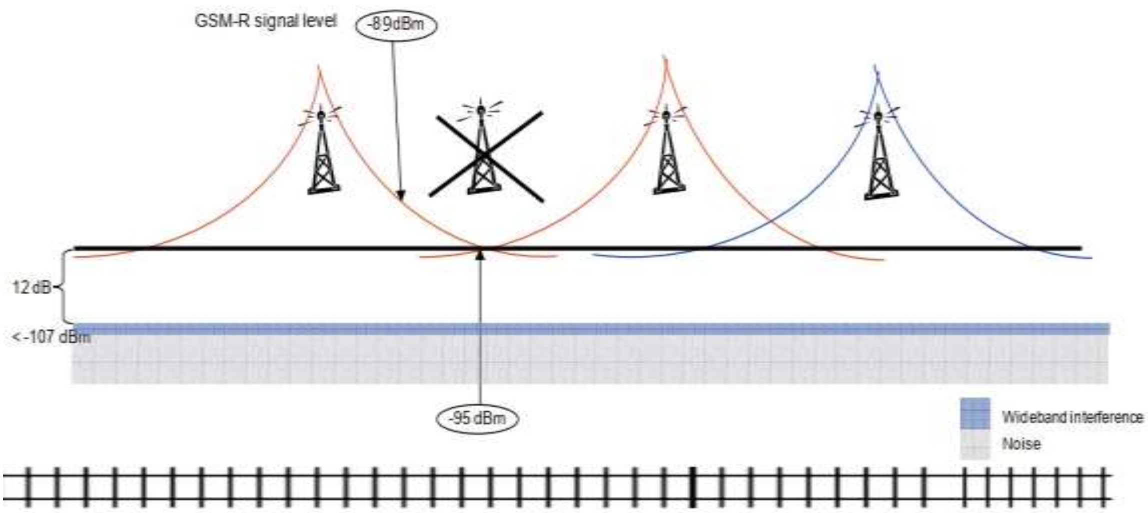

Figure 4-7: -95dBm coverage still available from redundant network even if one BTS has failed[63]

Two types of handover process exist in practice, one is where the handover process is governed by the base station supervised by the mobile switching center (MSC) and the other is where handover process is governed by the mobile station / Cab radio. In the first type where handover is governed by the BTS supervised by the MSC, the serving cell site examines the mobile's signal level every few seconds. If the signal level drops below a prescribed level, the system seeks another cell to handle the call. When a more appropriate cell site is found, the MSC sends a command, relayed by the old cell site, to change frequency for communication with the new cell site. At the same time, the landline subscriber is connected to the new cell site via the MSC. The periodic monitoring of operating mobile units is known as *locating*, and the act of changing channels is called *handover*[64]. This kind of handover is normally used in first generation analog cellular systems.

Another handover type is the Mobile Assisted Handoff (MAHO) whereby every mobile station measures the received power from surrounding base stations and continually reports the results of these measurements to the serving base station. A handoff is initiated when the power received from the base station of a neighboring cell begins to exceed the power received from the current base station by a certain level or for a certain period of time. The MAHO method enables the call to be handed over between base stations at a much faster rate than in first generation analog systems since the handoff measurements are made by each mobile, and the MSC no longer constantly monitors signal strengths[38]. This type of handoff (MAHO) has been chosen in this design to be used for handoff process on Isaka-Kigali GSM-R radio network.

4.3.10 Cell arrangement and frequency reuse plan

Cell arrangement must be done in such a way to minimize interference from other cells. As each channel has to be assigned a frequency channel, those cells don't have to interfere with each other. To increase capacity as the bandwidth is limited with only 18 channels to be used as traffic channel or control channels, cells have been grouped into clusters whereby a cluster is made of 7 cells with one frequency channel per cell except in areas such as Main Stations; Medium stations and yards where one frequency channel might not be enough to cater for the higher traffic due to number of trains and working personnel in that specific area, and hence, more than one frequency channel can be required. As the radio network coverage has been designed as a double coverage network to provide at least -89dBm as the minimum designed signal level and to provide full redundancy, two clusters are overlaid as seen in figure 4-8. Fourteen (14) frequency channels have been used in clusters, and four (4) frequency channels represented by their Absolute Radio Frequency Channel Number (ARFCN) have been reserved to be used in places where more than one frequency channel is needed such as in major station and medium stations. Those are ARFCNs: 319, 310, 315 and 320 chosen in such a way that their combinations with other frequency channels in one cell won't cause the Co-channel and Adjacent channel interference.

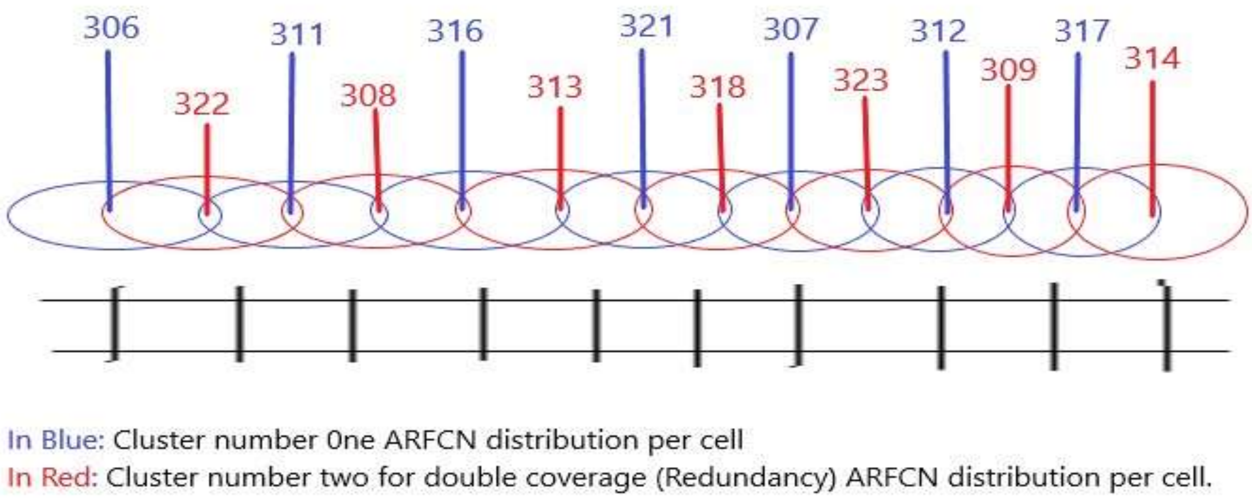

Figure 4-8: Double coverage with two overlaid clusters, one red and the other cluster blue.

Two types of interferences due to frequency channel distribution in clusters are available: Co-channel interference and Adjacent channel Interference. Co-channel interference is the interference from a ''nearby'' cell using the same frequency group as the cell of interest[65]. Co-channel interference assumes that all transmitters send only in the frequency channels assigned to them, and that all receivers have perfect bandpass filters that allow them to suppress all radiation outside the frequency channel they are listening to[66]. Adjacent-channel interference is interference caused by extraneous power from a signal in an adjacent channel. It may be caused by inadequate filtering, improper tuning or poor frequency control[67]. Co-channel and adjacent channel frequency interference is mainly caused by neighboring cells, Therefore, proper frequency channel allocation to cells is need to minimize them[68].

Frequency optimization methods seek to avoid interference between co-channels or adjacent channels using frequency allocation that meets the following requirements[69]:

- ✓ It is strictly forbidden to assign co-channel or adjacent channel frequencies to cells in the same station.
- ✓ A same frequency cannot be assigned to neighboring cells and should avoid adjacent channels.
- ✓ An azimuthal sector cannot rally with a co-channel or an adjacent channel.
- ✓ Other neighboring cells should avoid co-channels or adjacent channels.

Frequency allocation for this ISAKA-KIGALI Railway line has been done in such a way that in the two overriding clusters there be at least 3 frequency channel separation between the three overlapped cells as shown by figure 4-8. Directional antennas will be used in cells whereby each cell uses two directional antennas arranged in a back to back configuration making a total of two sectors per cell to provide highly directional radio signal coverage in the entire cell. The thick vertical lines in Red and Blue represents BTSs with their respective ARFCNs positioned in the center of their respective elliptical cells.

4.3.11 Tunnel Coverage

While building railway tracks, sometimes it becomes imperative to include tunnels especially when the line meets huge obstacles like mountains whereby contouring them would require making sharp curves for tracks which is dangerous for railway operations as trains run so fast. In that case, railway tunnels have to be made. ISAKA-KIGALI Railway line too has regions whereby tunnels are required. Two tunnels will be constructed at these locations: Km 386 +900 to Km 387+700 (800m long) and at Km 401+550 to Km 402+200 (650m long) making a total distance of 1,450m of underground rail track. As safety must be assured all over the railway line through efficient communication with running trains, railway tunnels too needs to be covered with radio signal. However, radio coverage planning in tunnels is done differently with the open space where railway lines passes as it is a kind of indoor propagation. Two different techniques are in use for radio coverage in tunnels today, namely Leaky Waveguides and Distributed Antenna Systems (DAS).

In general mobile communications, the spaced wave method is commonly used, where base stations and mobile stations communicate with each other by antennas through some distance of space. But in closed spaces such as a tunnel, radio waves are weakened rapidly and radio propagation becomes very short range. In order to solve this problem, Leaky Waveguide is commonly used in such spaces [70]. A leaky waveguide is a coaxial cable with periodic openings in its shielding to allow radio signals leak out or in, thus acting as a continuous antenna. Leaky waveguide is also known as leaky feeder, leaky cable, or radiating cable [71].

In leaky cable based Railway Radio communication Systems between Train and Trackside (RSTT), Leaky cable systems are laid at trackside all along the line and base stations are connected to the cables and transceivers. Through the cables and onboard antennas, radio communications between base stations and mobile stations are enabled[70]. The advantages of leaky waveguides are that they do not require complicated channel models for system design, and a good coverage in all types of tunnel is obtained and the close distance between leaky feeders and onboard antennas mitigates the effect of interference which results in much lower noise level compared to other spaced method, and it is possible to maintain stable communication regardless of the location of train, even in open-site or inside of tunnels [70], [72]. The disadvantages of using leaky waveguides are their high cost, difficulties in installation and maintenance and Leaky feeders proved to be unreliable, because of possible cuts in the case of fire, which consequently causes breakdown of communication in the entire tunnel [72],[24].

A distributed antenna system (DAS) is a way to deal with isolated spots of poor coverage such as inside a large building or tunnel by installing a network of relatively small antennas throughout the tunnel to serve as repeaters. The antennas are physically connected to a central controller which is connected to the wireless carrier network's base station. Deployment is the most expensive stage of a DAS project because installing antennas and stringing fiber optical or coaxial cable between antenna modules and the controller are all very labor intensive processes[73]. DAS are used when radio coverage is necessitated in long tunnels as the maintenance cost of leaky feeders is high compared to deploying antennas inside tunnels. Radio coverage planning in tunnels using DAS is not an easy task as radio propagation medium is different with the one outside tunnels, which is its drawback even though its maintenance cost is low compared to leaky feeders . Basically, two techniques can be used to calculate the propagation inside a tunnel: 1) modal analysis and 2) ray-optical modeling. Modal analysis is used in straight tunnels, and ray tracing is used only to calculate extra attenuation in curves and in the entrance and exit of the tunnel [24].

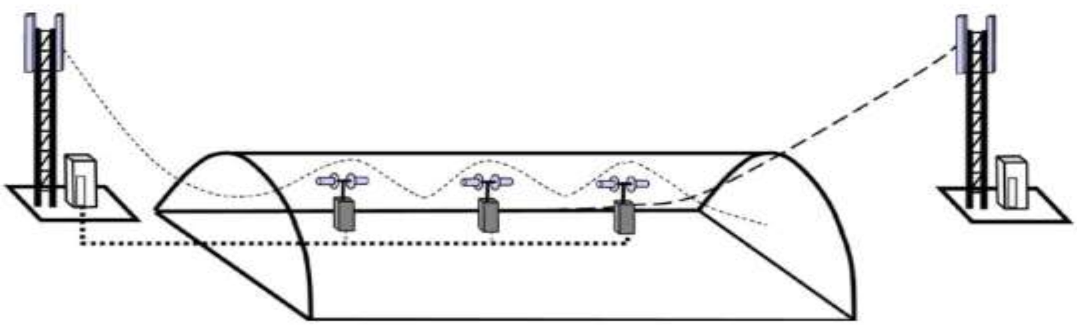

Figure 4-9: Distributed Antenna System for tunnel radio coverage[24].

The tunnel behaves like a waveguide with a cutoff frequency and different transmission modes. In tunnels, radio wave attenuations are caused by multiple reflections, diffractions and scattering on the tunnel's inner walls, floor and ceiling, and absorption on all the tunnel's elements mentioned above[22]. Tunnels can have different shapes such as circular shape, rectangular shape and arched shape; they can be straight tunnels or curved tunnels. In straight tunnels, the radio signal attenuation decreases with increased frequency while in curved tunnels it increases [21]. Two different regions have been identified in curved tunnels, namely near-field and far-field regions. In the near-field region, the field suffers strong fading and rapid decreases resulting from the contribution of many rays propagating from different grazing angles with high losses.

A far-field region can also defined, where the attenuation factor is smaller because there is only one mode propagating throughout the tunnel as other propagation modes have been suppressed [24]. It has been observed that in a Line Of Sight (LOS) region in a tunnel, dominant radio waves propagation are by free space propagation and in Non-LOS regions, propagation is mostly by reflections; and the best position for a transmitter antenna placement inside a tunnel is in the middle of the tunnel cross section, whereas the transmitter installed at the tunnel wall exhibits the worst propagation characteristic [21].

In their research about Considerations regarding the radio design of GSM-R systems, inside railway tunnels [22], Lăcrămioara Mihaela Nemţoi and his colleagues found that a straight tunnel section of average length (around 430 meters), can be covered successfully with a GSM-R base station or repeater antenna, placed in the proximity of the tunnel portal such as 10m away from the tunnel entrance / exit. The effect of the reflections on tunnel walls is negligible as the direct line of sight radio coverage is much larger than the strength of reflected signals. The received signal level inside the tunnel did not range below 96 dBuV/m (-41 dBm). The situation is however totally different for the case of a curved tunnel section. In this case, the reflections of the radio signals on tunnel walls have a very significant effect. The radio coverage is extended beyond the direct line of sight zone, along the tunnel. The reflected signal strength was found to be 20-40 dB lower than the signal received on the tunnel section that is still in direct line of sight with the GSM-R transmitter [22].

With the above descriptions about radio coverage in tunnels using either leaky feeders or Distributed antenna systems, After weighting the advantages and disadvantages of each technic, considering also the lengths of the two tunnels on Isaka-Kigali railway line and the fact that it is not known yet if they will be curved or straight, the perfect choice radio coverage will be provided by leaky feeders along the tracks as the tunnels are not long enough for deployment of distributed antenna systems, and hence, it has been chosen to be used in this thesis project.

5 CHAPTER FIVE: ISAKA KIGALI RAILWAY LINE GSM-R RADIO NETWORK SIMULATION RESULTS AND DISCUSSION

Radio network coverage simulation is very important in GSM-R radio network planning to estimate the number of BTSs required and identify best sites for BTSs deployment to cover the whole railway line. In this thesis project, I used Atoll Radio Frequency Network planning, Design and Optimization software to simulate radio coverage.

ATOLL RF Network Planning, Design, Optimization Software is a comprehensive multi-technology radio planning and optimization platform which includes unified multi-technology GSM/UMTS/LTE/NB-IoT (3GPP) and CDMA/LTE/NB IoT (3GPP2) traffic models, Monte Carlo simulators, and ACP (Automatic Cell Planning) module. Atoll can model the traffic-related aspects of multi-technology networks and dynamically distribute traffic between multi-technology layers including Wi-Fi and small cells. Atoll uniquely combines architectural and functional features that provide operators with a powerful, scalable, and flexible framework for streamlining their network design and optimization processes[74].

5.1 Isaka-Kigali GSM-R network design process in Atoll

According to UIC standards, for railway lines using ETCS level 2/3 with speeds less than 220Km/h, a -95dBm signal level must be achieved all over the railway line. The simulation done is to provide a minimum signal level of at least a -95dBm for the whole line. To simulate the radio network coverage, we firstly need to have a digital map of the railway line which serves as the first data input for simulation process. Thanks to Rwanda Transport Development Agency (RTDA) for providing the general alignment of Isaka-Kigali railway line. The simulation process starts by creating a new project in Atoll software whereby you select the type of radio network you need to simulate, here GSM GPRS EDGE was chosen for the simulation of GSM-R is the same with GSM except that coverage for GSM-R is only along the railway line, and this creates a 2G project template.

After creating a new project, we select the region where the network is to be deployed, that is geographical coordinates (Latitudes and longitudes) of the region where the railway line will pass. This Isaka-Kigali railway line will passes through 30 degree to 36 degree longitude East in Southern hemisphere. The following figure is the entire Isaka-Kigali railway line general alignment as it is in google earth. The line is represented by the whitish green zigzagging line from Isaka (Tanzania) to Kigali (Rwanda).

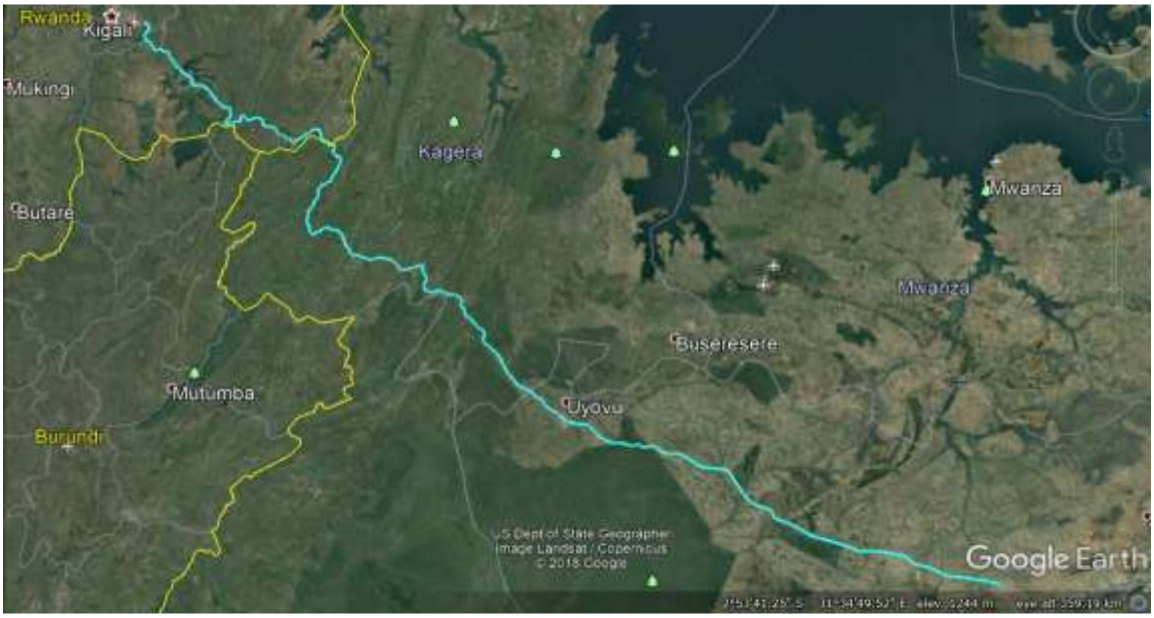

Figure 5-1: Isaka-Kigali Railway line general alignment in google earth

After setting the region's coordinates, we have to import the digital map of the railway line in the created template to start simulating the radio network. Here below is the already imported map in Atoll software for simulation.

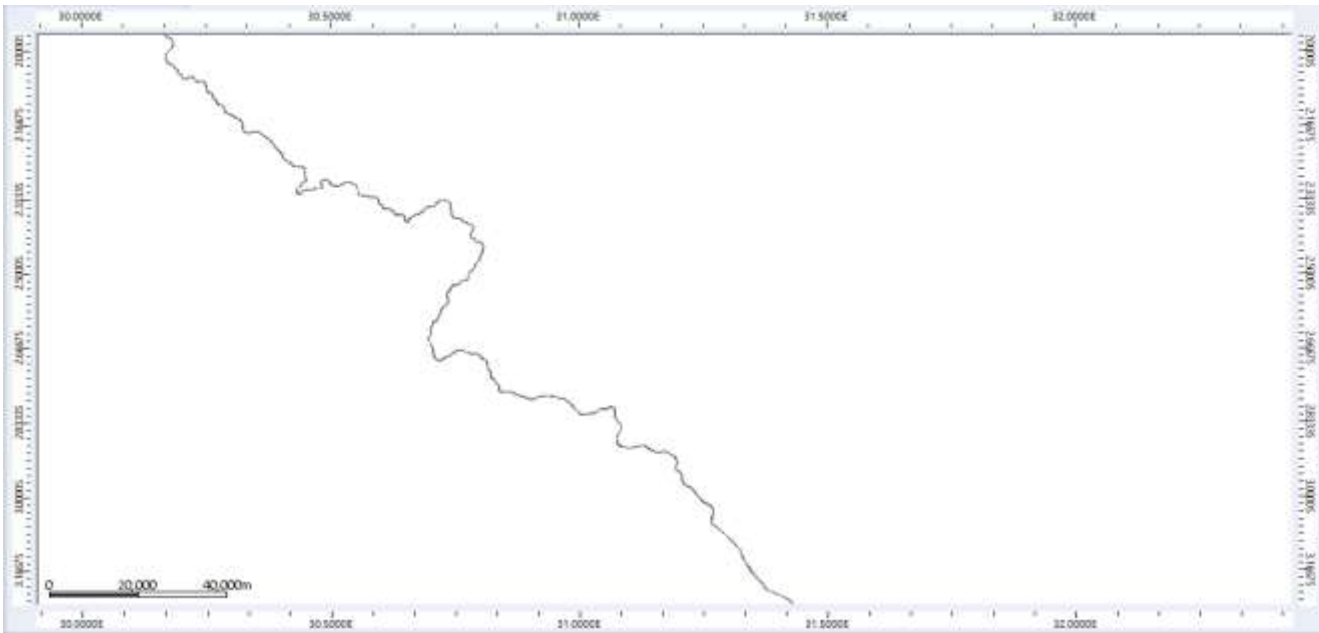

Figure 5-2: Imported map in Atoll software

After importing the general railway line alignment in Atoll software, the next step is to import selected sites for BTS deployment. A BTS site is characterized by its longitude, latitude and site name. Sites were initially selected depending on the location where network has to be provided and their spacing varies depending on cell radius its BTS will have according to its specific type (Suburban, Rural flat,…) and 46 sites were identified in the first round. The next step after defining site locations in Atoll is to add BTSs to those sites with their antennas alignment along the line, BTS site locations are given in Appendix section of this Thesis. As defined in the previous chapter, directional antennas were used whereby a cell has two sectors configured in back to back configuration, and 65deg 17dBi 2Tilt 900 MHz Kathrein antennas were used to provide coverage over the whole line. The last part of simulation is setting network parameters for this GSM-R network such as frequency planning, selecting the path loss propagation model, antenna heights, receiver sensitivity and other parameters according to those computed in previous chapter and then calculate coverage predictions to see if the required coverage is met and if not optimize the network until it is achieved.

5.2 Simulation results and discussion

Upon the first simulation round, 46 sites were identified where BTSs were deployed. Coverage prediction results obtained left many locations with signal level less than -95dBm which are not good coverage according to standards. Optimization was hence to be done through much iteration processes by identifying other new sites where BTSs are needed to be deployed and this resulted in a total number of 92 BTSs arranged in full redundancy configuration in a way that if half of the whole line BTSs fails, still a -95dBm signal level will be available all over the line. Coverage prediction in atoll software is expressed in a color code way where each color stands for specific expected signal coverage level and this figure below show the legend for color code used.

Figure 5-3: Coverage prediction color code legend

The below figure shows the coverage prediction all over the line from Isaka to Kigali.

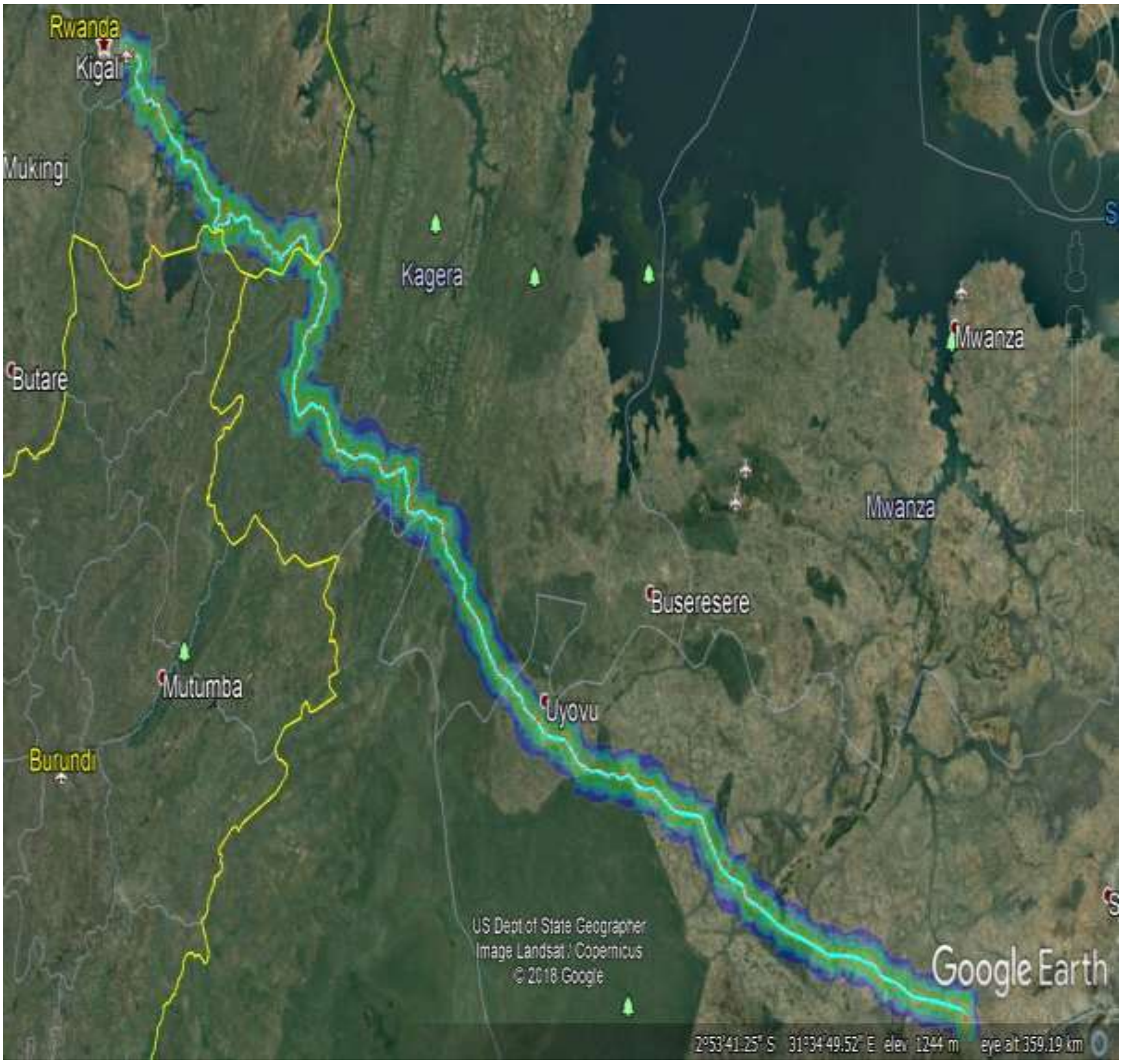

Figure 5-4: Isaka-Kigali GSM-R coverage prediction

The signal coverage level obtained was therefore found to be satisfactory as there is no single location along the entire Isaka-Kigali railway line where signal coverage drops below the required level which is -95dBm. This can be verified using point analysis tool of Atoll software whereby two random points are selected on this railway line to check signal coverage level. As this is a simulation, the confirmation that the required signal level is achieved can only be done after implementation of the project, hence, the obtained network coverage here is an image of what to expect when network roll out is carried according to this thesis design. Taking a random point between BTS site 14 and site 15, let us analyze the signal coverage available.

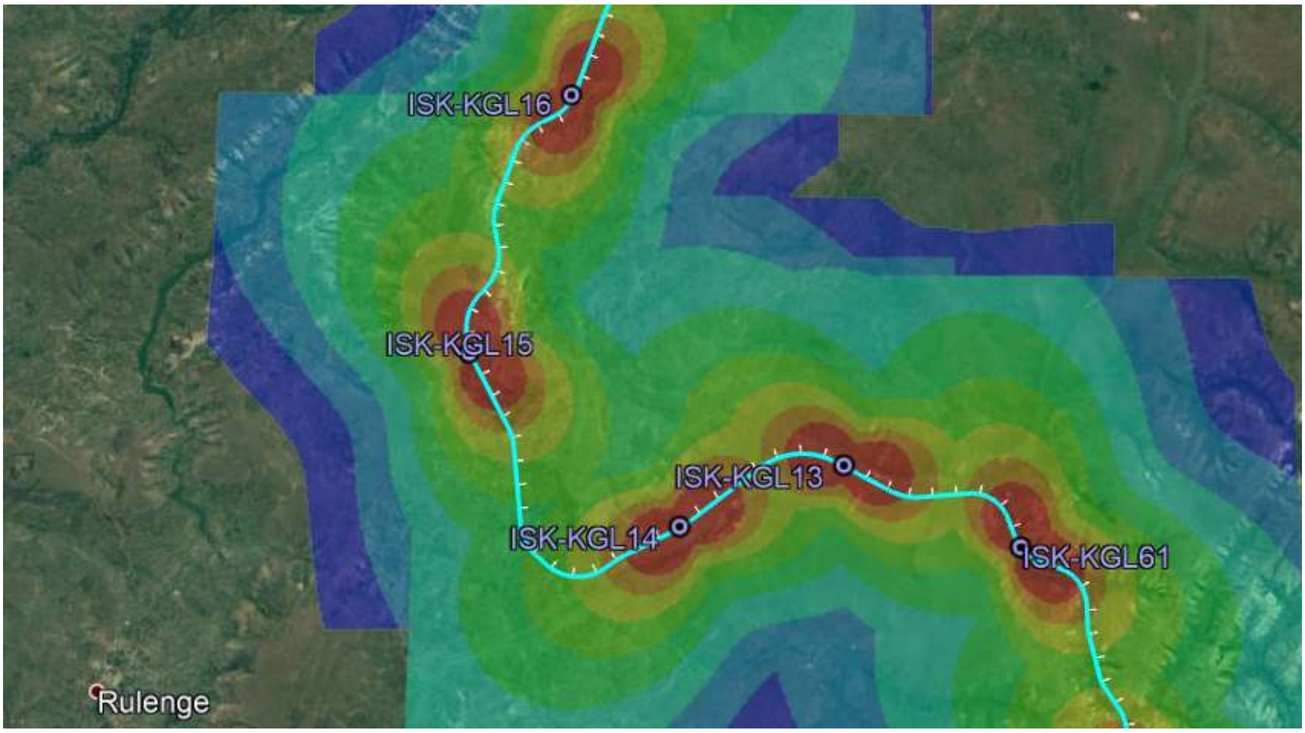

Figure 5-5: Signal coverage prediction between site 14 and site 15

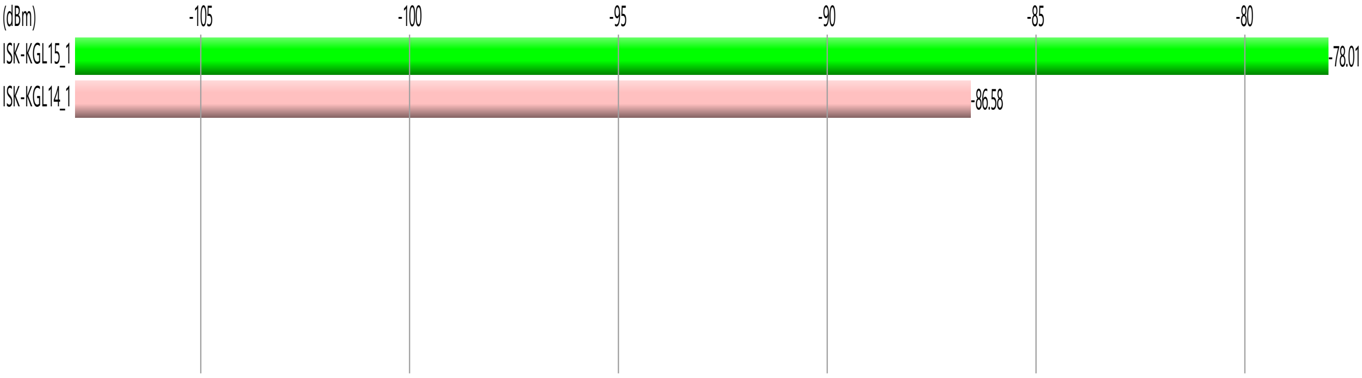

Figure 5-6: Signal coverage analysis of a random point between BTS of site 14 and BTS of site 15

A BTSs antenna configured in back to back configuration to make it have two sectors per BTS is shown by a black dot in a circle with the BTS site name written beside to it. It can be seen that signal coverage level between the two BTSs is above the minimum required signal level of -95dBm. Taking another random point between the BTS of site 44 and site 45 which are near Kigali, let us analyze the signal coverage between the two Base Transceiver Stations as shown by the following figures 5-7 and 5-8.

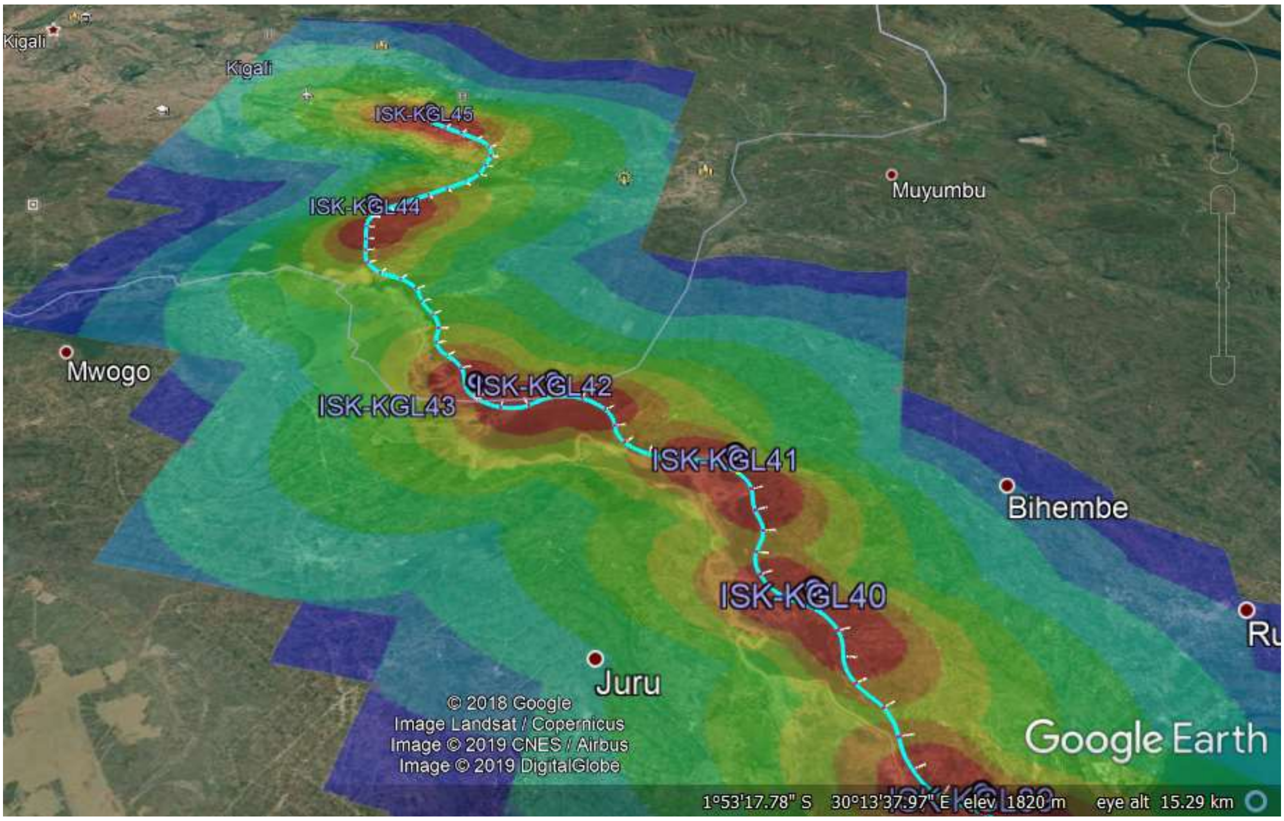

Figure 5-7: Signal coverage between site 44 and site 45

Coverage signal prediction between the two sites for the randomly selected point is shown in this below figure.

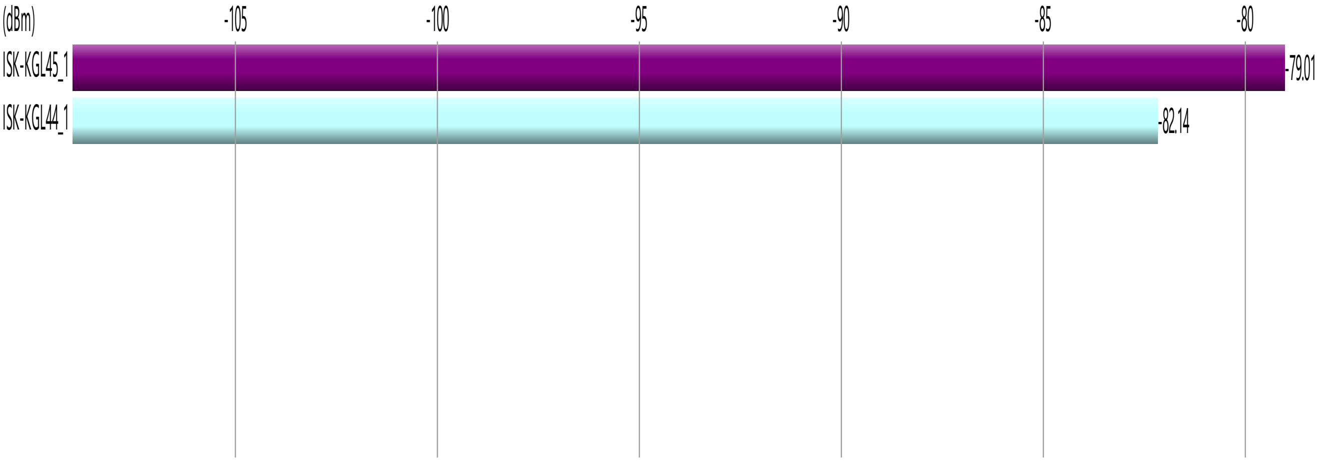

Figure 5-8: Signal coverage analysis of the random point selected between site 44 and site 45

It is clearly observed that the signal coverage between the two sites is way above the standard required minimum signal level coverage. In the testing of coverage for the whole line when the project is implemented, test has to be carried along the entire route which we cannot do in simulation software. Hence, only two points where selected to check the performance of this designed GSM-R network. The details about the selected point such as its distance from the two sites BTSs and Carrier to Interference ratio is shown in Figure 5-9 below. In this figure, the selected point is 5.161Km from Site 45 and 6.739Km away from site 44 and yet the coverage at that point is even greater than -89dBm design coverage level with a Carrier to Interference ratio above 30dB which is more than double the required level of 12dB .

x:30.211738872E y:1.967301015 z:0

Transmitter	Distance (m)	BCCH - C (dBm)	BCCH - C/I (dB)	Min C/I (dB)	TRX
ISK-KGL45_1	***5,161***	***-79.01***	***33.99***	***11.35***	***TCH MAL 314 318 323, MAIO {0 1 2}***
ISK-KGL44_1	6,739	-82.14	30.86	5.11	TCH MAL 317 319 321, MAIO {0 1 2}

Figure 5-9: Details about the selected point between site 44 and site 45

From the obtained results in the simulation process, the designed network will provide a GSM-R network that comprises with standards even if a half of the whole BTSs would fail as it is configured as a full redundant coverage network. Some locations require a high number of BTS towers such as between Km 401 + 000 and Km 410 +500 and in between of Km 332 + 000 and Km 380 + 500 due to the mountainous nature of those locations with too many corners around those mountains and a BTS is required around the corner to provide signal coverage on the other side of the mountain where the rail line passes.

6 CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Radio network planning and dimensioning before radio network deployment plays a very important part in the performance of the network when it is deployed. Same applies to railway radio networks using GSM-R, it is better to make an efficient planning and dimensioning of its network for the overall GSM-R efficiency. In the radio coverage planning part of this Thesis, based on Okumura-Hata empirical path loss model, three types of cells have been obtained for Isaka-Kigali railway line. These are Suburban cells **(Rsu)**; rural semi-flat and open areas cells **(Rrso)**, and rural flat open areas cells **(Rro)** with 5.75Km, 13.5Km and 18.6Km cell radius distance, respectively.

Each BTS of a cell will be assigned a single frequency channel except for Major station of Kigali and the other Medium stations of the line which will require two frequency channels or even more due to higher telecommunication traffics taking place at those stations, and frequency channel assignment to cells has been done in clusters whereby a cluster is made up with seven frequency channel arranged in such a way to minimize co-channel and adjacent channel interferences. Two clusters have been defined and four (4) frequency channels have been reserved to be used in those locations where more than one frequency channel per BTS is required. Isaka-Kigali railway line will have two potential tunnels and the coverage inside those tunnels will be achieved through use of leaky feeder cables. The whole railway line will need a total of 92 BTSs to provide a fully redundant network whereby if half of them fail; the rest will still provide the -95dBm required signal level coverage all over the line and the system has to be able to support a total traffic rate of **7.54Mbps** in busy hour.

In general, this thesis achieved all of its objectives by merging theoretical knowledge with practical simulation work; the GSM-R radio network planning and dimensioning has been achieved despite limitations faced such as insufficiency of funds to carry out this thesis which resulted in cancellation of field research and the research based on the already available information of the line. The second limitation has been unavailability of licensed software of radio network planning software which pushed us to use a non-licensed cracked version of Atoll Radio Frequency planning which can't perform fully as a licensed one but provides results nearly similar with those that should be obtained from licensed software.

6.2 Recommendation

GSM-R technology is a mature technology for railway communications as it has experience of more than a decade in use today. This thesis focused only on access network and interface dimensioning of GSM-R radio network for ISAKA-KIGALI railway line and did not analyze cost implication of its deployment and maintenance, and its service quality compared to other telecommunication radio networks which may be used as an alternative of GSM-R such as UMTS, GPRS, 3G, 4G LTE, and 5G LTE. It is therefore recommended to other researchers who will be interested to research on radio network planning over this line to work on such a comparison of those networks in order to recommend the best one in terms of service quality and cost implications.

GSM-R radio network encounters interference due to signal leakage from other telecommunication networks in adjacent bands to its band, it is therefore also recommended to do research on interference from other networks adjacent to the selected band of GSM 480. The GSM-R radio network optimization was done through many simulation iterations to come up to the maximum number of required BTSs being equal to 92. This is time consuming, and hence, it is recommended to future researchers on Railway communication system to research on mathematical optimization of Railway radio network coverage for an optimum number of required BTSs.

As of today, for ISAKA-KIGALI railway line no telecommunication system has been chosen to control and manage train movements on the line, this thesis work is recommended to Rwanda Transport Development Agency (RTDA) to serve as a reference document towards selecting a radio network to be used and standards it has to meet as well as knowing where attention will have to be put if European Train Control System (ETCS) using GSM-R network is selected for train control on the line.

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Appendix

BTS site location coordinates

Site Name	Longitude	Latitude	Site Name	Longitude	Latitude
ISK-KGL01	32°56'27.02"E	3°54'07.61"S	ISK-KGL47	32.652436888E	3.819024302S
ISK-KGL02	32°46'07.99"E	3°51'52.49"S	ISK-KGL48	32.415101537E	3.753516421S
ISK-KGL03	32°31'54.24"E	3°46'46.30"S	ISK-KGL49	32.202174607E	3.659892624S
ISK-KGL04	32°18'20.09"E	3°42'47.18"S	ISK-KGL50	32.041659473E	3.49725607S
ISK-KGL05	32°06'38.04"E	3°35'22.91"S	ISK-KGL51	31.844914371E	3.438149745S
ISK-KGL06	31°55'41.19"E	3°27'48.35"S	ISK-KGL52	31.645166759E	3.389995612S
ISK-KGL07	31°45'37.97"E	3°24'46.71"S	ISK-KGL53	31.441886023E	3.252532277S
ISK-KGL08	31°32'52.09"E	3°20'12.42"S	ISK-KGL54	31.265077722E	3.057133096S
ISK-KGL09	31°20'28.10"E	3°09'39.10"S	ISK-KGL55	31.238608134E	2.999297373S
ISK-KGL10	31°10'23.80"E	2°53'59.88"S	ISK-KGL56	31.080977261E	2.886593793S
ISK-KGL11	30°59'17.52"E	2°48'02.37"S	ISK-KGL57	31.08398542E	2.846063517S
ISK-KGL12	30°49'29.41"E	2°44'09.23"S	ISK-KGL58	31.065475491E	2.798942095S
ISK-KGL13	30°46'07.21"E	2°40'25.26"S	ISK-KGL59	30.904065558E	2.782353212S
ISK-KGL14	30°44'15.14"E	2°41'06.86"S	ISK-KGL60	30.733750851E	2.553305928S
ISK-KGL15	30°41'48.31"E	2°39'07.52"S	ISK-KGL61	30.802035129E	2.689185627S
ISK-KGL16	30°42'54.57"E	2°36'03.68"S	ISK-KGL62	30.844987489E	2.766180885S
ISK-KGL17	30°44'43.82"E	2°31'32.22"S	ISK-KGL63	30.940682643E	2.774696828S
ISK-KGL18	30°46'41.40"E	2°29'53.59"S	ISK-KGL64	31.01727731E	2.815118085S
ISK-KGL19	30°48'02.21"E	2°27'39.29"S	ISK-KGL65	31.120059061E	2.888033836S
ISK-KGL20	30°48'16.96"E	2°25'54.51"S	ISK-KGL66	31.195313777E	2.929128418S
ISK-KGL21	30°47'05.62"E	2°23'28.88"S	ISK-KGL67	31.203747127E	2.947878353S
ISK-KGL22	30°44'38.23"E	2°22'07.35"S	ISK-KGL68	31.29597086E	3.089330854S
ISK-KGL23	30°43'28.02"E	2°20'06.70"S	ISK-KGL69	31.311516758E	3.105624362S
ISK-KGL24	30°42'26.42"E	2°20'54.15"S	ISK-KGL70	31.370319922E	3.200871535S
ISK-KGL25	30°40'09.02"E	2°22'08.79"S	ISK-KGL71	31.391140715E	3.217164713S
ISK-KGL26	30°37'44.33"E	2°21'55.86"S	ISK-KGL72	31.478262658E	3.289568252S
ISK-KGL27	30°35'18.14"E	2°19'39.99"S	ISK-KGL73	31.501114917E	3.303964742S
ISK-KGL28	30°32'58.09"E	2°18'01.20"S	ISK-KGL74	31.596570378E	3.344270526S
ISK-KGL29	30°29'28.59"E	2°17'20.62"S	ISK-KGL75	31.607981384E	3.350717372S
ISK-KGL30	30°28'58.34"E	2°17'58.10"S	ISK-KGL76	31.682035429E	3.406290829S
ISK-KGL31	30°27'56.17"E	2°18'39.71"S	ISK-KGL77	31.704392056E	3.406203699S
ISK-KGL32	30°26'46.51"E	2°18'45.49"S	ISK-KGL78	31.794305922E	3.420747663S
ISK-KGL33	30°25'50.44"E	2°18'52.70"S	ISK-KGL79	31.879895935E	3.442940368S
ISK-KGL34	30°26'58.62"E	2°16'56.56"S	ISK-KGL80	31.965809572E	3.48784026S
ISK-KGL35	30°24'53.46"E	2°14'50.18"S	ISK-KGL81	31.983476921E	3.490935078S
ISK-KGL36	30°23'23.91"E	2°13'02.19"S	ISK-KGL82	32.073726148E	3.532856449S
ISK-KGL37	30°21'05.60"E	2°10'50.38"S	ISK-KGL83	32.083010561E	3.548361169S
ISK-KGL38	30°19'05.20"E	2°09'17.42"S	ISK-KGL84	32.15220997E	3.622559165S
ISK-KGL39	30°16'45.38"E	2°07'15.34"S	ISK-KGL85	32.24628665E	3.680619497S

ISK-KGL40	30°15'32.20"E	2°05'38.70"S	ISK-KGL86	32.354914041E	3.734757028S
ISK-KGL41	30°14'44.05"E	2°04'07.66"S	ISK-KGL87	32.465448417E	3.773071177S
ISK-KGL42	30°12'55.76"E	2°03'28.72"S	ISK-KGL88	32.589406395E	3.78854527S
ISK-KGL43	30°12'13.88"E	2°03'41.97"S	ISK-KGL89	32.611144442E	3.79442665S
ISK-KGL44	30°10'03.62"E	2°00'32.57"S	ISK-KGL90	32.703570224E	3.834766846S
ISK-KGL45	30°09'55.55"E	1°57'55.55"S	ISK-KGL91	32.809030778E	3.870007333S
ISK-KGL46	32.866891084E	3.878875316S	ISK-KGL92	32.915574227E	3.888091327S