Determination of Viable Connectivity Technology for e-Learning in Tanzania:
Case Study of Rural Secondary Schools

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I was away and hence I could neither see nor talk to you for the last time.
You were a nice brother & a very good friend of mine.
Rest in peace my dear brother.

ABSTRACT

In response to different development challenges, Tanzania is striving to achieve her fourth attribute of the National Development Vision, i.e. to have a well educated and learning society by the year 2025. The earmarked approach is to integrate Information and Communication Technology (ICT) in education system (e-learning), in order to improve teaching and learning processes, hence provision of quality education. However, Tanzania is challenged by lack of ICT infrastructures in rural areas, which affects integration of ICT in education.

This thesis presents a research work to determine a cost-effective and performance efficient connectivity technology for rural secondary schools to access e-learning resources. The research surveyed wireless technologies, in order to identify potential broadband access technologies suitable for rural areas of the developing countries. Because ICT is a very dynamic sector, the identified technologies were compared by using conceptual framework to study their sustainability and thereafter, analyzed by using techno-economic approach to determine a feasible and cost effective option. Results show that, a third generation (3G) Universal Mobile Telecommunications System (UMTS) operating at 900MHz is a feasible and cost - effective connectivity technology for rural areas of Tanzania.

Furthermore, the research employed a simulation modelling approach to study traffic differentiation and priority scheduling mechanisms in providing Quality of Service (QoS) for e-learning applications in UMTS networks. A simulation model of the UMTS network is developed and used to study performance of e-learning applications as perceived by users. Simulation results showed that, UMTS network configured with traffic differentiation and priority scheduling can guarantee delivery of e-learning services with the required QoS. The Public Private People's Partnership (PPPP) model is proposed by this research as an implementation strategy for sustainable broadband rural connectivity solution.

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LIST OF ABBREVIATIONS, SYMBOLS AND ACRONYMS

2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
AAL2	ATM Adaptive Layer 2
ADEM	Agency for Development Education Management
AF	Assured Forwarding
APN	Allocation/Retention Priorities
ARPU	Annual Revenue Per User
ATM	Asynchronous Transfer Mode
AuC	Authentication Centre
BSCs	Base Station Controllers
BTH	Blekinge Institute of Technology
CAPEX	Capital Expenditure
CD-ROM	Compact Disk-Read Only Memory
CF	Cash Flow
CN	Core Network
CNB	Core Network Bearer
COMARCI	The Commonwealth African Rural Connectivity Initiative
COSTECH	Commission for Science and Technology
dB	decibel
DCF	Discounted Cash Flow
DiffServ	Differentiated Service
DILES	Distance Learning Education Services
DL	Downlink
DSCP	Differentiated Service Code Point
EASSY	East African Submarine cable System
ECOSYS	techno-ECOnomics of integrated communication SYStems and services
EDGE	Enhanced Data Rates for GSM Evolution
EF	Expedited Forwarding
EIR	Equipment Identity Registe
EMIS	Education Management Information system
EPON	Ethernet PON
FDD	Frequency Division Duplex
FTTH	Fiber-To-The Home
GDP	Gross Domestic Product
GGSN	Gateway GPRS Support Node
GMSC	Gateway MSC
GPON	Gigabit PON
GPRS	General Packet Radio Service
GSA	Global Mobile Network Suppliers Association
GSM	Global System For Mobile Communication
HLR	Home Location Register
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSUPA	High Speed Uplink Packet Access
HTTP	Hyper Text Transfer Protocol

IAE	Institute of Adult Education
ICT	Information and Communication Technologies
ICT4E	ICT in basic Education
ICT-TPD	Information Communication Technology–Teacher Professional Development
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IFAD	International Fund for Agricultural Development
IMS	IP multimedia subsystems
IntServ	Integrated Service
IRR	Internal Rate of Return
ITU	International Telecommunication Union
LOS	Line Of Sight
LTE	Long Term Evolution
MCST	Ministry of Communication Science and Technology
ME	Mobile Equipment
MSC	Mobile services Switching Centre
MT	Mobile Termination
NECTA	National Examination Council of Tanzania
NEPAD	New Partnership for Africa´s Development
NGN	Next Generation Network
NGO	Non-Governmental Organization
NICTBB	National ICT Backbone
NLOS	Non-Line of Sight
NPV	Net Present Value
NREN	National Research and Education Network
NSCP	National School Connectivity Plan
NSN	Nokia Siemens Network
OFC	Optical Fibre Cable
OLT	Optical Line Terminal
ONU	Optical Network Units
OPEX	Operational Expenditure
OUT	Open University of Tanzania
P2MP	Point-to-Multipoint
P2P	Point to-Point
PAR	Participatory Action Research
PEDP	Primary Education Development Plan
PFFQ	Per-Flow Fair Queueing
PHB	Per-Hop Behavior
PON	Passive Optical Network
PPP	Public Private Partnership
PPPP/4Ps	Public Private Peoples Partnership
QoS	Quality of Service
RAB	Radio Access Bearer
RF	Radio Frequency
RLC	Radio Link Control
RNC	Radio Network Controller
RNS	Radio Network Subsystem
RSpec	Reservation Specification
RSVP	Resource Reservation Protocol
SDU	Service Data Unit
SEDP	Secondary Education Development Plan

SGSN	Serving GPRS Support Node
SLA	Service Level Agreement
SMEs	Small to Medium Enterprises
SONGAS	Songo Songo Gas Company
STHEP	Science Technology and Higher Education Program
TA	Terminal Adapter
TAE	Tanzania Education Authority
TANESCO	Tanzania Electric Supply Company
TanSSeL	Tanzania Secondary School e-Learning
TAZARA	Tanzania Zambia Railways Authority
TBC	Tanzania Broadcasting Commission
TCC	Tanzania Communication Commission
TCRA	Tanzanian Communications Regulatory Authority
TDD	Time Division Duplex
TE	Terminal Equipment
TERA	Techno-Economic Results from ACTS
TERNET	Tanzania Education and Research Network
TET	Tanzania Education Trust
TIE	Tanzania Institute of Education
TITAN	Tool for Introduction scenario and Techno-economic evaluation of Access Network
TLSB	Tanzania Library Services Board
TONIC	TechnO-EcoNomICs of IP optimised networks and services
TPC	Tanzania Postal Corporation
TPTC	Tanzania Postal and Telecommunication Company
TRC	Tanzania Railways Corporation
TSpec	Traffic Specification
TTCL	Tanzania Telecommunication Company Limited
TTISSA	Teacher Training Initiative for sub-Saharan Africa
TUT	Tampere University of Technology
UCAF	Universal Communications Access Fund
UDSM	University of Dar es Salaam
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunication System
UN	United Nations
USIM	User Service Identity Module
UTRAN	Universal Terrestrial Access Network
VLR	Visitor Location Register
WCDMA	Wideband Code Division Multiple Access
Wi Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability Microwave Access
WLAN	Wireless Local Area Networks
WSIS	World Summit of Information Society
WWW	World Wide Web

CHAPTER ONE
INTRODUCTION

1.1 Background

Rural areas of Tanzania or rural areas of the developing countries in general, present challenges in establishing Information and Communication Technologies (ICT) infrastructures. This is mainly due to difficulty rural environments that are characterized by unreliable source of power (electricity), limited or poor road infrastructure, diverse topology, low income community and low population density (Siochrú, 2005). One of the reasons for lack of ICT infrastructure in rural areas is the costs required in implementation and maintenance of such infrastructures. Moreover, the cost varies widely depending on the required network capacity and type of connectivity technology. The spearheading factor to the high costs is the fact that business models of ICT-based service providers/operators are profitable in urban settings. This situation creates a costing structure where prices become relatively higher for rural end users (Sheriff, 2007).

The non-existence or limited access to ICTs´ infrastructures and services to rural areas is not a unique problem to Tanzania; it is actually a global issue. Therefore, there are global efforts aimed to bring connectivity to the rural areas. There are initiatives pioneered by International bodies such as World Summit of Information Society (WSIS). The world summit on the information society, which was held in two phases, in Geneva, 2003 and Tunis in 2005, provided a forum in which multiple stakeholders including international organizations, governments, private sector and civil society discussed the opportunities of the new information and communication environment. The summits had an objective of addressing challenges such as the inequality in access to information and communication technologies services, which is called the 'digital divide'. Priorities discussed at WSIS includes the need for investment in infrastructure, the role of

ICTs in development, the relationship between ICTs, human rights and culture, and the new challenges posed by ICTs and the Internet for international governance. WSIS established targets for ICT deployment to run alongside other internationally agreed development goals. Among them, there are goals that are directly related to bringing connectivity to the rural areas and/or use of ICT in education (ITU-WSIS Targets, 2010). Another global effort is by International Telecommunication Union (ITU) in collaboration with private sectors, which aim to connect rural and remote communities to the ICT-based services. Apart from global initiatives, there are also regional and country level efforts. For example, the New Partnership for Africa´s Development (NEPAD) ´s eSchools program and the NEPAD´s ICT broadband project, which are regional initiatives aiming at integrating ICT in education and develop broadband infrastructure respectively.

1.1.1 Rural Connectivity Initiatives

The WSIS target number one is related to the provision of rural connectivity. The target reads *"Connect villages with ICTs and establish community access points"* (ITU-WSIS Targets, 2010). In most countries, especially developing countries, there is a wide gap between rural and urban areas in the availability of information and communication technologies infrastructures and services. The objective of WSIS target one is to ensure that rural areas are not excluded from the information society. Due to their isolation, rural areas can reap more benefits from connectivity, since ICT can deliver education, health and other services that are currently not available. The WSIS´s target one is charged with two tasks (1) connecting villages with ICTs (2) establishing community access point. The first task can be satisfied via the second task because the practical method in most of the developing countries to provide ICTs in rural areas is through shared access. It is estimated that about half of the world´s population live in rural areas, and one way to provide them with ICTs is by community access. The shared access is a cost-effective means for rural connectivity because of the low income level and hence individuals can not afford the ICT services related costs (ITU-WSIS Targets, 2010).

Another global initiative for rural connectivity is the partnership of ITU and technology companies such as Nokia Siemens Network (NSN) aimed at bringing affordable connectivity to the world's rural and remote areas. The ITU and NSN provide expertise and equipment to expand rural and remote connectivity. The partnership fulfills part of the ITU's "connecting villages initiative" that aims to connect the world's rural and remote areas. The NSN, which is an operator as well as a network equipment vendor, provides its "village connection" platform and technical expertise. The NSN´s village connection platform consists of compact GSM access points that a local community can use to provide individuals or families with a mobile connection. It is a cost effective, easy to implement and operate, and also present a model that creates business opportunities for local entrepreneurs as well as to the operator, hence a potential for the economic viability and sustainability of providing connectivity to rural areas (Ruonaja, 2009).

NEPAD´s ICT broadband is one example of regional efforts for ICT broadband infrastructures. The NEPAD ICT broadband infrastructure project aims to connect all African countries to one another and, in turn, to the rest of the world through broadband fiber-optic submarine cables (Akpan-Obong & Parmentier, 2007). Development of the NEPAD network started with two tracks: the NEPAD ICT broadband infrastructure network covering 23 countries in eastern and southern Africa and the NEPAD ICT broadband infrastructure network for west, central and north Africa, as shown in figure 1.1 and 1.2 respectively. The NEPAD submarine cable system is called UHURUNET while the terrestrial network is called UMOJANET (Katiti & Jere, 2010). UHURU is a Swahili word, which means Freedom. UHURUNET, a submarine segment of the NEPAD network, was named in recognition of the fiftieth anniversary of the beginning of Sub-Saharan independence from colonial rule as well as the importance of the cable for economic freedom in Africa. On the other hand, UMOJANET, a terrestrial segment of the NEPAD network, was named in recognition of the spirit of unity in action and united action by all the stakeholders of the countries of eastern and southern Africa involved in the project. UMOJA is a Swahili word meaning Togetherness (Katiti & Jere, 2010).

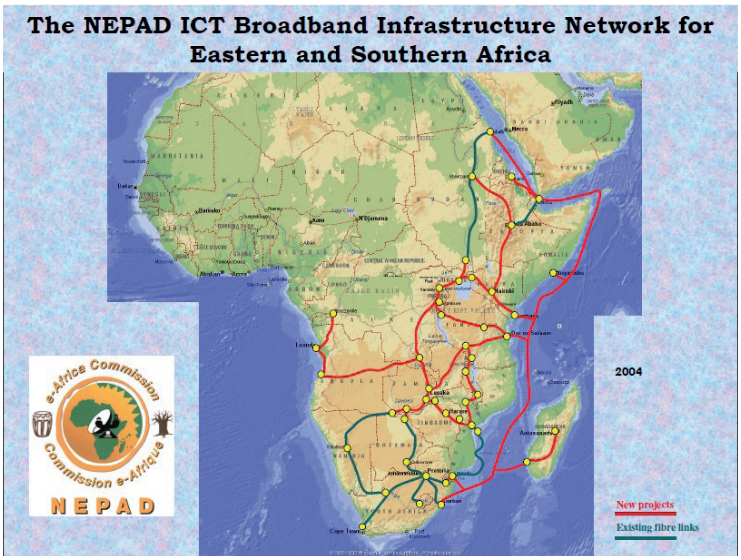


Figure 1.1: NEPAD´s Broadband ICT Infrastructure Network for Eastern and Southern Africa (Source: Katiti & Jere, 2010)

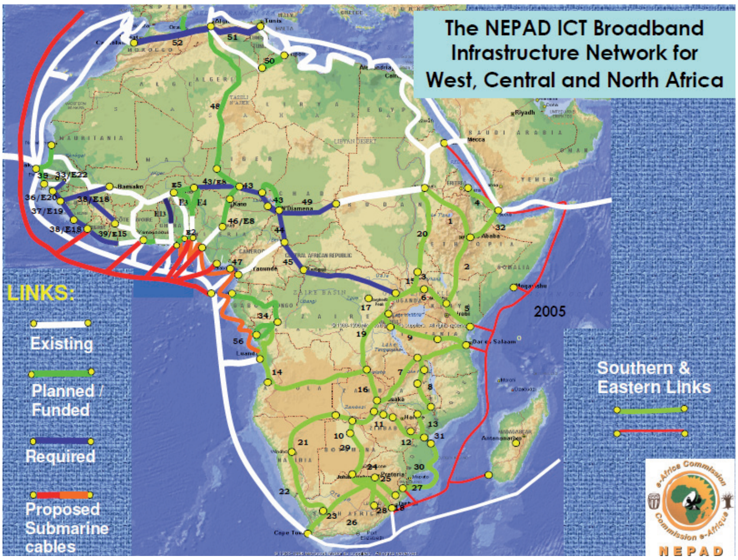


Figure 1.2: NEPAD's broadband ICT infrastructure for West, Central and Northern Africa (Source: Katiti & Jere, 2010)

1.1.2 Connectivity for Education Sector Initiatives

There are initiatives that are specific to provide ICT infrastructures for educational purposes. An example is the WSIS target number two, which was formulated intentionally to integrate ICT in education. Target two of WSIS reads *"Connect universities, colleges, secondary schools and primary schools with ICTs"* (ITU-WSIS Targets, 2010). There are many benefits in providing access to information and communication technologies within educational systems. One of which is to prepare students for the changing needs of labor markets and knowledge-based societies. Connectivity provide platform for students to acquire ICT skills as well address shortage of books, laboratory chemicals and teachers. Other benefits are support to teachers training through ICT enabled distance-education and improve administration of educational institutions so as to enhance teaching and learning process as well as quality and efficiency of service delivery (ITU-WSIS Targets, 2010).

Another example of a global initiative of ICT for education is the ITU´s *"Connect a school, connect a community"* initiative. This is a public-private partnership launched in 2009 to promote broadband school connectivity in order to serve both students and the nearby communities. Connected schools have the potential to serve as community ICT centers and hence provide access to nearby community (Schorr, 2010). The results achieved since the *"Connect a school, connect a community"* initiative was launched, including an online toolkit to share best practices, small-scale projects to develop national school connectivity plans, an e-accessibility toolkit for policy-makers, and a number of multipurpose community telecentres in developing countries (Schorr, 2010).

Apart from global initiatives, there are also regional efforts heading towards the same target of integrating ICT in educational systems. An example of a regional initiative for Africa is the NEPAD´s eSchools´ program. The NEPAD e-Schools initiative was publicly launched in Durban, South Africa, at the Africa summit of the world economic forum on June 12, 2003. The NEPAD e-Schools initiative is considered as a continental undertaking aimed at ensuring that African youth graduate from schools with the skills that will enable them to participate effectively in the global information society. The aim of the initiative is to impart ICT skills to young Africans in primary and secondary schools as well as harness ICT technology to improve, enrich and expand education in African countries. It is stated that, a NEPAD e-School should have the following as its main attributes (eSchool- Framework, 2004):

1. Appropriate ICT equipment and infrastructure
2. Connected to the Internet
3. Teachers trained to impart ICTs skills to students according to agreed curriculum and content
4. Teachers trained to use ICTs for teaching and learning
5. Access and contributes to appropriate teaching and learning materials
6. ICTs as tools to enhance the administration and management of the school
7. Equipped with a health centre.

1.1.3 ICT for Education Initiatives in Tanzania

Tanzania also has a number of initiatives aimed at integrating ICT in her educational system. The initiative includes development plans, policies and pilot projects.

The Tanzania education system consist of seven (7) years of primary education, four years (4) of ordinary level secondary education, two (2) years of advanced level secondary education and three to five (3 - 5) years of university or college education. In order to improve quality and access to education, in the year 2001 the Government prepared a five years (2002 - 2006) development plan for primary education, called Primary Education Development Plan (PEDP). The plan had five main objectives: (a) expand access to primary education; (b) improve education quality at that level; (c) increase pupils retention and completion; (d) improve institutional arrangements; and (e) enhance capacity building for efficient and effective delivery of education services (PEDP, 2001). In order to absorb output from PEDP, the government also prepared another five years (2004 - 2009) development plan for secondary level, called Secondary Education Development Plan (SEDP). The SEDP outlines the framework for achieving greater access to secondary education while simultaneously tackling equity, retention, quality and management issues (SEDP, 2003).

Inline with SEDP objectives, the Government in collaboration with the community succeeded to build over 3000 secondary schools at ward level within 3 years (2007 - 2010). It is estimated that the expanded number of secondary schools can absorb all qualified pupils from primary school into secondary education. Tanzania's significant achievements have not been without challenges. It has not been possible to match the schools expansion with the supply of qualified teachers. Hence, Tanzania was faced with two simultaneous challenges: (1) to provide the enrolled secondary students with the opportunity for a comprehensive and quality education; and (2) to enhance the teaching and learning environment as well as teaching capacity and competency in the secondary education level. These shortcomings and challenges in the teaching and learning process provide opportunities to deploy information and communication technologies to improve the process. One way to use ICT in education is through e-Learning (ICT-PolicyTz, 2003; ICT4E-PolicyTz, 2007). The e-Learning includes a wide variety of learning strategies and technologies, from Compact Disk-Read Only Memory (CD-ROMs) and computer based instruction to videoconferencing, satellite-delivered learning and virtual educational networks (Lating, 2009; Lujara, 2010). In contrast to traditional forms of teaching and learning that require participation in specific courses at specific times and locations, e-Learning can take place anytime and anywhere and from any source. The e-Learning's "anytime, anywhere" approach places different responsibilities on the individual learner, who must now be able to find, analyze, integrate, store and retrieve information in self-directed ways.

The Government of Tanzania through its ministry of education promoted literacy in ICT by issuing a syllabus of computer studies for secondary schools in 2000, which was revised in 2002. In 2007, the Government took further steps by developing an ICT policy to guide integration of ICT in basic education (ICT4E). The strategic integration of ICT in education is expected to improve access, equity, quality and relevance at all levels of basic education. The policy covers pre-primary, primary, secondary and teachers' education as well as non-formal and adult education (ICT4E-PolicyTz, 2007).

There are several initiatives on ICT for education underway in the country. The initiatives range from provision of ICT services to teachers training colleges, primary and secondary schools as well as implementation of ICT infrastructures. The implementation approach of most of initiatives is a public-private collaboration between the government through its Ministry of Education and Vocation Training (MoEVT) or its agencies and the private bodies such banks, technology companies or international development agencies. Agencies related to educational system in Tanzania are the Tanzania Education Authority (TAE) (www.tea.go.tz), the Tanzania Institute of Education (TIE) (www.tie.go.tz), the Tanzania Library Services Board (TLSB) (www.tlsb.or.tz), the Institute of Adult Education (IAE), National Council for Technical Education (NACTE), the Agency for Development Education Management (ADEM) (www.ademtz.com) and the National Examination Council of Tanzania (NECTA) (www.necta.go.tz).

It is worth to note that the use of ICT in education is dynamic, especially in developing countries, because ICT is a very dynamic sector. Therefore, different initiatives are announced on approximately monthly basis and therefore, ICT for education initiatives in Tanzania presented in this thesis should be regarded as indicative rather than exhaustive. They should be seen as a snapshot that was current at the time of writing this thesis. The initiatives on ICT for teachers training and secondary education are summarized in Table 1.1 and Table 1.2 respectively.

Table 1.1: ICT initiatives for teachers training sector

S/N	Initiative (projects)	Description
1.	Teacher Training Initiative for sub-Saharan Africa (TTISSA)	Implemented by The United Nations Educational, Scientific and Cultural Organization (UNESCO) and its main objective is to support countries in sub-Saharan Africa to develop Education Sector Management Information System (ESMIS)
2.	Information Communication Technology–Teacher Professional Development (ICT-TPD)	Under MoEVT aim to address shortage of teachers in key subjects (Mathematics, Science and English). It trains and supports pre-service and in-service teachers to use the existing ICT infrastructure in the teacher training colleges.
3.	ICT Implementation in Teachers Colleges (MoEVT and SIDA)	This is a collaborative effort between the MoEVT and The Swedish International Development cooperation Agency (Sida), aimed at introducing ICT in all teacher-training colleges. The project was initiated in 2005. By 2009 all 34 teachers training colleges were connected to the internet via VSAT technology. The programme's main goal is to improve the quality of teacher education by using ICTs in pre-service and in-service sessions. Tutors are expected to become ICT literate and able to use ICT as a tool for teaching and learning as well as for management and administration.
4.	ICT-based in-service teacher education for secondary school teachers in Tanzania (SPIDER, OUT, Mid Sweden University)	Under the Open University of Tanzania (OUT), Mid Sweden University (MiUn) and The Swedish Program for ICT in Developing Regions (SPIDER). Aims to equip teachers with basic ICT skills. Develop models for communication and distribution of learning material for different technical environments (broadband, VSAT, mobile phones, CD/DVD, memory cards etc). Encourage teachers and students to be involved in the development of ICT applications to enhance the teaching-learning process. Encourage and facilitate the use of the Internet as a research and communication tool among students, parents, teachers, and members of the community.

Table 1.2: ICT initiatives for secondary schools

S/N	Initiative (projects)	Description
1.	Tanzania beyond Tomorrow	An e-learning initiative launched by MoEVT in partnership with technology companies (Accenture, Intel, Microsoft and Cisco) and NGOs (NetHope, AMREF, World Vision) in 19th April, 2010. Aims to integrate ICT in teaching and learning process
2.	TanSSe-L (CoICT-UDSM)	The project is under the College of Information and Communication Technology (CoICT), University of Dar es Salaam. The project aims to provide e-learning services to rural secondary schools. It has three pillars: interactive learning management system, e-learning contents for self-learning and connectivity solution.
3.	The e-School Forum	Nine task forces were formed, focusing on key areas for ICT in secondary education (1) ICT infrastructure development (2) technical resources, (3) student management (integrated EMIS) (4) content and curriculum development (5) e-learning (6) sensitization (7) human resources (8) programme co-ordination (9) funding. At the time of writing this thesis, the e-School programme proposal was still under review by the MoEVT.
4.	Science, Technology and Higher Education Program (STHEP).	Is a programme under the MoEVT and the Ministry of Communication Science and Technology (MCST) aims to improve development of human capital in area of science and technology and create knowledge-based economy. This program focuses on National Research and Education Network (NREN), Education Management Information system (EMIS), e-Library and e-Learning.
5.	Zain, Build a Nation project	670 schools in Tanzania had benefited with textbooks or educational tools such as computers provided by the then Zain, now Airtel mobile network operator.
6.	Bridge IT project	The project is implemented under the management of International Youth Foundation. It is about the use of mobile phones to teach Maths and Science in class 5 and 6. It is operational in 150 primary schools. Pearson Foundation does development of course materials, hosting of the course materials is done by Vodacom. Delivery of the course materials is through Nokia phones to television set in the classrooms. Contents assist teachers in the classrooms.
7.	Computer for Schools Project	Barclays bank and Digital Links International company formed a partnership to spur the growth of ICT in schools across three countries in East Africa (Tanzania, Uganda, and Kenya). The project sets a target to place 10,000 computers in approximately 500 schools. The implementation strategy is through collaborative partnerships with organizations in each country. For Tanzania, the project is implemented by Tanzania Education Authority (TEA), Tanzania Commission of Science and Technology (COSTECH), and Mkombozi Centre for Street Children.
8.	Distance Learning Education Services (DILES) (IICD Supported)	Provide distance learning tools and services Develops teaching and learning materials for secondary schools These resources are available online (http://www.diles.or.tz).

The ICT for education initiatives summarized in Table 1.1 and Table 1.2 illustrates that Tanzania has a number of ICT for education initiatives running concurrently. Many of these initiatives are pilot projects, that are not well-documented, no clear strategic plan for their implementation and there is no centralized coordination. The missing coordination and strategy for implementation to the many ICT for education initiatives implies that opportunities to combine, or associate related projects are missed, hence duplication, lack of experience sharing, and a potential for ineffective use of resources and opportunities is inevitable.

Tanzania is currently preparing a National School Connectivity Plan (NSCP) under the Ministry of communication, science and technology in collaboration with ITU. The NSCP aims to provide an ICT broadband infrastructure master plan to facilitate implementation of broadband connectivity solution for primary and secondary schools as well as to tertiary education. Among other targets, the NSCP aims to address the lack of coordination and absence of a single ICT for education implementation strategy. During the time of writing this thesis, the NSCP was still under formulation.

1.2 Research Problem, Research Objectives and Research Questions

The initiatives for rural connectivity and integration of ICT in educational system are inline with the fourth attribute of the Tanzania National Development Vision, also known as Vision-2025. The Vision-2025 lists five attributes to be achieved by the year 2025. The attributes are (1) High quality livelihood (2) Peace, stability and unity (3) Good governance (4) A well-educated and learning society (5) A competitive economy capable of producing sustainable growth and shared benefits. The motivation for this research is the fourth attribute of the Vision-2025; that is to have “a well educated and learning society by the year 2025”. It has been noted that ICT is considered as an enabling tool to improve teaching and learning process and hence achieve the fourth attribute of the national development vision - 2025. The e-Learning, which is one of the ICT-based services, has the capability to address shortage of teachers, books and the inefficient teaching and learning process.

In order to deliver e-Learning services, a proper solution to the existing lack of connectivity and electrical power is a requirement. It is worth noting that wireless technologies, which includes Wireless Fidelity (WiFi), Worldwide Interoperability Microwave Access (WiMAX) and cellular mobile wireless technologies have been earmarked as potential candidates for communication in rural and low population density environments of developing countries (Islam et al., 2006; Raman & Chebrolu, 2007; Simba et al., 2009b). However, practical experiences in various developing countries showed that implementation of such technologies at affordable installation and operational costs is still a problem (Anatory et al., 2004; Simba et al., 2009).

It has been noted that there are efforts underway to reduce connectivity costs. For example, most of the African countries have liberalized their telecommunication regulations to enable more competition and diversity of service providers (Farrell et al., 2007; Calindi et al., 2008; ICT-PolicyTz, 2003). Although, this approach has an effect to lower cost of access to ICT services; costs of establishing ICT infrastructure remain unaffordable for most of the rural community and educational institutions, especially those in the rural areas. There is a huge gap between urban and rural areas in terms of ICT infrastructures and access to ICT services (Farrell et al., 2007).

Unfortunately, the many initiatives of ICT for education in Tanzania, that could facilitate e-learning to secondary schools, miss coordination and strategy for sustainable implementation. Almost all of them are pilot projects funded through donor projects, which reflects a challenge for their sustainability. The common implementation approach of the existing initiatives is a "top-down" model. This model usually lack contextual touch to the end users. This means that the initiatives might miss readiness for its adoption by schools, or the schools might be inadequately prepared to receive the initiative´s output such as infrastructure or services. Consequently, schools will remain with poor ICT infrastructures and lack of ICT-based service, especially those in rural and remote areas.

From the background information, it is clear that efforts are underway to develop ICT infrastructure for rural areas. However, the current status is that, rural areas have limited or total lack of ICT infrastructures, especially the last mile connectivity, which is also known as access network, to support e-Learning services. The lack or limited access is spearheaded by the high cost of implementation and maintenance of ICT infrastructures in rural areas. In order to address the earmarked problem, the research work presented in this thesis was done based on the following research objectives:

1.2.1 General Objective

The general objective of this work is to determine a viable connectivity technology for e-Learning uses in rural secondary schools in Tanzania.

1.2.2 Specific Objectives

1. To determine a cost-effective access network technology for the rural areas.
2. To evaluate performance of e-learning applications delivered over the identified cost-effective connectivity technology.

1.2.3 Research Questions

The research journey towards achieving the set objectives was guided by the following research questions:

1. What constitutes a cost-effective access network technology for rural areas?
2. What are the network´s key performance parameters in order to deliver e-learning services with the required quality of service?

1.3 Research Scope, Context and Significance

This research deals with the secondary schools part of the Tanzania educational system with focus on the rural schools. The prioritization of rural secondary schools is because they are the disadvantaged group in terms of access to qualified teachers, teaching materials, ICT infrastructures and ICT-based services. Traditionally, the term "rural" was applied to the countryside and often used as the opposite of "urban". A rural area may consist of scattered settlements or small towns located several tenths or hundreds of kilometers from an urban or city center. However, in some cases a suburban area may also be considered a rural area. A rural area usually exhibit at least one of the following characteristics (Kawasumi, 2000):

1. Low population density, low level of education, low per capita income and low level of economic activities mainly based on agriculture, fishing and handcrafts.
2. Scarcity or absence of public facilities such as electricity, water and access roads.
3. Difficult topographical conditions such as lakes, rivers, hills, mountains or deserts which result in a high cost in construction of telecommunication infrastructures.
4. Underdeveloped social infrastructures such as health and education sectors
5. High cost of ICT based services, reflecting the scarcity of the service, as a result, a large number of people rely on single shared access facility.

In this study, the term "rural" refers to areas poorly served by ICT facilities, where various factors interact to make the establishment of ICT services difficult or expensive. It should be noted, that a rural secondary school should not necessarily be located at the defined rural areas. A secondary school is referred to as rural school, regardless of its geographical location as long as it is characterized by a shortage of teachers, limited teachers´ competence, shortage and/or use of outdated textbooks and a lack of or limited access to basic ICT infrastructures. This definition is inline with the definition provided by Kalinga (2010).

Results of the research work presented in this thesis can be a useful input to the Government and to other stakeholders such as donors or management of the ICT for education initiatives. Having a scientific procedure presented in chapter four that can lead to identify a cost-effective connectivity solution to rural areas, can be a helpful decision support tool to any project aiming at implementing ICT infrastructure in the rural areas. The results can also serve as indicative information to the Government in its budgeting processes on deciding how much is to be allocated for ICT to secondary schools.

The research has recommended a model of strategic implementation of rural ICT infrastructure projects to ensure sustainability, usefulness and adoption to the community they were aimed at. This result can be useful to the Ministry of communication, science and technology in its national school connectivity plan project, which aims to prepare an ICT broadband infrastructure master plan to facilitate implementation of broadband connectivity solution for primary, secondary schools and to tertiary institutions in the country.

The fundamental aim of e-learning applications performance evaluation is to come up with the key network performance parameters that can provide e-learning services with the required quality of service. Thereafter, these parameters can be recommended to the network or service providers for their network configuration processes in order to effectively deliver e-learning services.

1.4 Thesis Organization

This thesis is composed of seven chapters. Chapter one is the introduction presenting background information with regard to rural connectivity and ICT for education initiatives globally, regional-wise and specific ones in Tanzania. Chapter one also presents research problem, research objectives and research questions. Significance of the research, scope and context are also part of chapter one. Chapter two reviews concepts that are relevant in the research reported in this thesis. The main concepts reviewed are traffic engineering, quality of service, wireless radio network planning, techno-economic analysis and emerging research approaches. Research methodology is covered in chapter three. Chapter four explains different techniques which were used to determine a cost-effective access network suitable for the rural areas. Chapter five present development of a network simulation model. The model is further used to evaluate performance of e-learning application for quality of service. A model for provision of sustainable broadband rural connectivity is presented in chapter six. Research conclusion, contributions and direction for further research work finalizes the thesis in chapter seven.

CHAPTER TWO
CONCEPTS OVERVIEW

This chapter provides an overview of concepts that were relevant and therefore, they have been used in the research work reported in this work. The main concepts reviewed are traffic engineering, quality of service, wireless radio network planning, techno-economic analysis and emerging research approaches.

2.1 Traffic Engineering

Traffic engineering is defined as the application of set of theories and techniques to find solutions of problems concerning planning, performance evaluation, operation and maintenance of data communication or telecommunication systems (Braun et al., 2008; Iversen, 2004). More generally, traffic engineering can be viewed as a discipline of planning where the tools (stochastic processes, queuing theory, mathematical and simulation modelling) are taken from operations research discipline. The theory of traffic engineering was originally conceived by a Danish mathematician called A.K Erlangs who developed methods of signal traffic measurement in the early 1900s (Michiel & Laevens, 1997). Quality of service, radio network planning and optimization, in telecommunication networks, are the main activities that make use of traffic engineering (Svoboda, 2008).

Performance evaluation, which is part of radio network planning and optimization, can be solved by using teletraffic theory. Performance evaluation usually seeks to identify the achievable performance of a system. That is to find a balance between quality of service (QoS), network capacity and traffic demand. It is basically to balance the QoS against cost of operating and maintaining the network. Therefore, QoS is an output parameter, while demand and capacity are input parameters (Svoboda, 2008). Performance evaluation is crucial in the setup phase of a network, and later on in the optimization process. The optimization process is basically fine tuning the network configuration, such as finding out how much capacity needs to be added in order to meet the target QoS for a given increase in demand. There are three different approaches to solve a teletraffic engineering problem: analytically, by simulation or by measurement.

An analytical solution is usually a closed form equation, or at least a numerical approximation, describing the relationship between QoS, demand and capacity. This has several advantages for understanding the investigated network elements. The solution can be calculated directly and hence provides a deep insight into how the three parameters (QoS, network capacity and traffic demand) are linked together. Analytic solutions are commonly used in science and engineering disciplines (Zukerman, 2000). However, many of the real world systems, especially telecommunication system, are very complex to be accurately represented mathematically. In such situation, it is often necessary to simplify the analytical models, also known as mathematical models, as long as the accuracy still holds, otherwise an alternative solution is to use simulation approach (Mbiydzenyuy, 2010; Maria, 1997).

Simulation approach is a scientific way of representing complex systems under study. Taking an example of telecommunication networks, simulation software can represent (simulate) properties of all network elements between sender and receiver of the traffic, including the protocols. Ideally, simulation provides similar results as if the performance evaluation was done by taking measurements from a real world network. However, due to computational restrictions simulations approach often apply simplifications, which in turn can compromise the accuracy. The main advantage of simulations models is the fact that they are simpler to implement than analytical models and more flexible than real world measurements. It is due to their implementation simplicity and flexibility that makes them be often used in network performance evaluations and optimizations (Laiho et al., 2006; Holma & Toskala, 2004). Both, analytical and simulation based approaches often have to make assumptions to simplify the problem. Measurement based evaluations are important in verifying the results of these two approaches; analytical and simulation. However, measurement methods for network performance evaluation or validation of analytical or simulation results is only possible if the real-world network exists and it is operational.

Analytical and simulation models usually require presence of traffic models to facilitate performance evaluation. Thus, traffic models are specifically designed to generate an input load for evaluation, either analytically or by simulation. In the case of analytical modelling, it must be possible to describe the traffic model in a closed mathematical form. Simulation based experiments are not limited to such restrictions; in fact some simulations use recorded traces as input sources for traffic models. In communication networks, traffic models can be developed with regard to different layers of the protocol stack, e.g. packet level, flow level or application level traffic models. At packet level, the parameters for the traffic model define the arrival process for each packet and the size distribution of all packets. The models usually use stochastic processes to describe the arrival. At the packet layer, there is no differentiation between packets, such as user data and application signaling. Therefore, this approach is strongly limited when QoS of the application is a target output for the simulation. (Svoboda, 2008; Khalifa & Trajkovic, 2004).

Both models (packet and flow level) cannot reproduce user interactions happening at the client side. This input can only be implemented in the source traffic models (Staehle et al., 2001). The source traffic models reproduce the usage of applications and their objects, e.g., a source traffic model for Hyper Text Transfer Protocol (HTTP) browser application describes the arrival process of user sessions in terms of requests to a web server and the properties of the web pages. A webpage is a resource for information in the World Wide Web (WWW). The advantage of source traffic models is the fact that the parameters are related to application properties, e.g., a question like how much traffic is generated in case the user population doubles can be answered. In addition, source traffic models are independent of the underlying transport network, e.g., the same e-mail model can be used for second generation (2G) and third generation (3G) networks. This is not the case for the packet and flow level models. In packet modelling, one model is able to describe all the traffic in a link, while source traffic model for each service has to be modeled separately (Svoboda, 2008).

Another approach to generate traffic for performance evaluation is the playback of measurement-based traces. These traces can be used as an input vector for network simulations. Although it seems like measurement-based traces are precise method to reproduce traffic, as they were directly taken form a real network; a playback of such traces lacks some of the interaction that took place on the real network. For example in a real world network setup, TCP congestion control would reduce data rate of each flow as congestion arises, but this effect can hardly be represented in measurement traces.

2.2 Quality of Service (QoS)

The International Telecommunications Union is a body of the United Nations (UN) responsible for aspects of telecommunications. It has three sectors: Radio Communication (ITU-R), Telecommunication Development (ITU-D) and Telecommunication Standardization (ITU-T). The ITU-T sector is responsible for the creation of telecommunications standards, which are published as ITU-T recommendations. Recommendations are developed by technical groups known as study groups, each of which is responsible for a specific technical area, e.g. ITU-T study group 12 abbreviated as ITU T SG 12, is the lead study group for work on performance and QoS in Telecommunication systems.

The ITU-T define quality of service in its recommendation E.800 as *"The collective effects of service performance which determine the degree of satisfaction of a user of the service"* (ITU-T-Rec-E.800, 2008). Quality of service is also defined by Braun et al., (2008) as a measure of the ability of network and computing systems to provide different levels of services to selected applications and associated network flows. The term QoS is extensively used today, not just in the analogue telecommunications world in which it has its roots, but also increasingly in Internet Protocol (IP)–based networks. According to ITU-T-Rec-E.800, (2008), the QoS definition can be viewed in four different perspectives: customer's QoS requirements, QoS planned by service provider, QoS achieved by the service provider and QoS perceived by the customer as shown in Figure 2.1.

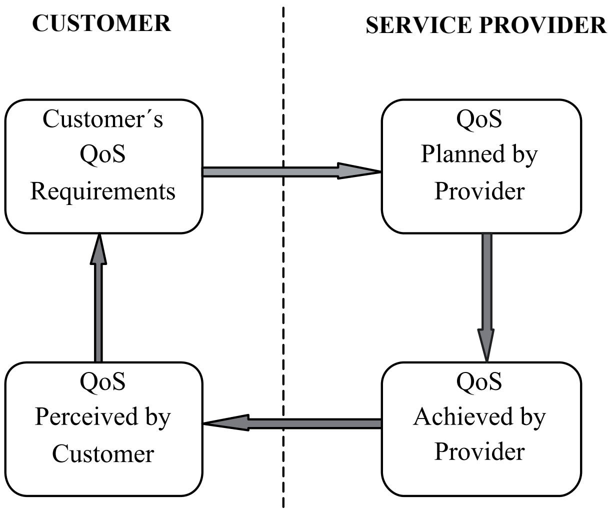


Figure 2.1: The Four Viewpoints of QoS

ITU-T-Rec-E.800, (2008) and ITU-T-Rec-G.1000, (2001) defined characteristics of the four viewpoints of QoS as follows: QoS requirements by the customer are the statement of the level of quality of a particular service. The level of quality can be expressed by the customer in technical or non-technical language. A typical customer is not concerned with how a particular service is provided or with any of the network's internal design, but only interested with the resulting end-to-end service quality. QoS planned by the service provider is a statement of the level of quality expected to be offered to the customer by the service provider. The level of quality is expressed by values assigned to QoS parameters. The service provider may express the offered QoS in non-technical terms for the benefit of customers and in technical terms for use within the business. QoS achieved by the service provider is a statement of the level of quality provided to the customers. It is expressed by values assigned to parameters, which should be the same as those specified for the planned QoS so that the two can be compared. QoS perceived by the customer is a statement expressing the level of quality they believe they have experienced. It is also known as Quality of Experience (QoE). It is expressed in terms of degree of satisfaction and not in technical terms.

The next sections presents how QoS is supported in the Internet, which is the widest global communication network and then specifically how QoS is supported in the Universal Mobile Telecommunication Systems (UMTS), the 3G network technology.

2.2.1 QoS Support in the Internet

The Internet was originally designed to offer best effort data services, that is all services share network resources equally: they get the same bit rate and experience the same delay (Jiang, 2006). In other words, best efforts networks means, packets forwarding is performed without guaranteeing bandwidth or delay bounds (Braun et al., 2008). Due to vast development and deployment of multimedia applications such as video conferencing, video streaming, interactive web browsing and database access, the best effort approach was not capable enough to deliver these services efficiently. Therefore, there was a need to support or replace the existing best effort with a model in which applications can be treated differently according to their required quality of service. With this requirement, the Internet Engineering Task Force (IETF) developed two extensions to support provisioning of quality of service required by different applications. The extensions are called Integrated Service (IntServ) approach and the Differentiated Service (DiffServ) approach (Jiang, 2006; Costa, 2002).

2.2.1.1 Integrated Services (IntServ)

The Integrated Services (IntServ) approach adopts a reservation-based architecture. It provides end-to-end service guarantees on a per-flow basis. In this architecture, an application session requiring QoS guarantees must send a resource request along its path before the session starts. Along the path, each network equipments, especially routers determine whether they have sufficient resources (buffers, link bandwidth, etc) enough to satisfy this request. If the router has these resources, mechanisms are applied to reserve them for the flow. IntServ relies on three techniques (1) a signaling protocol for the resource request and notification once the request is successful, (2) an admission control process to determine whether the router should accept or reject the resource request and (3) a resource reservation mechanism to guarantee that the corresponding resources are reserved for the application session, if the resource request was accepted.

For the signaling protocol, IntServ uses resource reservation protocol (RSVP). The RSVP is a receiver-initiated resource reservation protocol. When an application session with QoS requirement needs to reserve resources along its path, it sends a path message with a traffic specification (TSpec) of the data stream that the sender is going to generate. Upon receiving the path information and TSpec, the receiver initiates the resource reservation request based on the TSpec along the reverse path of the data stream (Deering et al., 2002;Jiang, 2006).

For admission control, each router along the path of the application session makes decision based on the (TSpec) of the session and its reservation specification (RSpec). TSpec specifies the traffic characterization of the session, whose parameters include token rate, bucket depth, peak traffic rate and maximum packet size. RSpec describes the level of service desired by the session such as desired bandwidth and delay guarantees (Jiang, 2006).

For resource reservation, usually the router adopts per-flow fair queuing (PFFQ) to reserve desired resources, particularly bandwidth, to the session based on its traffic specification, TSpec and reservation specification, RSpec. There are two categories of PFFQ scheduling disciplines: timestamp-based fair queueing and round robin-based fair queuing (Jiang, 2006).

IntServ defines two classes of service, which are guaranteed service and controlled load service, in addition to the existing best-effort service (Jiang, 2006). The Guaranteed service is a deterministic service, it specifies a service that provides firm bounds on the queuing delays that a packet of a session experiences along the path of the session. Controlled load service is a stochastic service, it provides a service whose quality received by a session is closely approximating the quality of service that it would receive from an unloaded network. In addition, such a service quality is assured even when the network element is overloaded (Jiang, 2006).

2.2.1.2 Differentiated Services (DiffServ)

The adoption of per-flow resource reservation in IntServ implies that a router has to maintain per-flow states and processes each flow passing through it. Since in a large network, the number of flows can be very large, per-flow processing becomes a significant overhead, which leads to scalability and performance challenges. To address challenges encountered in the IntServ scheme; Differentiated service (DiffServ) approach is considered as a good compromise between high scalability for large IP networks and relative QoS guarantees. In the DiffServ architecture, instead of manipulating per-flow state at each router, relative QoS guarantees are assigned to traffic aggregates, which are defined at network edges. In DiffServ, flows with similar performance requirements are aggregated. Information on per-flow classification is implemented only at edge routers. In the core network, routers provide service guarantees only on a class basis rather than the per-flow basis. In addition, as opposed to end-to-end service guarantees in IntServ, DiffServ provides service guarantees mainly in a hop-by-hop or node-by-node manner based on the defined Per-Hop Behavior (PHB) (Blake et al., 1998). An undergoing effort is to define Per-Domain Behaviors (PDBs) to describe edge-to-edge service guarantees provided by a DiffServ network or domain (Jiang, 2006). DiffServ has defined two PHBs, namely Expedited Forwarding (EF) PHB and Assured Forwarding (AF) PHB group. The expedited forwarding (EF) class is used for low-latency and low-loss service, and the assured forwarding (AF) classes are used for non-delay stringent services. The AF PHB group defines four independently forwarded classes, AF1, AF2, AF3, AF4 (Jiang, 2006).

2.2.2 QoS Support in UMTS Network

The Universal Mobile Telecommunication System (UMTS) is a standard developed for the third generation (3G) wireless mobile communications. The third generation partnership project (3GPP) is responsible for UMTS standardization. This section provides brief overview about architecture of UMTS network, UMTS traffic classes, UMTS bearer services, QoS differentiation in UMTS networks and QoS mapping between UMTS networks and external Internet Protocol (IP)-based networks.

2.2.2.1 Architecture of UMTS Network

The network architecture of UMTS is made up of three logical entities: the end terminal called user equipment (UE), the Universal Terrestrial Access Network (UTRAN) and the Core Network (CN) (Holma & Toskala 2004; Molisch, 2011). Figure 2.2 depicts the architectural components of the UMTS network.

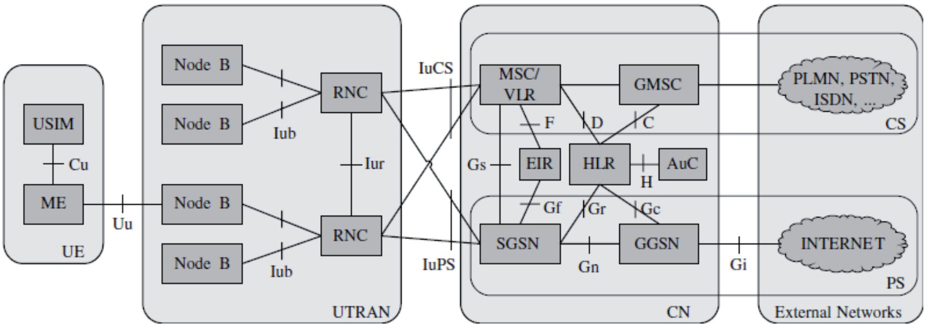


Figure 2.2: The 3G UMTS Architecture Showing Elements and Interfaces (Source: Holma & Toskala, 2004).

The user equipment (UE) domain consists of User Service Identity Module (USIM) and Mobile Equipment (ME), which comprises of Terminal Equipment (TE), Terminal Adapter (TA) and Mobile Termination (MT). UMTS mobile station (UE) can operate in one of three modes of operation:

- PS/CS mode of operation: The MS is attached to both the packet switched (PS) domain and circuit switched (CS) domain, and the MS is capable of simultaneously operating PS services and CS services.
- PS mode of operation: The MS is attached to the PS domain only and may only operate services of the PS domain. However, this does not prevent CS-like services to be offered over the PS domain (like VoIP).
- CS mode of operation: The MS is attached to the CS domain only and may only operate services of the CS domain.

Wideband Code Division Multiple Access (WCDMA) technology was selected for UTRAN air interface in the UMTS networks. The UTRAN part contains one or more Radio Network Subsystem (RNS). The RNS consists of one Radio Network Controller (RNC) and one or more Node Bs (also known as base station). The Node Bs are responsible for performing air interface layer1 processing (channel coding and interleaving, rate adaptation, spreading, etc.), based on the WCDMA technology. The RNCs are the network elements responsible for controlling the radio resources of the

UTRAN. The main function of UTRAN is to provide air interface access method for user equipment (Holma & Toskala, 2004; Molisch, 2011).

The main function of the core network is to provide switching, routing and data connections to the external networks. Core network also contains databases and network management functions. The core network is divided in circuit switched and packet switched domains. Some of the circuit switched elements are Mobile services Switching Centre (MSC), Visitor Location Register (VLR) and Gateway MSC (GMSC). Packet switched elements are Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN). Some network elements like EIR (Equipment Identity Register), HLR, VLR and AuC (Authentication centre) are shared by both domains. The Asynchronous Transfer Mode (ATM) is defined for UMTS core transmission.

As mobile networks evolve, they provide various services including voice, video, data, and multimedia. In order to efficiently support various services with QoS requirements, ATM based transmission schemes have been introduced in radio access networks (RAN). In particular, ATM Adaptive Layer 2 (AAL2) schemes have been standardized to support QoS and efficient link transmission utilization (Holma & Toskala, 2004; Molisch, 2011).

The WCDMA technology for UMTS has two basic modes of operation: Frequency Division Duplex (FDD) and Time Division Duplex (TDD). The UMTS entities are connected with each other through interfaces which are briefly described as follows (Holma & Toskala, 2004; Molisch, 2011):

- Uu interface: This is the WCDMA radio interface through which the UE accesses the UTRAN part of the system
- Iub interface: The Iub connects NodeB and RNC. This is an interface between the base stations and its controller
- Iur interface: This interface allows soft handovers between RNCs and is defined between every two RNCs
- Iu interface: This interface connects UTRAN to the CN. The Iu interface is of two type to cater for circuit switched and packet switched parts of the system. The IuCS is between RNC and MSC/VLR, used for circuit switched traffic and IuPS is between RNC and SGSN, used for packet switched traffic.

2.2.2.2 UMTS Traffic Classes

The third generation partnership project (3GPP), which is the body responsible for standardization of UMTS, has specified four types of QoS classes, referred to as traffic classes, for the UMTS network. The four traffic classes defined are conversational, streaming, interactive and background (Holma & Toskala, 2004; Molisch, 2011). The main distinguishing factor in the QoS requirements of traffic classes is how delay sensitive the traffic is. The conversational class is meant for very delay-sensitive traffic, while the background class is the most delay-insensitive. Conversation and streaming classes are aimed at real time applications such as audio conversation, video conferencing and video streaming. Interactive and background classes, are intended to cover all traditional Internet applications, such as web browsing, email, and file transferring.

The conversational class is characterized by low end-to-end delay and symmetric or nearly symmetric traffic between uplink and downlink in person-to-person communications. The streaming class requires bandwidth to be maintained like conversational class but it tolerates some delay variations that are hidden by dejitter buffer in the receiver. This class carries traffic of a video or audio stream from a host machine to a human end-user, and is a one-way transport. Streaming class requires the time relation between the traffic consecutive entities be reserved. However, it has much lower delay sensitivity when compared to the conversational class. Examples of its application are video streaming or Internet radio.

Both conversational and streaming classes require the guaranteed bit rate and the transfer delay parameters. The guaranteed bit rate defines the minimum bearer bit rate that the UTRAN must provide and it can be used in admission control and in resource allocations. The transfer delay defines the required 95th percentile of the delay. It can also be used to define the radio link control (RLC) operation mode (acknowledged, non-acknowledged or transparent mode) and the number of retransmissions (Holma & Toskala, 2004).

The interactive class is characterized by the request response patterns, a sort of client-server communication. At the message destination, in the interactive class, there is an entity expecting the message (response) within a certain time. Example applications are web browsing and database queries. The background class is also a sort of request-response patterns, but it assumes that the destination is not expecting data within a certain time. Data is sent or received in the background mode without any delay sensitivity. Examples of such kind of application are email and downloads for automatic software updates (Holma & Toskala, 2004).

2.2.2.3 UMTS Bearer Services

UMTS network technology provides data, video and voice services. The services traffic passes through different network nodes on their way from source terminal equipment (TE) to the destination TE. Therefore, the end-to-end QoS provisioning in UMTS network depends on the performance of three distinct parts: the terminal equipment/ mobile termination (TE/MT) bearer service, the UMTS bearer service, and the external bearer service as shown by the UMTS end to end QoS architecture in figure 2.3 (Garg & Yu, 2000; Agharebparast & Leung, 2002). A bearer service in UMTS network incorporates all aspects needed to provide a pre-defined quality to a particular service.

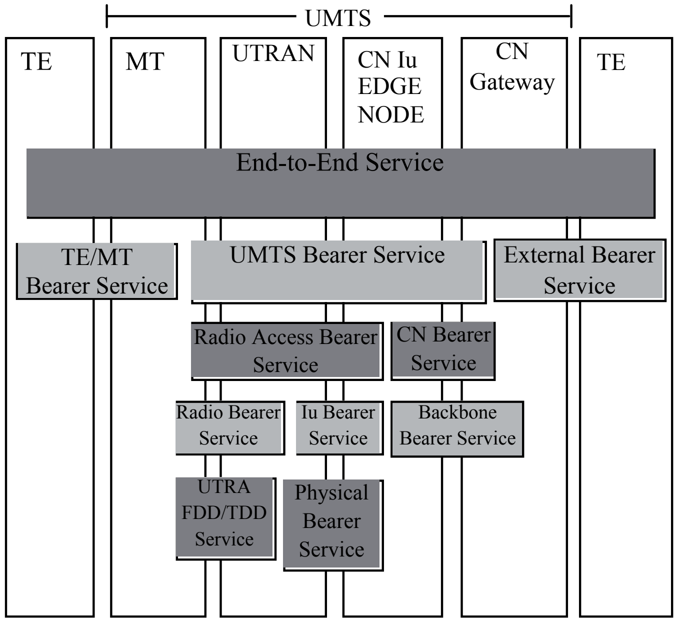


Figure 2.3: UMTS QoS Architecture (3GPP-TS-23.107, 2002).

The UMTS bearer service consists of two parts: The Radio Access Bearer (RAB) service and the Core Network Bearer (CNB) service. The RAB service provides a secured transport of signaling and user data between MT and CN edge node through the Iu inteface, with QoS adequate to the negotiated UMTS bearer service (Garg & Yu, 2000; Agharebparast & Leung, 2002). The core network bearer (CNB) service connects the Iu edge node with the core network gateway to the external network. The role of this service is to efficiently control and use backbone network to provide the contracted (agreed upon) UMTS bearer service. The Iu bearer service together with physical bearer service provides transport between UTRAN and CN. The CNB service is selected according to operator's choice to satisfy the QoS requirements of the CN bearer service (Garg & Yu, 2000; Agharebparast & Leung, 2002).

In UMTS network, when a terminal attaches itself to the network, a tunnel is established between the terminal and the GGSN. This tunnel, also known as Packet Data Protocol (PDP) context, provides the UMTS bearer services. An example of PDP context setup process is shown in figure 2.4.

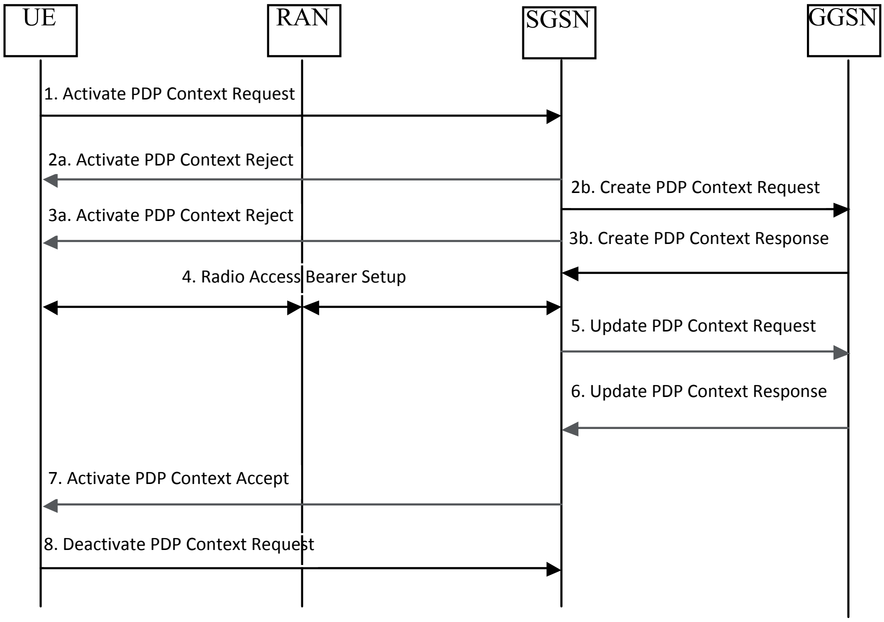


Figure 2.4: PDP Context Setup

QoS is one of the most important attributes of a PDP context and is negotiated during PDP context setup. QoS requirements are communicated by using QoS profiles, which has a number of attributes. The QoS profile is negotiated with the user as part of the PDP context establishment process. It indicates the type of traffic class (conversational, streaming, interactive or background), for which the context is negotiated. Other attributes that are negotiated during PDP context setup are; common to all traffic classes: maximum bitrate, delivery order, maximum Service Data Unit (SDU) size, SDU error ratio, residual bit error ratio, delivery of erroneous SDUs and allocation/retention priority. Common to the conversational and streaming classes: SDU format information, the transfer delay and the guaranteed bit rate. Figure 2.5 illustrate mechanisms used to define and provide the QoS parameters in radio access bearer set-up (Holma & Toskala, 2004).

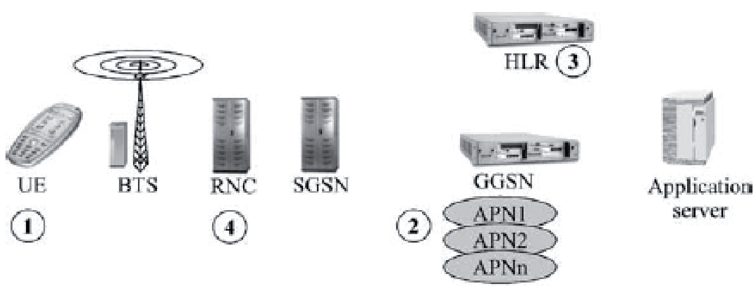


Figure 2.5: The role of UE, GGSN and HLR in defining QoS class

1. UE requests QoS parameters. The QoS parameters are requested by the UE and given by the core network to the radio network in radio access bearer set-up. For example, if the application requires guaranteed bit rate services such as conversational class, it has to be requested by UE, otherwise, the network cannot provide it.
2. Different Access Point Nodes (APNs) in GGSN can be used to provide different QoS parameters according to operator´s settings. Some services may be accessed via certain APNs, that allows the operator to control the QoS parameters for different services and makes it possible to prioritize operator-hosted services compared to accessing other services.
3. The home location register (HLR), may contain subscriber specific limitations for the QoS parameters.
4. The WCDMA radio network must be able to provide the QoS differentiation in packet handling according to different services´ QoS requirements.

The UMTS bearer attributes and radio access bearer attributes values and their relationships for each traffic class are summarized in Table 2.1 and Table 2.2.

Table 2.1: Value Ranges for UMTS Bearer Service Attributes

Traffic Class	**Conversa-tional Class**	**Streaming Class**	**Interactive Class**	**Background Class**
Maximum bit rate (Kbps)	Up to 2000	Up to 2000	Up to 2000	Up to 2000
Delivery Order	Yes/No	Yes/No	Yes/No	Yes/No
Maximum SDU size (octets)	1500	1500	1500	1500
Delivery of erroneous SDU	Yes/No	Yes/No	Yes/No	Yes/No
Residual BER	5*10-2, 10-2, 5*10-3, 10-3, 10-4, 10-5, 10-6	5*10-2, 10-2, 5*10-3, 10-3, 10-4, 10-5, 10-6	4*10-3, 10-5, 6*10-8	4*10-3, 10-5, 6*10-8
SDU Error ratio	10-2, 7*10-3, 10-3, 10-4, 10-5	10-1, 10-2, 7*10-3, 10-3, 10-4, 10-5	10-3, 10-4, 10-6	10-3, 10-4, 10-6
Transfer Delay	Max. 100ms	Max. 280ms	-	-
Guaranteed bit rate (kbps)	Up to 2000	Up to 2000	-	-
Traffic handling priority	-	-	1,2,3	-
Allocation/retention priority (ARP)	1,2,3	1,2,3	1,2,3	1,2,3

Table 2.2: Value Ranges for Radio access (UTRAN) Bearer Service Attributes

Traffic Class	Conversational Class	Streaming Class	Interactive Class	Background Class
Maximum bitrate (Kbps)				
Delivery Order	Yes/No	Yes/No	Yes/No	Yes/No
Maximum SDU size (octets)	1500	1500	1500	1500
Delivery of erroneous SDU	Yes/No	Yes/No	Yes/No	Yes/No
Residual BER	5*10-2, 10-2, 5*10-3, 10-3, 10-4, 10-5, 10-6	5*10-2, 10-2, 5*10-3, 10-3, 10-4, 10-5, 10-6	4*10-3, 10-5, 6*10-8	4*10-3, 10-5, 6*10-8
SDU Error ratio	10-2, 7*10-3, 10-3, 10-4, 10-5	10-1, 10-2, 7*10-3, 10-3, 10-4, 10-5	10-3, 10-4, 10-6	10-3, 10-4, 10-6
Transfer Delay	80ms	250ms	-	-
Guaranteed bit rate (kbps)	Up to 2000	Up to 2000	-	-
Traffic handling priority	-	-	1,2,3	-
Allocation/retention priority (ARP)	1,2,3	1,2,3	1,2,3	1,2,3

Because conversational and streaming applications require guaranteed bit rate and transfer delay, therefore in order to ensure that the interactive applications do not suffer excessive delays, the 3GPP-TS-23.107, (2002) recommended that interactive and background flows be separated (differentiated) by giving interactive traffic a higher priority in scheduling than background traffic. The background applications will only use transmission resources when interactive applications do not need them. Such scheduling is particularly important in a wireless access environment due to the constraints on bandwidth.

2.2.2.4 QoS Differentiation in UMTS Networks

The UMTS network supports delivery of multiple services; therefore, it is important to prioritise different services according to their requirements. The prioritization is called QoS differentiation or service differentiation. With QoS differentiation, each service is served according to its QoS requirements. The 3GPP QoS architecture is designed to provide this differentiation. It is a framework designed to make applications work in loaded multiservice scenario (Holma & Toskala, 2004).

Figure 2.6 shows an example of the best effort service delivery, where all the services have the same treatment. In this case, all services share network resources equally, they get the same bit rate and experience the same delay. The network dimensioning must be done in such a way that, this bit rate or delay fulfils the most stringent requirements of the services provided in the network. As a consequence, other services such as sending of MMS, the background type of service, will get the same quality, which is unnecessarily good and wastage of network resources (Holma & Toskala, 2004).

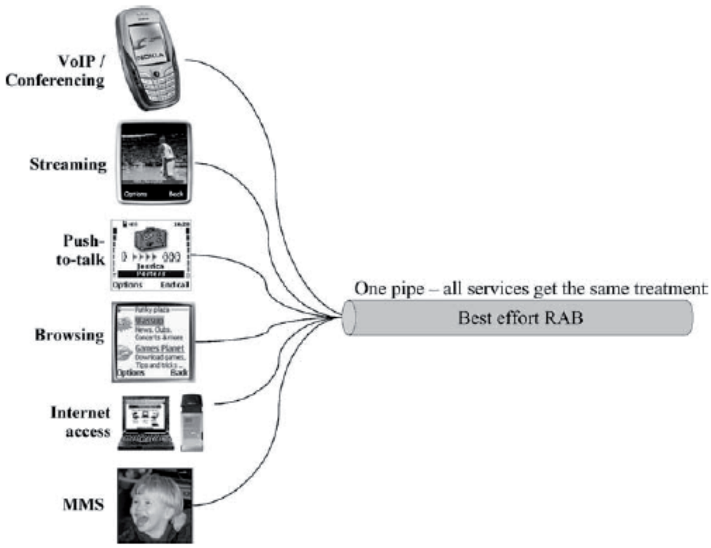


Figure 2.6: No QoS differentiation (Best effort) – all services use the same QoS parameters (Source : Holma & Toskala, 2004).

However, the QoS differentiation becomes useful for network efficiency during high network load, and when services have different QoS requirements. If the radio network has knowledge about the delay requirements of the different services, then it become possible to prioritize the services accordingly and improve the efficiency of the network utilization. An efficient gain (performance improvement) can be obtained by using the allocation and retention parameters to introduce prioritized classes (Holma & Toskala, 2004). Figure 2.7 shows the case where there are three different pipes with QoS prioritization in packet scheduling and figure 2.8 adds two more pipes with guaranteed bit rates. These approaches provide QoS differentiation.

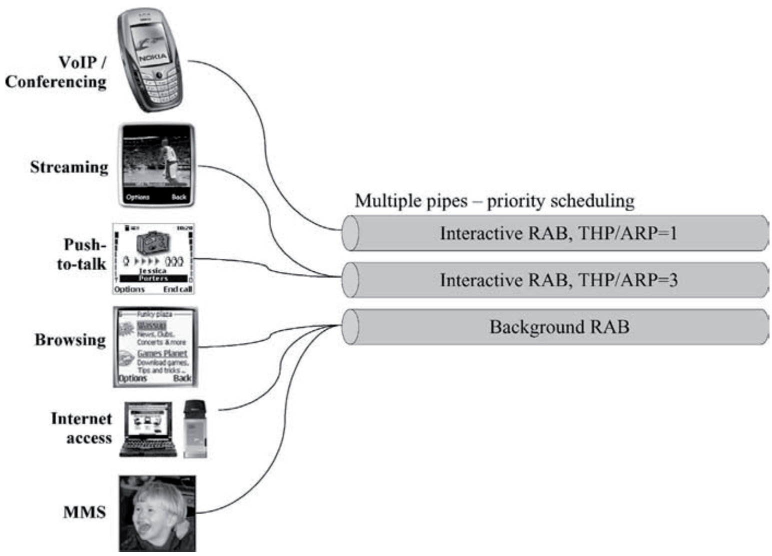


Figure 2.7: QoS prioritization used with three classes (Source: Holma & Toskala, 2004).

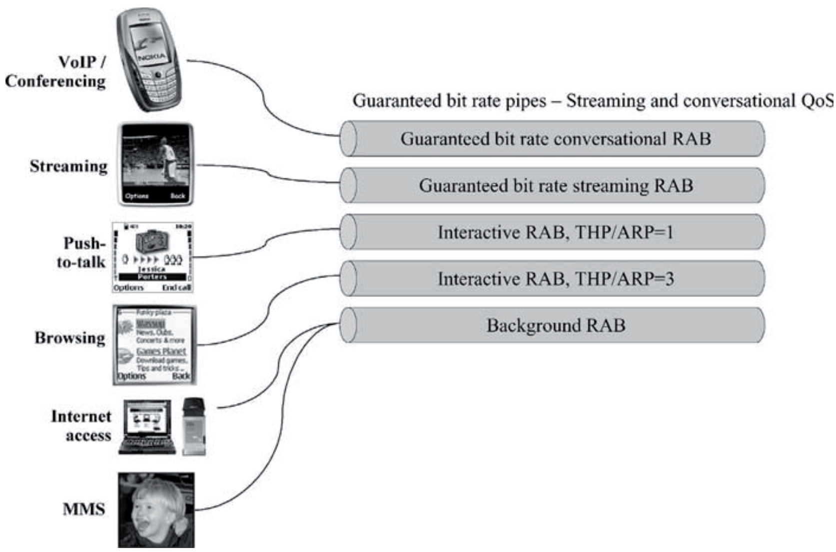


Figure 2.8: QoS differentiation with two guaranteed bit rate classes and three classes for non-real time prioritization (Source: Holma & Toskala, 2004).

2.2.2.5 QoS Mapping Between UMTS and the External IP Network

In order to efficiently deliver the internet-based application via the UMTS network, a mapping mechanism is required between the UMTS domain and the IP domain. When a packet passes to (from) the UMTS Iu bearer from (to) the backbone network, the QoS characteristics corresponding to it should be translated to ones understandable by the new QoS system. Mapping is usually done between the UMTS QoS classes and the IP QoS attributes (Agharebparast & Leung, 2002; Garg & Yu, 2000). In case the external IP network support Integrated services, the mapping will be between UMTS QoS classes to the appropriate IntServ traffic specifications (TSpec) (Costa, 2002). On the other hand, if the external IP network support differentiated services, the mapping will be between the UMTS QoS classes and the appropriate DiffServ code points. The mapping from UMTS QoS classes to differentiated services code points depends on bandwidth and network resources among different differentiated service classes which service providers control to satisfy users´ performance requirements (Garg & Yu, 2000). One of the responsibilities of a DiffServ domain ingress (edge) router is to map the QoS parameters of the incoming packet into the QoS PHB supported by the new DiffServ domain, while providing the same grade of service. Therefore, if a packet is marked by an appropriate differentiated service code point (DSCP), the other nodes (DiffServ domain core nodes) will have to perform traffic classification based on the packets DSCP (Garg & Yu, 2000).

2.3 Wireless Radio Network Planning

Radio network planning is a procedure that involves network dimensioning, capacity and coverage planning, network performance evaluation and optimization. Procedures for radio network planning differ from one technology to the other. For example, coverage planning in the second generation; the GSM technology, depends on the base station sensitivity, which is typically assumed to be constant, therefore coverage threshold is the same for each base station. However, for the case of third generation network based on WCDMA technology, the base station sensitivity depends on the number of users and bit rates used in cells, thus coverage is cell- and service-specific (Holma & Toskala, 2004). For WCDMA network, the radio planning process can be visualized as shown in figure 2.9 (Holma & Toskala, 2004; Laiho, 2002; Laiho et al., 2006).

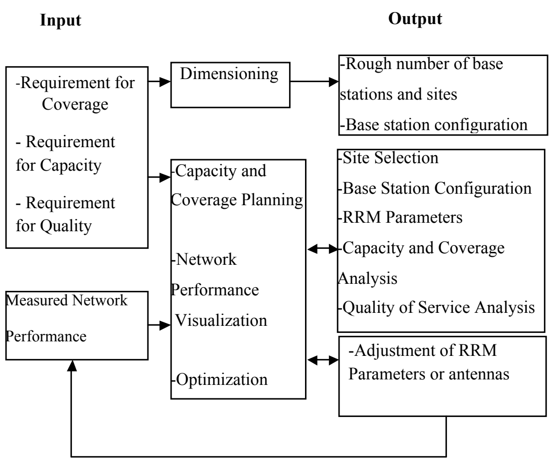


Figure 2.9: WCDMA radio network planning process (Holma & Toskala, 2004)

2.3.1 Dimensioning

WCDMA radio network dimensioning is a process through which possible configurations and the amount of network equipment are estimated, based on the operator's requirements in relation to coverage, capacity and quality of service. The configuration and estimation of equipments also depends on the radio propagation characteristics in a given area (Holma & Toskala, 2004). Dimensioning activities include radio link budget, coverage and capacity estimation, estimations on the required number of sites and base station hardware, radio network controllers (RNCs), and core network equipments i.e. circuit switched domain and packet switched domain core networks equipments (Holma & Toskala, 2004; Laiho, 2002; Laiho et al., 2006). The main aim of link budget is to calculate the maximum propagation loss that can be tolerated (allowed) within a radio cell. The maximum allowed propagation loss that is usually calculated in decibel (dB) can be converted into cell range in kilometers by using propagation models. Having the cell range, the cell area can be calculated, which will provide a basis to estimate how many cells (base stations) are required to provide coverage of a given geographical area.

The second phase of dimensioning is to estimate the amount of supported traffic per base station site. This value is called load factor and it can be estimated in the uplink and in the downlink direction. Load factor equations predict amount of noise rise over thermal noise due to interference. When the load factor becomes close to 1, the corresponding noise rise approaches infinity and the system reaches its pole capacity (Holma & Toskala, 2004).

2.3.2 Capacity and Coverage Planning

Capacity and coverage are closely related in WCDMA networks, and therefore both must be considered simultaneously. In WCDMA, all users are sharing the same resources in the air interface. Each user is influencing the others and causing their transmission powers to change. This makes prediction for capacity and coverage to be done iteratively until the transmission powers stabilizes. The iterative process for capacity and coverage planning as illustrated by Holma & Toskala, (2004) is shown in figure 2.10.

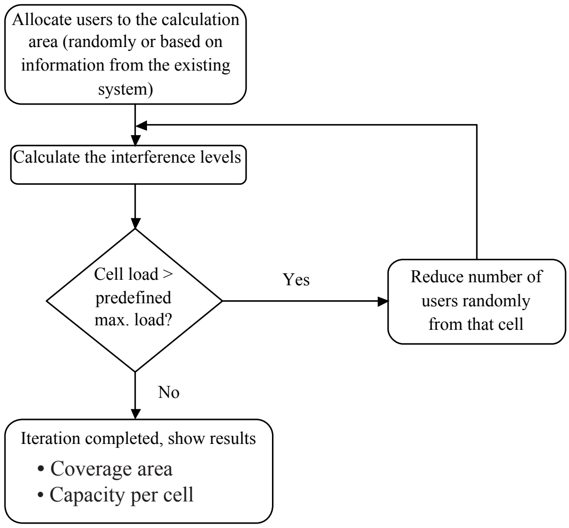


Figure 2.10: Iteration for coverage and capacity calculations

2.3.3 Network Optimization

Network optimization is a process to improve the overall network quality as experienced by the mobile subscribers and to ensure that network resources are used efficiently. When a network is in operation, its performance can be observed by measurements, and the results of those measurements can be used to visualize and improve (optimize) its performance. Optimization process usually includes measuring performance of the network according to the specified key performance indicators. Obtained results are analyzed (visualized) to identify what are the required adjustments and/or corrections. With the knowledge of the required corrections, then an updates (fine-tuning) can be performed in the network configurations and parameters. Figure 2.11 summarizes network optimization process (Holma & Toskala, 2004).

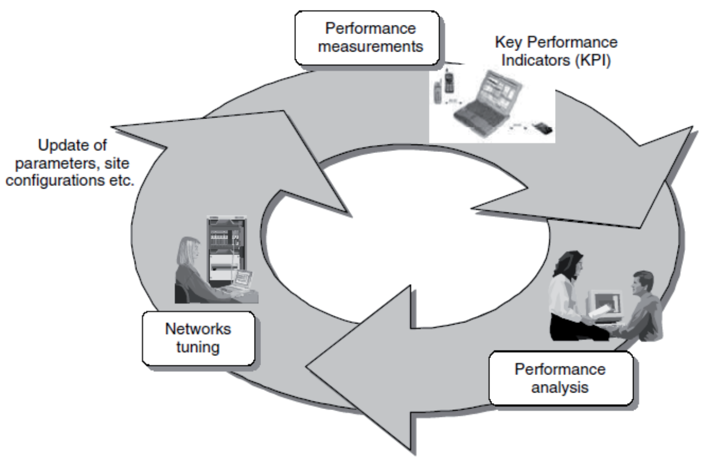


Figure 2.11: Network Optimization Processes (Source: Holma & Toskala, 2004).

2.4 Techno-economic Analysis

Techno-economic analysis is defined as a systematic analysis with the aim to recognize opportunities and threats. Techno-economic analysis is a common method used to evaluate projects or investments, taking into account the time value of money. The cash flow, discounted cash flow, Net Present Value (NPV), Internal Rate of Return (IRR), payback period and sensitivity analysis are the economic terms often used in techno-economic analysis (Ross et al., 2000). This section gives a brief description of the mentioned economic terms.

2.4.1 Cash Flow (CF)

Cash flow is the amount of cash flowing to/from a company or a project during a given period of time (Ross et al., 2000) . Cash flowing out of the company or project in terms of expenditure is called cash outflow and cash flowing into the company or project as revenues or benefits is called cash inflow.

2.4.2 Discounted Cash Flow (DCF)

Discounted cash flow is defined as the value of cash flow adjusted for the time value of money. This means that future cash flows are estimated and discounted with a proper discount rate to give them a present value (Ross et al., 2000). DCF is calculated by using the formula in equation (2.1):

$$DCF_t = \frac{CF_t}{(1+r)^t} \tag{2.1}$$

Where CFt = cash flow, r = discount rate and t = a selected time, usually the economic lifetime of a project.

2.4.3 Net Present Value (NPV)

Net present value is the difference between an investment's market value and its costs (Ross et al., 2000). In other words, NPV can be defined as the future stream of benefits and costs converted into equivalent values today. This is done by assigning monetary values to benefits and costs, discounting future benefits and costs using an appropriate discount rate, and subtracting the sum total of discounted costs from the sum total of discounted benefits. NPV is an indicator of how much value an investment or project adds to the firm. An investment should be accepted if its net present value is positive and rejected if it is negative. The decision should be indifferent if the NPV is zero. This is because with zero NPV, it means the investment would neither gain nor lose value (Ross et al., 2000). The NPV is calculated by using formula given in by equation (2.2):

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} \tag{2.2}$$

2.4.4 Internal Rate of Return (IRR)

Internal rate of return is defined as the discount rate that makes an NPV of an investment equal to zero. This rate is called the "internal" rate in the sense that it only depends on the cash flows of that particular investment, not on rates offered elsewhere (Ross et al., 2000). Due to the fact that, the IRR of an investment is the required return that results in a zero NPV when used as the discount rate, then an investment is accepted if the IRR exceeds the required return, otherwise it should be rejected (Ross et al., 2000). If the IRR is greater than the discount rate used for the project, then the investment is judged profitable. This criterion is useful in comparing projects of different types and sizes. The IRR gives a good indication of the value achieved with respect to the value invested.

2.4.5 Payback Period

In the start of any investment, the accumulated cash flow, also known as cash balance, generally goes negative because of high initial investments. Once revenues are generated, the cash flow turns positive and the cash balance starts to rise. If a curve of the cash balance is plotted over a given period of time, then the lowest point in the curve gives the maximum amount of funding required for the project. The point in time when the cash balance turns positive represents the payback period for the project. Therefore, the payback period is defined as the amount of time required for an investment to generate cash flows sufficient to recover its initial cost. It can be taken as the number of years to wait until the accumulated discounted cash flows from the investment equal or exceed the cost of investment. Based on the payback period rule, an investment is accepted if its calculated payback period is less than a pre-specified number of years; often the economic life time of the project (Ross et al., 2000).

2.4.6 Sensitivity Analysis

Sensitivity analysis is defined as the change in output brought about by a specified change in input. It is a way to predict the outcome of a decision if a situation turns out to be different compared to the key prediction(s). Sensitivity analysis is useful when attempting to determine the impact of a particular variable if it differs from what was previously assumed. By creating a given set of scenarios, the analyst can determine how changes in one variable will impact the target variables (Ross et al., 2000).

Calculations of the described economic terms during techno-economic analysis can be done either manually or most often by using computer software. The techno-economic tools (sofware) can be as simple as an excel workbook to sophisticated commercial and/or proprietary software. Typical examples of proprietary techno-economic softwares are TERA (Techno-Economic Results from ACTS), TONIC (TechnO-EcoNomICs of IP optimised networks and services), TITAN (Tool for Introduction scenario and Techno-economic evaluation of Access Network) , and ECOSYS (techno-ECOnomics of integrated communication SYStems and services) tools developed from European research projects during the year 2000 to 2002 (Smura, 2004).

2.5 Emerging Research Methods

Traditionally, research work is often understood as basic research done within a single discipline and the main approaches are either qualitative or quantitative research methods. However, there are emerging types of research methods, which involve different actors into the research practice as well as working across disciplines. Research results obtained by using these approaches are envisioned to be context relevant with high uptake by the intended beneficiaries. The readiness to accept and use research results is due to the understanding and a feeling of ownership of the results, which usually develops when beneficiaries of the research results are involved in the whole process of looking for the solution to their problem. A brief description of the emerging research methods, which are not yet mainstreamed in a traditional academic context, is given hereunder.

2.5.1 Participatory Action Research (PAR)

Dick, (1995) explains action research as a research approach, which has the dual aims of action and research: (a) action to bring about change in a community, organization or programme, and (b) research to increase understanding on the part of the researcher, beneficiaries, or both. The philosophy of action research is interpretive, incorporating social inquiry based on the views and interpretations of the participants (De Villiers, 2005). The important distinction between action research and other kinds of research is the researcher's involvement in the whole action process as a change agent. Action research has ambitions to contribute to changes of certain conditions experienced by the community as unsatisfactory with the intention to collaborate with the participants to control their own destinies more effectively (Balcazar et al., 2006). Action research is distinguished from consultancy work because it is practical, research based, collaborative, democratic and involves dialogue between insiders and outsiders (Selener, 1997; Reason & Bradbury, 2008). Selener, (1997) describes four types of action research called diagnostic, empirical, experimental, and participatory. In the diagnostic approach, a researcher collects data on a problem identified by the participants and then provides a recommendation. Changes may or may not be implemented. In empirical research, the main aim is to test a hypothesis about the impact of actions taken by either researcher or client, while in experimental research, control groups are used to test the relative effectiveness of the changes implemented (Selener, 1997). These three approaches have similar characteristics; they are not participatory, in that there is a clear division in terms of the roles of the researcher and the beneficiaries. In contrast, participatory action research involves participants in both the research and change process and it integrates research and action in an ongoing participatory process (Selener, 1997). Therefore, participatory action research is defined as systematic investigation, with the collaboration of those affected by the issue being studied, for educational purposes and/or taking action to effect the required changes for development purposes (Selener, 1997; Rydhagen, 2002). It empowers community members to collaborate with researchers to better understand their own problems and to find effective and viable solutions (Balcazar et al., 2006).

2.5.2 The “Mode 2” of Scientific Knowledge Production

“Mode 2” is a concept used to describe a way of scientific knowledge production. According to Gibbons et al., (2004) this form of knowledge production is context driven, problem focused and trans-disciplinary. It is a broader research approach including what is called “mode 1”, where knowledge is produced strictly within a given discipline. The mode 2 of knowledge production involves different mechanisms of generating knowledge and of communicating them. It involves more actors coming from different disciplines and backgrounds, as well as different sites/locations in which knowledge is being produced. The trans-disciplinary aspect of mode 2 type of scientific knowledge production, implies that it corresponds to a movement beyond a disciplinary structure in the constitution of intellectual agenda, in the manner in which resources are mobilized and deployed, in the way in which research is conducted, results communicated and outcomes evaluated. In the production of trans-disciplinary knowledge, the intellectual agenda is not set within a particular discipline. It is prepared from the context of usage or application, thus it cuts across disciplines as well as across academia and society boarders. The mode 2’s dispersed and transient way of knowledge production leads to results, which are highly conceptualized. Therefore knowledge produced under these conditions is characterized by aiming at a use or action that is towards application in its broadest sense (Gibbons et al., 2004).

Triple helix is a model of collaborative relation between three main actors namely University, Industry and Government. Mode 2 is the concept for the process of triple helix collaboration. Etzkowitz & Leydesdorff, (2000) explain, that future development in the knowledge economy is driven by incremental innovation within industry. The innovation achievement can be enhanced as a result of an alliance between government, industry and the academia. This is a triple helix alliance collaboration. The purpose of the triple helix is to stimulate knowledge-based economic development, drawing resources from all the three members of the helix. It is evident that communications, negotiations and collaboration. that takes place between institutional partners in the triple helix alliance, is a strong foundation for implementation of mode 2 type of knowledge production.

CHAPTER THREE
RESEARCH METHODOLOGY

3.1 Research Approaches Used

The research started by conducting a survey to establish status of information and communication technologies infrastructure available in the country at large and then, specifically streamlined to the pilot schools. More details of this survey can be found in (Simba et al., 2009b); (Kalinga, 2010) and (Lujara, 2010).

The research further surveyed broadband access network technologies in order to earmark potential candidates, which are capable to provide connectivity solution for multimedia services such as e-learning to rural areas. The earmarked suitable broadband access network technologies were analyzed by using a conceptual framework for wireless technologies competitions to identify their sustainability in the market. Thereafter, a techno-economic approach was used to determine a cost-effective connectivity technology. Furthermore, the research simulated the determined cost-effective connectivity technology. The simulated network model was used to evaluate performance of e-learning services delivered over the network.

Surveys and technology comparison employed the qualitative research methods. However, data collected from surveys, some of them were of quantitative nature. On the other hand, the techno-economic analysis and network simulation modeling for application performance evaluation used the quantitative research method. Collaboration that started during survey stage with teachers from pilot schools and technical staffs from mobile network operators, and continued throughout the study time, created a foundation for participatory action research. In order to achieve all the tasks mentioned above, the research employed knowledge from different disciplines, such as communication networks, traffic engineering, economics (techno-economic analysis) and simulation modeling. Bringing all these pieces of knowledge from different disciplines, as well as from partners outside the academy to solve a particular problem made the research in this thesis a trans-disciplinary one.

The research work reported in this thesis is considered as a mode 2 type of knowledge production because it focuses to solve an existing problem (problem focused), in collaboration with those affected by the problem (context driven), while drawing knowledge from different disciplines and partners (trans-disciplinary), in the search for a suitable solution. The employed methodological approach brings together academia (researchers from UDSM), industry (network/service providers) and the government (pilot school management) in order to find a solution for the rural schools' connectivity needs seeking to improve teaching and learning process. It also reflects elements of triple helix. The mode 2 methods used by the researcher in this thesis were the strategic approach in order to deliver research results that are context relevant and hence can be of direct use by the intended beneficiaries. The following are the collaborative activities done by the researcher with stakeholders, which illustrate experiences for mode 2 type of knowledge production.

i. Development of Students' Registration Database System

   Apart from integrating ICT in teaching and learning process, management activities in schools can also be made easy by the use of ICT services. In order to introduce pilot schools to the use of ICT services, as well as building trust and collaboration environment with stakeholders, the project developed a Student Registration Management Information System. This system is capable of keeping records of registered students in digital formats rather than the manual (paper-based) format, which was the main method used by almost all secondary schools in the country. To start with, only pilot schools were considered and a student registration database was designed for Waliul-Asr Girls' Seminary. In 2005/6, the two pilot schools were visited frequently during the design and development of a student registration management information system. The main activities were to study the existing manual students´ registration system in order to establish system requirement when designing the digital registration system. The designed students' registration database is illustrated in details by Kalinga (2008). The database could suit any secondary school, subject to slight modifications as per individual school requirements. For the success of the e-learning (TanSSe-L) system, it was imperative to be close to end users, teachers in this case, because they are the ones who know what the deficits are in the education system and what is needed in order to improve their performance. The students' registration database was a stepping-stone to be close to these stakeholders of the TanSSe-L system.

ii. Introduction of e-learning Project to Stakeholders

In September – October, 2007, a visit was made to the two pilot schools and the Ministry of Education and Vocational Training (MoEVT) for the purpose of officially introduce and discuss the proposed e-Learning system for secondary schools in Tanzania i.e. the TanSSe-L system to the stakeholders. Visits to schools required researchers to get permission from the Regional Administrative Secretary (RAS), District Administrative Officer and the Regional Education Officer (REO). Through this procedure of seeking permissions, researchers had an informal chance to introduce and conduct discussions regarding the e-Learning project at regional (Pwani) and district (Kibaha) levels prior to the formal project introduction. The informal introduction served as a foundation for the better discussion during the official presentation to introduce the project. Objective of the official project introduction was to seek views and opinions of stakeholders on the relevance of the project as well as suggestions to improve the project.

iii. e-learning Project Awareness and Publicity Seminar

A project awareness and publicity seminar was conducted at the college of engineering and technology (CoET) in late November, 2007.The purpose of the seminar was to formalize the project with the MoEVT and make it known to the public. The seminar attendance comprised of representatives of the MoEVT and the two pilot schools, the college principal, deans of faculties at CoET, the research and publication coordinator at CoET, e-Learning project members, journalist, supervisors, PhD and MSc students involved in the project. The project coordinator, PhD students and one MSc student made presentations for the seminar. Thereafter, as semi-guided discussion was conducted among all seminar participants, that resulted into valuable suggestions for the benefit of the project.

iv. Collaboration with Network Operators and Service Providers

In 2008 and 2009, wireless (Vodacom, Tigo, Zain and Zantel) and wired (TTCL, Zantel), network operators and internet service providers (Simbanet, Africaonline, TTCL) were consulted many times to study capabilities, constraints and costing structure of different connectivity technologies with regard to rural areas. During this time, a software system for connectivity cost calculation was developed. One of the limitations for connectivity development in rural areas of Tanzania is the high cost of establish the ICT infrastructures. Furthermore, the cost of connectivity is technology dependant and at the same time, the cost is different from one operator to another within the same country. Development of software system to calculate cost of connectivity to rural areas of Tanzania was done to make an easy access of connectivity cost from different technologies and different operators. The development of the calculator followed the V-model software development lifecycle. Network operators´ and service providers´ technical staffs were involved in each design and development stage of the connectivity cost calculator. The main activity during this collaboration was for technical staffs to help in design and evaluate whether the software is correctly taking into account the technologies´ capabilities, constrains and costing structure of different operators. Development of connectivity cost calculator served as a way to bring stakeholders on board in the search for a cost-effective connectivity technology for rural areas. Fully implementation of the connectivity cost calculator is envisioned to close the connectivity cost information gap. Details of the design and development of the connectivity cost calculator software are available in the Simba´s Licentiate thesis (Simba, 2010) and the published paper (Simba et al., 2009a).

v. Establish status of ICT infrastructure (e-readiness) in schools

In 2004, the e-learning project conducted a survey in 40 secondary schools from 12 districts in Tanzania. The aim of the survey was to find out status of ICT infrastructures in secondary schools (referred to as "e-readiness"). Survey results show a poor e-readiness because most of the surveyed schools have very few computers and computer literacy personnel, in a range of 1-5. There were only four (4) schools with internet connectivity among the surveyed 40 schools. However, Kibaha and Waliul-Asr secondary schools, were selected to serve as pilot schools in this project based on easy accessibility by road and availability of computers. During the year 2008, the researcher made many visits to the pilot schools (Kibaha and Waliul Asr secondary schools) for the purpose of observing and obtaining information about the status and usage of computers in the schools. Details of the survey for schools´e-readiness can be found in publisghed paper I (Simba et al., 2009b). During these visits, the researcher mainly collaborated with teachers responsible for computer studies and system administrators, who are responsible in managing schools computers.

vi. Seminar to Communicate Progress of the e-learning Project

In 2010, the progress of the e-Learning project was presented to Kibaha Secondary School and Waliul-Asr Seminary. The aim was to update stakeholders on the progress of the project as well as to get their contributions and suggestions to fine-tune project products. After presentations, time was given for discussion about the presentation and later a guided discussion continued based on open-ended questions. During the discussions, more information and clarification from users on issues, which were not obvious to researchers nor well documented in the literature and surveys, were acquired.

vii. Collaboration with Rural NetCo

Rural NetCO (T) Ltd is a wireless network operator aiming to extend coverage of broadband 3G wireless network to rural areas of Tanzania. During the year 2010, the researcher collaborated with Rural NetCo in seeking the possibility to implement broadband connectivity to rural schools. The collaborative activities were for the researcher to work together with a team of radio network planning in locating coordinates of some selected rural schools. In addition to locating schools´ coordinates, the researcher also participated in studying coverage of the rural NetCo network, in order to establish if the selected schools are within the coverage area of the network. Working with network operator on technical issues was a good foundation, which will be required during the implementation stage of connectivity solution for rural areas.

3.2 Research Design

Research design refers to the structure of an enquiry. It is a logical task undertaken to ensure that the evidence collected and tasks conducted enable to answer research questions or to test theories as clearly as possible (Creswell, 2009). The main or general objective of the research presented in this thesis is to determine a cost-effective and performance efficiency connectivity solution for rural secondary schools to access e-learning resources. The research was designed based on two specific objectives, each aimed to achieve cost and performance target of the general objective respectively. A qualitative research method was used to identify the viable technology for access network to the rural areas. Then a quantitative research method was used to evaluate cost and performance of the identified viable technology for e-learning service quality. Figure 3.1 summarizes different research approaches used in order to achieve research sub-targets, which collectively build up to achieve the general objective of the research in this thesis.

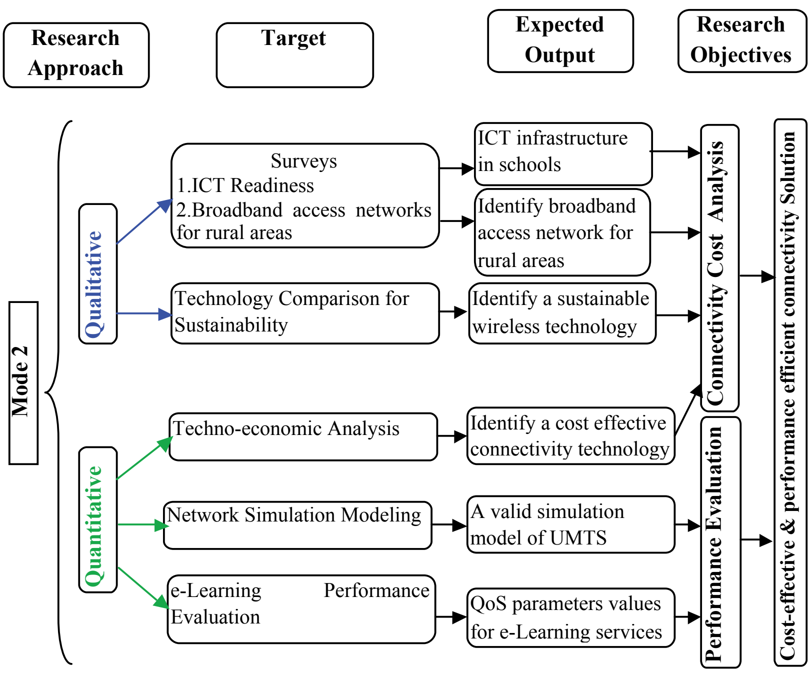


Figure 3.1: Research Methodology Approaches

3.3 Data Collection

Data collected was of both qualitative and quantitative in nature. The techniques employed for data collection were:

i. Extensive literature-based document analysis such as technical reports, technology standardization documents, technical forum´s white papers, websites, technology global-updates documents, and ICT statistics-based documents.

ii. Semi-guided oral interviews via telephone or face to face.

iii. Observation during site visit.

Data was collected in different stages: during surveys, data was collected by using semi-guided interviews and observation during researcher's site visit in order to understand status of ICT infrastructure in the country and specifically to establish ICT readiness of the pilot schools. On the school side, particular interest was on the availability of basic ICT infrastructure, cost and coverage of networking technologies that can implement communication network to such a school. From operators' survey, data was collected by conducting semi guided oral interviews via telephone or face to face with the operator's technical staff as well as consulting their respective websites, technical reports and brochures. The intention was to collect data/information on the network coverage, technology constraints/limitations and costing structure of the earmarked technology for rural connectivity solution. Data was as well collected during researcher´s on site collaboration with the pilot schools.

During technology comparison for sustainability and techno-economic analysis to investigate a cost-efficient option, data was mainly collected from literature sources such as access to ITU´s ICT statistics database, TCRA statistics reports, and technical report from standardization bodies such as Institute of Electrical and Electronics Engineers (IEEE) and the Third Generation Partnership Project (3GPP). Other sources of data were reports and white papers prepared by technology-specific forums such as UMTS forum, WiMAX forum and Global mobile network Suppliers Association (GSA). The reports and white papers were consulted in order to get updates of a particular technology on its global wise network deployment, terminal and network equipment penetration and its market potential.

3.4 Related Work

The work done reported by this thesis is not a unique case, there is other research found in literature, which report similar work, but with some noted differences. Researches found in literature, that relate to the work done reported in this thesis are explained in the following paragraphs.

i. Use of conceptual framework to forecast technology sustainability

Yuan et al., (2006) proposed a theoretical framework to assess and compare XLT and 3G technologies from four perspectives: technology, market demand, business models and government policy. The XLT is a type of mobile phone system based on Personal Handy Phone System (PHS) for wireless access of fixed-line telephone networks, widely used in China. This work was based only in China, since the XLT technology was only deployed in China, so it is missing the wide context. Lehr & McKnight, (2003) compares and contrasts 3G and WiFi technologies for delivering broadband wireless Internet access services. The comparisons and contrasts were based on technology aspects, business models and deployment strategies, spectrum policy and management. Similarly, Bauer et al., (2004) proposed a framework for the study of next-generation wireless services and related policy issues. In this comparison, the evolution of wireless industry is seen to be determined by the dynamic interaction of technology, public policy, supplier strategies, and consumer behavior. Suarez, (2004) proposed an integrative framework for understanding the process by which a technology achieves dominance when battling/competing against other technologies. This study focuses on describing different stages of dominance battle and finally proposed five battle milestones that in turn define five key phases in the process. The phases are (1) research and development build up (2) technical feasibility (3) creating the market (4) decisive battle (5) post dominance. Smura, (2006) constructed a conceptual framework for analyzing emerging wireless technologies based on the four viewpoints: (1) end user, (2) technology, (3) value network, and (4) policy and regulations.

The technology competition done by the previous works, apart from work of Smura, (2006), basically focused on parameters such as technology, spectrum policy and business models. The framework proposed by Smura, (2006) captured wide parameters that interact in the process of technology competition ranging from end user devices, technology, value network, and policy and regulations. The conceptual framework developed by Smura, (2006) was adapted by the research reported in this thesis and used to compare and hence analyze sustainability of UMTS at 900MHz and UMTS at 2100MHz technologies. This part of the research work differ from Smura, (2006)´s work in the sense that technologies which are compared here are very similar in terms of technical aspects, design target and market potential. Therefore a high competition is expected compared to Smura, (2006)´s work which dealt with relative different technologies, WiMAX and High Speed packet Access (HSPA).

ii. Use of techno-economic analysis to identify a cost-effective connectivity technology

There is a noted body of research work where a techno-economic analysis has been used to analyze the cost aspects of communication technologies. However, most of the works deal with single technology. Typical examples are by Smura, (2005), conducted a techno-economic analysis of WiMAX. Pazi et al., (2010) performed a techno-economic analysis of the Tanzania national fiber optic broadband backbone and Hoikkanen (2007) performed a techno-economic analysis of 3G Long-Term Evolution for broadband. It has been noted that most of the techno-economic analysis done were also using software systems to perform the techno-economic analysis calculations. The techno-economic analysis reported in this thesis differs from the related techno-economic work described in the sense that, it is done by considering two technologies.

Another work done by Ovum-Consulting, (2007) reported a techno-economic analysis in terms of comparing two technologies: the UMTS network implemented at 900MHz frequency band and the UMTS network implemented at 2100MHz frequency band. This work is quite similar to the part of research work in this thesis, but the only difference is that Ovum-Consulting, (2007)´s work had used only a high level analysis which gave a general picture and provides some useful insights of the benefits that are expected with the deployment of UMTS900 networks. Ovum-Consulting (2007) recommended that, results that are more accurate could be obtained by using a detailed approach that uses country's specific data such as market and geospatial characteristics. Therefore, in this research, the techno-economic analysis was done on a specific country level; Tanzania in this case, with specific geographical area for coverage requirement, number of end users, service costs and service usage profile.

iii. Use of simulation modeling approach to analyze performance of e-learning services delivered over UMTS network.

Most of the research work found in literature concentrated on network-oriented performance evaluation of UMTS networks. They include studies on impact of base station and antenna configuration to improve cell capacity (Jarno Niemelä, 2003; Niemela & Lempiainen, 2003). Holma, (2003) studied the WCDMA link level performance in uplink with simulations and measurements. The main objective was to investigate the effects of mobile speed, multipath profile and base station antenna diversity to the performance of WCDMA radio link (UTRA FDD). The above research works concentrated on the network specific characteristics leaving out the application aspects concerning performance. Other research works deal with access network dimensioning to optimize cost of network deployment and support for multiple applications with different QoS constraints (García et al., 2002). Further studies in literature on application-oriented performance, which is also referred to as user-perceived QoS were done analytically (Stasiak et al., 2009; Samhat et al., 2004) or based on measurements from live operational networks (Chevul, 2006, Isaksson et al., 2005; Garriga et al., 2009). The research work presented in this thesis focused on the e-learning application performance over wireless networks by using simulation modeling approach.

CHAPTER FOUR
COST-EFFECTIVE ACCESS NETWORK FOR RURAL AREAS

4.1 Survey of Broadband Access Networks for Rural Connectivity

This chapter aims to investigate the available technologies for wireless broadband access networks with the potential to provide rural connectivity. The investigation was done by extensive literature survey. Broadband access wireless technologies comprises of Wireless Fidelity (WiFi), Worldwide Interoperability for Microwave Access (WiMAX) and the cellular mobile wireless technology from 3G to 4G. The Institute of Electrical and Electronics Engineers (IEEE) standardized the Wi Fi and WiMAX technologies as the IEEE 802.11 and IEEE 802.16 standards respectively. The UMTS also known as IMT-2000 is an example 3G mobile wireless technology. The wireless broadband technologies kept on evolving due to requirements for capacity and demand for performance improvement. WiMAX has evolved from fixed networks, the IEEE 802.16e standards to the mobile WiMAX, the IEEE 802.16m standard. The 3GPP standardization body had done a lot of improvement to their IMT-2000 standard from UMTS-Rel99, UMTS-Rel4, High Speed Downlink Packet Access (HSDPA-Rel5), High Speed Uplink Packet Access (HSUPA-Rel6), high speed packet access (HSPA+-Rel7), Long Term Evolution (LTE-Rel8) and then to LTE-advanced also known as Next Generation Network (NGN). This section describes in details the capabilities of the surveyed broadband wireless technologies for their potentials to provide rural connectivity.

The survey of broadband technology in this section aims to investigate technologies based on the following criteria: capacity to support multimedia service; coverage, preferably wide coverage, which is the better option for rural environment; global deployment status which implies a technology maturity; existence of basic infrastructure for final deployment. Where the basic infrastructures exist, capital expenditure is reduced and hence a potential for cost-efficiency. The surveyed technologies were further compared based on the mentioned criteria to identify the most suitable technology among them for rural connectivity. The surveyed wireless technologies were cellular mobile wireless technology, WiMAX and the hybrid network of fiber optic and wireless. The WiFi technology was not included in this survey, because the technology was specifically designed to unwire the local area network, so it is an indoor and short-range technology, while the focus of this thesis is on access network (last mile connectivity) to the rural areas. Therefore, it is out of the scope of this work. The survey done for cellular mobile wireless technology includes only the third generation due to the fact that, during the time of conducting surveys the successor technologies of 3G networks were still under standardization. However, description on the evolution of mobile wireless technology includes all standards up to the next generation network for completeness.

4.1.1 Cellular Mobile Wireless Technologies

The world has experienced an ever-going evolution of cellular mobile wireless technology from first generation 1G in the late 70s to the fourth generation 4G in 2010. The first generation cellular system was an analog mobile phone system working at 850 MHz, developed by AT&T Bell Laboratories in the late 1970s (Molisch, 2011; Schiller, 2003).The system was mainly used for the basic telephone voice services. To maintain the first generation subscriber service quality, especially in a heavily populated area, was difficult due to tremendous system complexity and lack of control. As a result, these analog networks were switched off in 2000 (Schiller, 2003; Svoboda, 2008). The second generation (2G) cellular wireless network was developed in early 1990s which also marked the beginning of fully digital systems. The Global System for Mobile Communication (GSM) is one of the 2G cellular mobile networks widely deployed in Europe, which later gained worldwide acceptance and became the world's most popular mobile technology.

End terminals in the 2G networks could only process audio (voice) as input data. Therefore, users had to use a modem to transfer data traffic via GSM at a rate of 9.6 kbps. This method of data transport is quite inefficient to support modern multimedia rich Internet applications, like web browsing, videoconferencing and multimedia streaming. Therefore, some new standards were developed based on 2G technologies, such that the existing 2G equipment can be upgraded to provide higher transmission rates. They are generally categorized as 2.5G mobile communication systems. Examples of 2.5G systems are the General Packet Radio Service (GPRS) and Enhanced Data Rates for GSM Evolution (EDGE), offering data rate (downlink/uplink in Kbps) of 40/14 and 384/53 respectively. The 2.5G technologies only served as temporary data solution for the exploding internet services, which eventually lead to evolution of the third generation (3G) systems. The 3G systems provide much higher data rates from 384 Kbps to 10Mbps in the downlink direction as well as more services. The fourth generation (4G) is designed to offer up to 100Mbps in high speed mobiles and up to 1Gbps for fixed or low mobility (Nakamura, 2009).

The second generation, GSM network, is widely deployed worldwide except in USA where IS-95, also known as cdmaOne technology, standardized by the 3GPP2, was their choice for 2G technology. Figure 4.1 indicates deployment of 2G and 3G technology in a worldwide map. The map shows countries that are offering 2G and 3G services commercially. Observing this map it is clear that 3G technologies are currently available in most of the African developing countries, while 2G is available in all countries. Figure 4.2 show the migration path of the cellular mobile wireless technology from the first generation to the fourth generation. The figure show evolution path of cellular mobile wireless technologies, however almost all these technologies still exist and run in parallel.

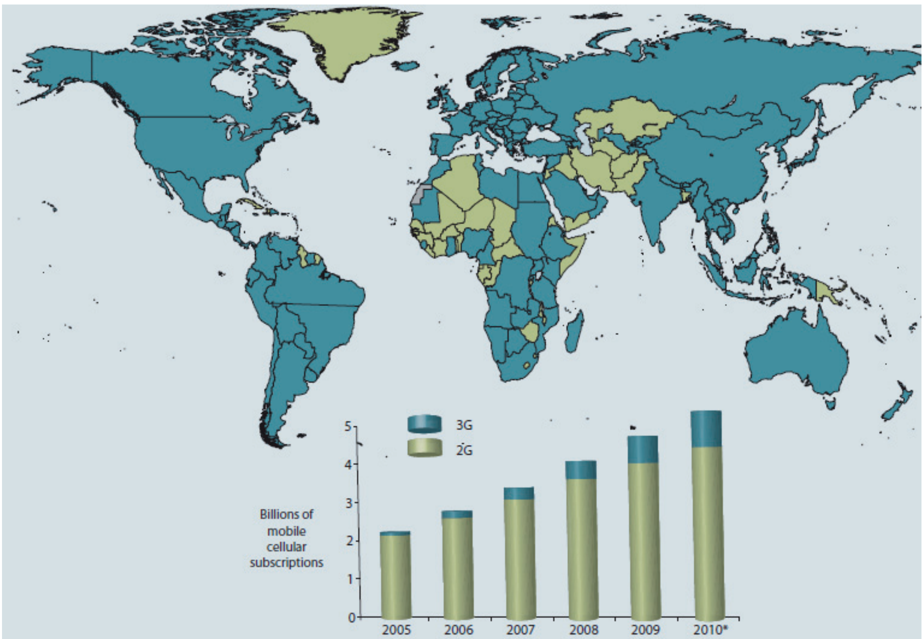


Figure 4.1: Countries that are offering 2G and 3G services commercially (ITU-D, 2010).

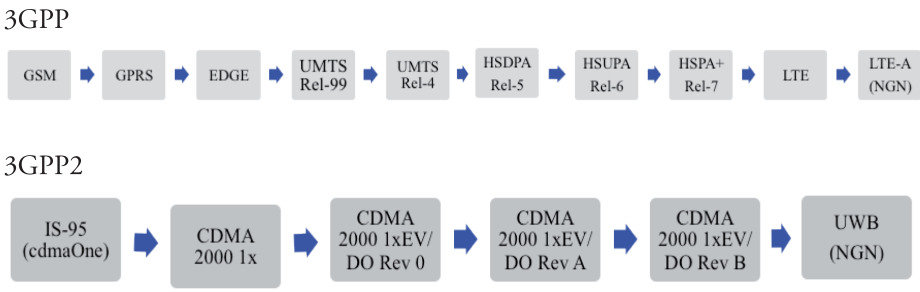


Figure 4.2: Evolution path of cellular mobile wireless technologies

For the rest of this chapter, the research considers technology evolved from the GSM which is widely deployed worldwide. Their respective data rates and coverage are shown in table 4.1.

Table 4.1: Data rates for different mobile wireless technologies

Technology	Downlink (DL)	Uplink (UL)	Coverage (Cell radius)
2G (GSM)	9.6 kbps	9.6 kbps	10-35 km
2.5 (GPRS)	171kbps	14kbps	10-35 km
2.75 (EDGE)	384 kbps	14kbps	10-35 km
3G (UMTS Rel 99)	2Mbps	384 kbps	2km
3G (UMTS Rel 4)	2Mbps	384 Kbps	2km
Rel. 5 (HSDPA)	14.4 Mbps	384 Kbps	2km
Rel. 6 (HSUPA)	14.4 Mbps	5.8Mbps	2km
Rel. 7 (HSPA+)	42 Mbps	11 Mbps	2km
Rel. 8 (LTE)	100Mbps	50 Mbps	5km
LTE-Advanced	100 Mbps high speed & 1Gbps low mobility		

However, the existing deployments of cellular mobile wireless technology, especially the 3G variants, are faced by coverage challenges. The widely deployed 3G systems are implemented at 2100MHz frequency band. At this high frequency, radio waves propagation path loss is high, which results in a shorter distance coverage. As a result, the 3G networks are mainly deployed in urban areas and in cities; this is a business strategies to tap a number of customers in a small single area. Nevertheless, deploying 3G networks in lower frequencies such as 900MHz frequency band can address the coverage challenge of the existing 3G networks. This is an emerging technique which has the potential to address the coverage problem as well as providing 3G data capacity and services (UMTS-Forum, 2009). The technique to implement 3G network at 900MHz bring about an added advantage of making use of the existing GSM sites, to implement 3G networks, especially in rural areas. The practical experience was pioneered by Nokia Siemens Networks, which implemented a pilot 3G network at 900MHz in Finland. This experience demonstrated a deployment of 3G WCDMA in 900 MHz, without impairing 2G services running on the same frequency band (NSN, 2010).

A growing number of mobile operators are deploying UMTS/HSPA services alongside their existing GSM networks operating in the 900MHz band. According to UMTS-Forum, (2009), there were around 10 operators in 2009 (in Australia, Estonia, Finland, Iceland, New Zealand, Thailand and Venezuela) - commercially running UMTS/HSPA operations in 900MHz band. Deploying UMTS with HSPA in rural areas by re-using the existing GSM sites is envisioned as a cost-effective solution for mobile operators to offer mobile broadband services, such as high data rate multimedia services. By re-using the existing lay-out of the GSM infrastructures within the existing service area generates further benefits such as quicker network deployment, reduce capital expenditure by re-using existing antenna systems and feeders and operational expenditure through re-use of network management systems. Costs are lowered and roll out is faster through re-using the existing sites which, eliminates site acquisition costs and civil works (UMTS-Forum, 2009; NSN, 2010). From an implementation point of view, operators only need either to add a new UMTS base station cabinet, or to replace the existing GSM base station by a multimode GSM+UMTS/HSPA base station subject to site situation or manufacturer's design (UMTS-Forum, 2009). For the existing GSM operator, the most cost-effective solution is to re-use the existing GSM site for UMTS deployment. The existing antennae and feeders can be re-used to implement the UMTS base station operating in 900MHz.

Another significant benefit of UMTS/HSPA deployment in the 900MHz band comes from the fact that radio wave propagation path-loss in 900MHz frequency band is smaller. Therefore, at the lower frequency, cell sizes are two to three times larger than that of a UMTS/HSPA at 2100MHz. This wider cells enable coverage with fewer sites (UMTS-Forum, 2009). This is illustrated in figure 4.3. The wider coverage is a useful feature especially to rural areas where customers/subscribers are scattered.

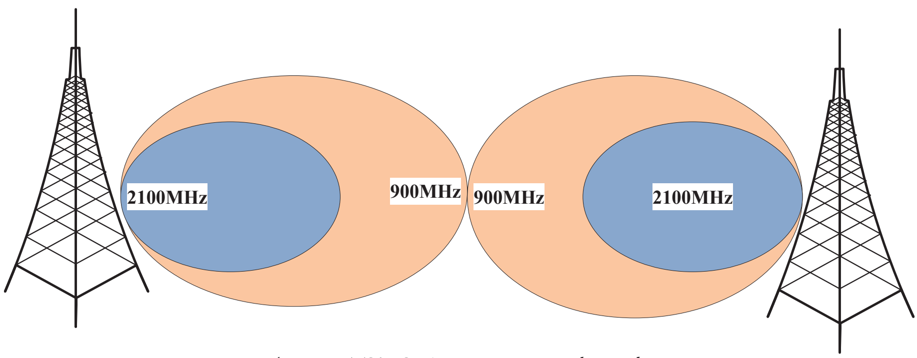


Figure 4.3: UMTS/HSPA at 900MHz enhanced coverage

According to UMTS forum, (UMTS-Forum, 2009); in order to offer the same coverage, the required number of base station sites in 900MHz band is reduced by 60% compared to that needed by 3G UMTS at 2100MHz, as shown in table 4.2.

Table 4.2: Required Cell Sites/Base stations (UMTS-Forum, 2009).

Services	2100MHz band	900MHz band	Number of site reduction (%)
Circuit Switched, 64kbps	224	90	60
Packet Switched, 384kbps	468	181	61

The 3G network at 2100MHz has the potential to offer connectivity in rural areas due to its high data rate and diversity of services supported. However, it is not widely deployed, especially in the rural areas of developing countries. This is due to high frequency used that provide shorter distance coverage (smaller cells), which consequently leads to high cost of network implementation. The emerging technique to implement 3G network at low frequency; the 900MHz, which can co-exist with the widely deployed 2G GSM cell site, is envisioned as a cost-effective approach to bridge the 3G network coverage to the underserved rural community.

4.1.2 WiMAX

WiMAX is a generic term used to describe wireless systems standardized by the Institute of Electronics and Electrical Engineers as the IEEE 802.16 air interface standard. It is intended for wireless Metropolitan Area Networks (MAN). The IEEE 802.16 standard has undergone different amendments for improvements. The earlier amendments, IEEE 802.16a/b/c standards, were withdrawn from the market and the current available standards are 802.16d, 802.16e, 802.16m (Scarfone et al., 2009). WiMAX is defined into two systems: the fixed WiMAX standardized as IEEE 802.16d and the mobile WiMAX standardized as IEEE 802.16e. The IEEE 802.16m is an amendment to the 802.16 standard air interface in order to support both fixed and mobile users. Figure 4.4 show WiMAX technology evolution (Scarfone et al., 2009; Wimax Forum, 2011).

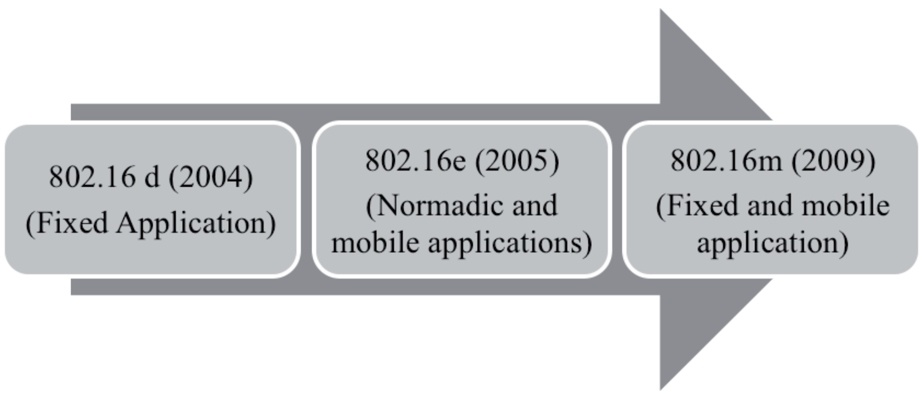


Figure 4.4: Roadmap for WiMAX evolution

The respective brief description, data rates and coverage (cell ranges) of WiMAX standards are summarized in table 4.3.

Table 4.3: IEEE 802.16 Standards Descriptions

S/N	Standard	Description	Data Rates	Cell Range
1	802.16d (802.16-2004)	This amendment is also known as 802.16-2004 in view of the fact that it was released in 2004. It was a major revision that provided a number of fixes and improvements to the earlier variants of 802.16 standards. Upon its release, all previous standards were withdrawn. The standard only support fixed operation.	70 Mbps	8km P2P 48km P2MP
2	802.16e (802.16-2005)	This standard, also known as 802.16-2005 in view of its release date, designed for nomadic and mobile use.	15 Mbps	2 - 5km
3	802.16m	This is an amendment to the air interface; it can support both fixed and mobile users.	100 Mbps for mobile applications and 1 Gbps for fixed applications	2 -5km

The WiMAX network consists of two key components: a base station and a subscriber device. The WiMAX base station is mounted on a tower or tall building to broadcast the wireless signal. The subscriber can receive signals on a WiMAX-enabled notebook or mobile internet device. For fixed WiMAX deployments, a Customer Premises Equipment (CPE) is needed to act as a wireless modem providing interface to the WiMAX network for a specific location, such as a home, cafe, or office. There are three topologies for WiMAX network: fixed point-to-point (P2P), fixed point-to-multipoint (P2MP) and mobile WiMAX (Scarfone et al., 2009).

A point-to-point (P2P) topology consists of a dedicated long range, high-capacity wireless link between two sites. The central site hosts the Base Station (BS), and the remote site hosts the Subscriber Station (SS), as shown in figure 4.5. The BS controls communications and security parameters in establishing the link with the SS. The P2P topology is used for high-bandwidth wireless backhaul services at a maximum operating range of approximately 48 km using Line Of Sight (LOS) or Non-Line Of Sight (NLOS) signal propagation (Scarfone et al., 2009).

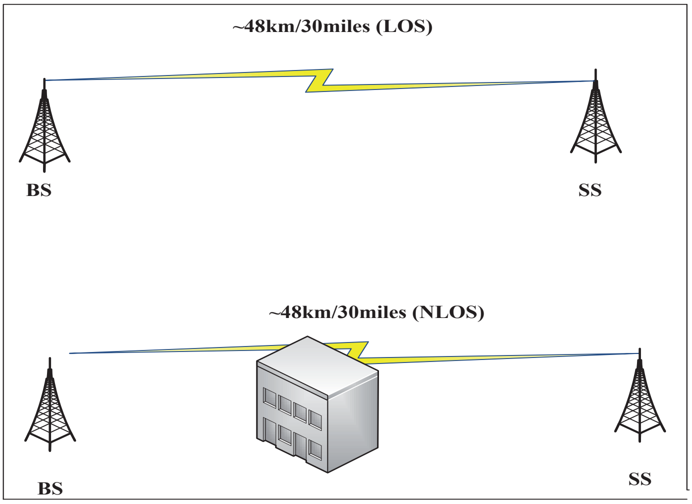


Figure 4.5: WiMAX Point to Point (P2P) Topology

A point-to-multipoint (P2MP) topology is composed of a central BS supporting multiple SSs, providing network access from one location to many other locations. It is commonly used for last-mile broadband access such as private enterprise connectivity to remote offices, and long range wireless backhaul services for multiple sites. P2MP networks can operate using LOS or NLOS signal propagation. Each P2MP BS has a typical operating range of 8 km (Scarfone et al., 2009) as illustrated in figure 4.6.

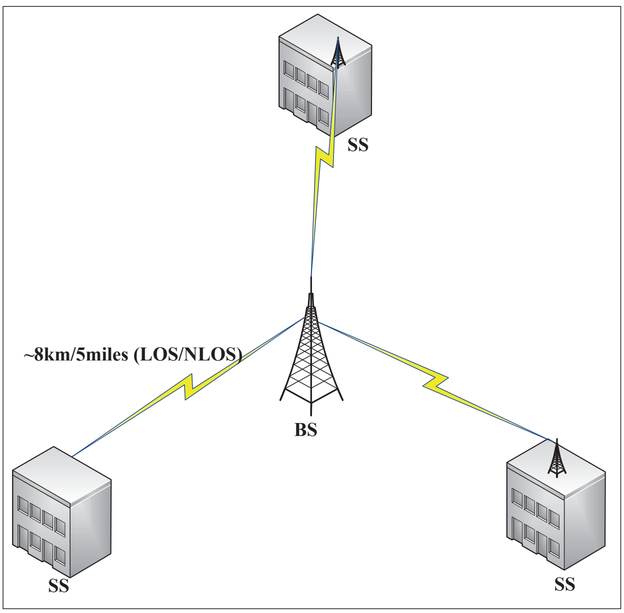


Figure 4.6: WiMAX Point to Multipoint Topology

A mobile WiMAX topology is similar to a cellular network because multiple BSs collaborate to provide seamless communications over a distributed network to both SSs and Mobile Subscribers (MSs). Coverage for a geographical area is divided into a series of overlapping areas called cells. Each cell provides coverage for users within its vicinity. The wireless connection is handed off from one cell to another when a user is crossing the border between two cells. Mobile WiMAX is designed with typical cell radius of 2 to 5km at theoretical peak throughputs of 30Mbps while operating on 10MHz channels. One major advantage of mobile WiMAX (802.16e) over the fixed WiMAX (802.16d) is that it can operate over NLOS enhancing better connectivity. As of October, 2010 the deployment status of WiMAX technology around the world was as shown in table 4.4.

Table 4.4: WiMAX Deployments by Regions (Wimax Forum, 2011)

Regions	**Deployments**	**Countries**
Africa	117	43
Asia-Pacific	109	23
Eastern Europe	86	21
Western Europe	76	17
North America (USA + Canada)	53	2
Middle East	29	10

4.1.3 Hybrid Fiber-Wireless Access Network

Optical fiber technology is another option for access networks; it can provide high capacity bandwidth in the range of giga bits per second. Variant of optical fiber technology called Passive Optical Networks (PONs) are widely deployed to implement the fiber optic access networks (Ghazisaidi et al., 2009). A PON is usually viewed as the final segment of optical fiber-to-the home (FTTH) or close to it (FTTx). Commercially available and widely deployed PON access networks are the IEEE 802.3ah Ethernet PON (EPON) with a symmetric rate of 1.25 Gbps, or the ITU-T´s G.984 Gigabit PON (GPON) with an upstream rate of 1.244 Gbps and a downstream rate of 2.488 Gbps (Ghazisaidi et al., 2009).

Recent advances in fiber optic technology have led to significant increase in capacity of optical networks. Data can be carried at terabits per seconds (Tbps) bandwidth across long distances. However, carrying information to the residential customer still depends on legacy low-bandwidth access networks. The situation is even worse in rural context where the reach of fiber optic backbone is rather limited. While fiber optic technologies offer high bandwidth, they cannot be deployed everywhere due to their implementation constraints such as distance limitation and its vulnerability to vandalism. On the other hand, wireless technologies have the potential to reach everywhere, providing mobility as well as faster deployment. Therefore, combining fiber optic and wireless technologies implies reaping benefits of both. To cater for the increasing bandwidth requirement and to reach the isolated rural areas where implementing wired network is not feasible, a hybrid fiber-wireless broadband access network can be considered to serve the purpose (Ghazisaidi et al., 2009; Luo et al., 2006). The hybrid fiber-wireless is a broadband access architecture, which captures the best of both; the optical and the wireless worlds. By combining the capacity of optical fiber networks with the mobility of wireless networks, hybrid fiber-wireless networks form a powerful platform to support the emerging as well as future applications and services (Ghazisaidi et al., 2009; Luo et al., 2006). Furthermore, the hybrid fiber-wireless architecture is envisioned as an economic way to bridge the connectivity gap between rural and urban area (Luo et al., 2006).

The hybrid fiber-wireless network can be implemented by using either Wi Fi or WiMAX technology as the wireless front-end connected to a fiber optical backhaul. Currently, Wi Fi technologies (IEEE 802.11 a/b/g/n), are widely exploited due to their low cost, technological maturity, and high product penetration. However, since these protocols were originally designed for wireless local area networks (WLANs), they cannot be efficiently optimized for outdoors long distance access networks. For outdoor long distance networks, proprietary Wi Fi technologies and WiMAX have been used instead (Patra et al., 2007). Unlike Wi Fi, IEEE 802.16 (WiMAX) allows point-to-multipoint wireless connections and can be used for longer distances. WiMAX also expands the scope of wireless access by operating in both licensed and unlicensed frequency bands (Ghazisaidi et al., 2009).

There are two possible architectures to enable fiber-wireless integration: The first option, illustrated in figure 4.7, is for optical fiber running from an edge node, probably from central office, to WiMAX base station's antennas that can each serve a relatively large number of subscribers in a relatively large cell. Local upstream traffic from the end users is aggregated at the antenna locations while network management is centralized at the edge node. Multiple optical interfaces at the edge node are necessary to support the deployment of multiple WiMAX cells (Luo et al., 2006).

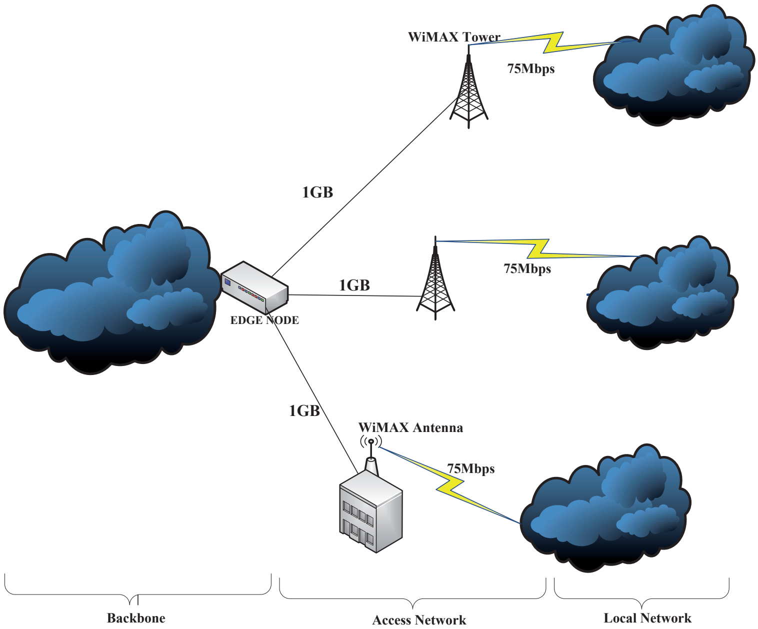


Figure 4.7: Optical Fiber and WiMAX Integration

The second approach, shown in figure 4.8, employs passive optical network as the access network, supporting WiMAX base station antennas in the lower tier. A PON segment is headed by an Optical Line Terminal (OLT) that drives several Optical Network Units (ONUs), which in turn serve end users. PON lowers the cost of network deployment and maintenance by eliminating multiplexers and demultiplexers, this is a replacement of active electronic components with the less expensive passive optical splitters. This technique makes the passive optical network to be the cost-effective choice for fiber access network deployment (Luo et al., 2006). Standardized by both ITU and IEEE, PON covers longer distance from the service provider central offices to the customer sites, and provides up to 2.5 Gbps transmission data rate (Ghazisaidi et al., 2009; Sarkar et al., 2008). In contrast to the traditional PON architecture, in which the optical network unit, ONU, bridges the local users using wired connections; in this hybrid mode as proposed by Sarkar et al., (2008), ONU is a combination of fiber with WiMAX to facilitate wireless communications. The OLT enables upstream local data aggregation and downstream data broadcast.

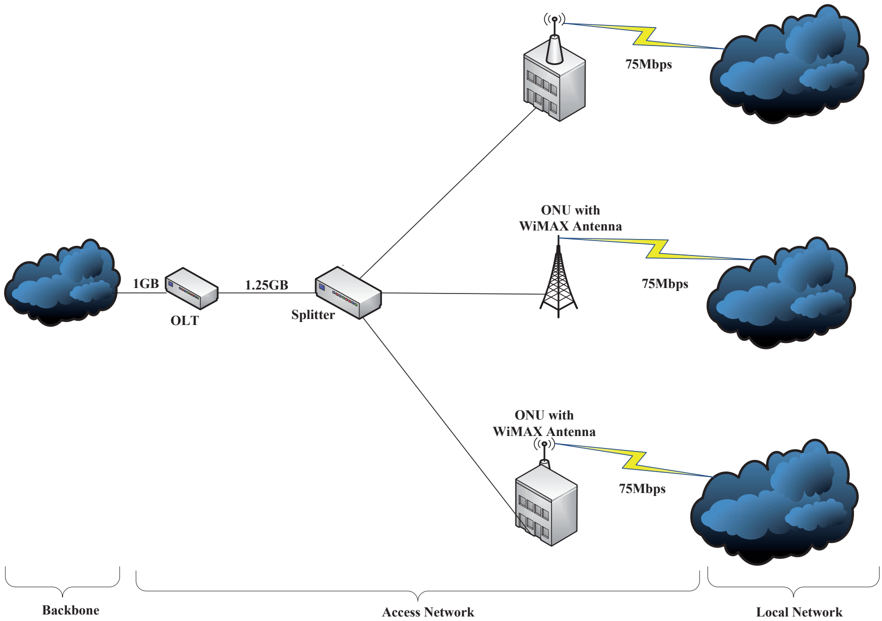


Figure 4.8: PON and WiMAX Integration

The two deployment architectures discussed offers centralized management at the edge nodes and simplified processing at the access point, resulting in a faster deployment and lower system cost. The PON and WiMAX integration presents an added advantage of cost serving by using passive equipments. The use of passive equipment is a low-cost option for the rural area access networks.

All the surveyed technologies: cellular mobile wireless, WiMAX and the hybrid fiber-wireless access technologies have demonstrated enough potential and capabilities in terms of coverage and data rates to offer broadband access networks to rural areas. The capabilities are summarized in table 4.5.

Table 4.5: Coverage and Capacity of Broadband Access Technologies

Technology	Data Rate (Mbps)	Coverage (Cell Radius)
Fixed WiMAX	75	48km P2P/8km P2MP
Mobile WiMAX	75	8km
3G at 2100MHz	14.4	2 - 3 km
3G at 900MHz	1	2 - 3 times of 3G at 2100MHz
Hybrid Optical fiber-WiMAX	75	8km
Hybrid PON-WiMAX	75	8km

In order to identify the most suitable technology for rural connectivity among the surveyed candidates, the technologies were further compared based on rural connectivity requirement criteria with regard to the context of this thesis. The required criteria for rural connectivity were: (1) Wide network coverage in order to cater for the scattered rural subscribers, (2) A network with broadband capacity in order to carry multimedia contents, (3) existence of basic infrastructure to facilitate final network deployment, hence relative cost-effective option, (4) rural areas required affordable end user terminal equipment. Comparison of the surveyed technologies based on the rural connectivity requirements are summarized in table 4.6.

Table 4.6: Technology comparison based on rural connectivity requirements criteria

Technology/ Criteria	**3G-2100 (HSDPA)**	**3G-900**	**Fixed WiMAX**	**Mobile WiMAX**	**Hybrid Fiber + Wireless**
Coverage (cell range/radius)	2km	8km	48km P2P 8km P2MP	2 - 8km	8km
Capacity (DL theoretical max)	14.4 Mbps	1Mbps	75Mbps	75Mbps	75Mbps
Cost efficiency due to existence of basic infrastructure	No	Yes	No	No	No
Cost of terminal (end user) equipments	low	low	high	low	High

From the comparison in table 4.6, the 3G at 900MHz qualified for all the criteria of rural connectivity. However, the 3G at 900MHz technology come into existence as a solution to address the coverage problem of 3G at 2100MHz technology (Simba et al., 2011). As a result, the 3G at 900MHz are often deployed in the rural or suburban area to extend coverage of 3G data network where there is no coverage of 3G at 2100MHz. With this scenario, it had became important to analyze future trend of the two technologies (3G at 900MHz and 3G at 2100MHz) whether their co-existence will be sustainable or one of them will emerge a dominant technology and hence sustainable. The analysis is done in the following section 4.2.

4.2 Use of Conceptual Framework to Forecast a Sustainable Wireless Technology

A conceptual framework is defined as a set of coherent ideas or concepts organized in a manner that makes them easy to communicate to others with an intention to get answers from a problem being investigated. The broadband access wireless technologies for rural connectivity identified by the survey done in section 4.1 were further analyzed by using a conceptual framework developed by Smura, (2006) in order to identify their sustainability.

The conceptual framework for analyzing competition between emerging wireless technologies by Smura, (2006) is based on four viewpoints: (1) end user (2) technology (3) value network (4) policy and regulations.

i. End user viewpoint aims to identify use cases where technologies complement and/or substitute each other.

ii. Technology viewpoint analyze and compares the relative techno-economic characteristics of the technologies under comparison.

iii. The value network viewpoint focuses on analyzing the capabilities of industrial players to deliver a `whole product` to the end user. Whole product in this case is defined as a combination of networks, terminals, applications and contents.

iv. Policy and regulation viewpoint focuses on external factors having an effect on both the capability of the network as well as the strategies and decision of players in the value network.

An illustration of the conceptual framework for analyzing competition between wireless technologies is shown in figure 4.9. Smura, (2006) explained that the value network model, which is a part of the conceptual framework is a series of inter-twined value chains where some nodes are simultaneously involved in more than one value chain. This approach is inline with the view of Li & Whalley, (2002). The rounded boxes in figure 4.9 are interpreted as roles, not as separate players, as one player can have one or many roles. For example Nokia, a wireless technology vendor, is both a network vendor and a terminal vendor. In some emerging markets, it is increasingly becoming a network operator as well. Similarly, some incumbent mobile operators usually take the role of both network operator and service providers, and are also involved in the provisioning of terminals and contents (Smura, 2006).

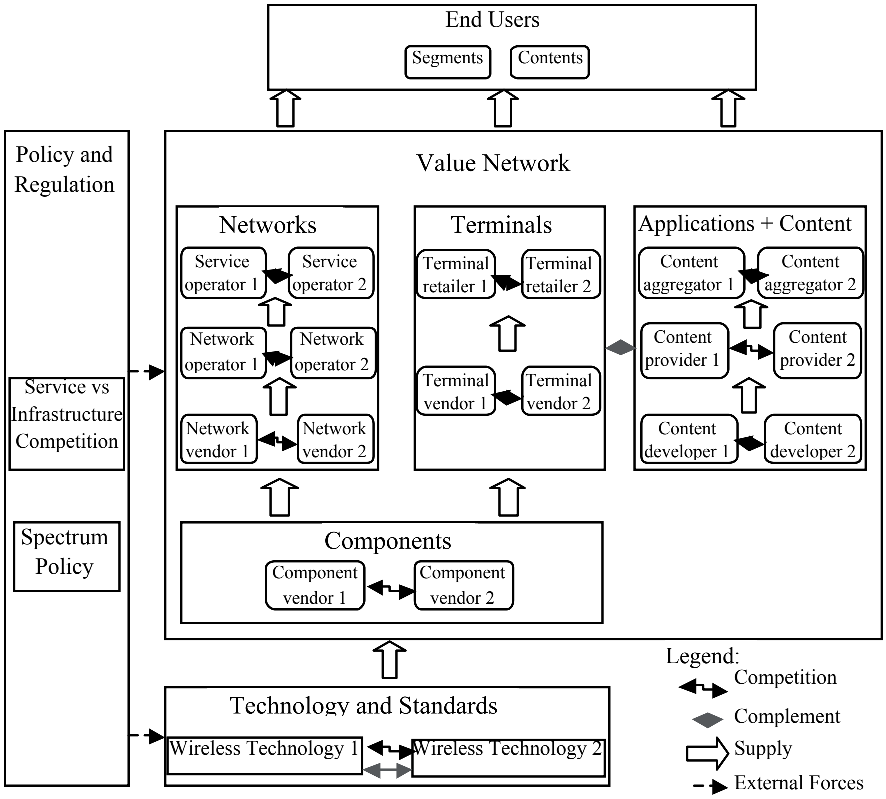


Figure 4.9: Conceptual framework for analyzing competition between emerging wireless technologies

According to Smura, (2006), when two or more technologies are close substitutes of one another and are targeted at the same markets, a battle often takes place for technological dominance. However if technologies under comparison are complementary, they can co-exist peacefully. The outcome of the technological battle will strengthen trust to the customers of the services offered as well as building confidence to the equipment vendors or suppliers (Suarez, 2004).

By using the conceptual framework developed by Smura, (2006), the 3G technologies at 900MHz and at 2100 MHz, were analyzed in order to find out which one among them will be the sustainable technology. The framework investigated the complementary and substitutive nature of two 3G technologies, based on the four viewpoints:(1) end-user (2)technology (3)value network (4) policy and regulations.

4.2.1 End-user Viewpoint

End-user viewpoint aimed to identify use cases where technologies complement and/or substitute each other. Use cases for end-user viewpoint in this research were device, applications, context (place). Devices considered in this research were desktop, laptop and mobile phones, assuming that users are willing to have broadband connectivity to their laptop and mobile phones. Table 4.7 show the relationship between devices, application, and context use cases. Considering the rural context (environment) which is the focus of this research, the availability of mobile phone is relatively high compared to laptop and desktop computers.

Table 4.7: Relationship between devices, application, and context use cases

Context/ Application	**At home**	**At work**	**Hotspots**	**On-the-move**
Voice calls	F, M	M,F	M,L	M
Surfing the internet	D,L,M	D,L	L,M	M
Video streaming/video calls	D,L	D,L	L	M
Reading e-mails	D,L,M	D,M,L	L,M	M

D = Desktop, L=Laptop, M = Mobile phone, F = Fixed line phone (Bolded = Preferred in case of availability of more than one device)

Both technologies, 3G at 900MHz and 3G at 2100MHz, are targeting customers with devices/terminals that can connect to the broadband network to access contents of a certain application. Therefore, the two technologies are targeting more or less the same type of customers. The two technologies are capable of delivering multimedia applications and can provide connectivity to all contexts (at home, at work, hotspots and on the move). Devices are differently preferred in different context and for different applications. Therefore, the two technologies are substitutive with regard to end user viewpoint; they are both aimed at similar use cases, therefore this will lead a technological battle for dominance.

4.2.2 Technology viewpoint

In the technology viewpoint, the technologies are compared according to the following techno-economic characteristics:

i. Capacity

ii. Coverage

iii. Mobility

Table 4.8 shows values of capacity in mega bits per seconds (Mbps), coverage in kilometers (kms) and support for mobility.

Table 4.8: Coverage, Capacity Values and Mobility Support

Technology/Characteristics	**3G-900**	**3G-2100 (HSDPA)**
Coverage (cell radius)	8km	2km
Capacity (data rate)	1Mbps	14.4 mbps
Support for mobility	Yes	Yes

In most cases and especially in the developing countries, 3G at 900MHz networks are deployed to extend the coverage of 3G at 2100MHz especially to the rural areas (Roskilde, 2006). Therefore, in regards to the coverage, the two technologies are complementary. The two technologies both support mobility and they have enough data capacity to support multimedia contents. This suggests that under the capacity and mobility criteria, the two technologies are substitutive.

4.2.3 Value Network Viewpoint

A value network can be defined as a set of connections between organizations and/or individuals interacting with each other to benefit the entire team. The value networks can be visualized with a simple mapping tool showing nodes (members) and connectors (relationships). In business and commerce, value networks are an example of an economic ecosystem. Each member relies on the others to foster growth and increase value. Value network members can consist of external members such as customers or internal members such as researchers and development teams. Weakness in one node can affect the entire network (Li & Whalley, 2002).

In telecommunication industry, the value network is usually targeted to analyze the capabilities of industrial players to offer the `whole product` consisting of network, terminals, and application and contents to end-users. Smura, (2006) emphasize that in order for a particular technology to be useful to the end users, both the network and terminals must be available, as well as relevant applications and contents to run into these infrastructure. Therefore, this research analyzes the complementarity or substitutive nature of the two technologies (3G at 2100MHz and 3G at 900MHz) based on the `whole product` elements of the value network.

4.2.3.1 Networks

The key role players in a competition of network technologies are the component manufactures and network equipment vendors. Their sustainable supply of end user terminals and network equipments assures the sustainability of the network technology. The major vendors for 3G at 2100MHz technology are Ericsson, Nokia Siemens Networks, Alcatel-Lucent, and Motorola. According to UMTS forum, as of April, 2011, a total number of 3G at 2100MHz networks worldwide was 801 which is made up of 369 WCDMA, 344 HSPA and 88 HSPA+ networks.

On the other hand, the idea to implement WCDMA at lower frequency, 900MHz, got a positive response from different operators worldwide. As of March, 2011, there were 27 operational network deployed in 19 countries as shown in table 4.9 (GSA, 2011). Network vendors, providing equipments for WCDMA network at 900MHz includes Qualcomm, Ericsson and Nokia Siemens Networks.

Table 4.9: UMTS900 Network Deployment

Country	Operator	Service Launched
Finland	Elisa	Nov, 2007
Estonia	Elisa	Jan, 2008
Thailand	AIS	May, 2008
Australia	Optus	May,2008
Belgium	Mobistar	May, 2008
Belgium	Proximus	July, 2008
New Zealand	Vodafone	July, 2008
Finland	DNA	October, 2008
Iceland	Siminn	October, 2008
Venezuela	Digitel	March, 2009
Finland	TeliaSonera	June, 2009
Croatia	Tele2	July, 2009
Australia	Vodfone	August, 2009
Faroe Islands	Faroese Telecom	November, 2009
Armenia	Orange	November, 2009
Latvia	LMT	November, 2009
Poland	Aero2	November, 2009
Ghana	MTN	December, 2009
Hong Kong	CSL Limited	Jan, 2010
Romania	Vodafone	April, 2010
Estonia	EMT	June, 2010
Bulgaria	Vivacom	June, 2010
Slovenia	Tusmobil	July, 2010
Greenland	TELE	August, 2010
South Africa	MTN	March, 2010
South Africa	Cell C	September, 2010
Poland	P4 (Play mobile)	January, 2011

4.2.3.2 Terminals

As of Feb, 2011, Global mobile Suppliers Association (GSA) confirmed that 2,922 UMTS2100 HSPA-enabled user devices were launched in the market by 255 suppliers. The terminals comprises of personal computers (PC) cards, USB adapters (dongles) for laptops, mobile phones, notebooks, wireless routers, personal media players, e-book readers, mobile tablets, and cameras. In addition, laptop manufacturers such as Acer, Dell, HP, and Lenovo, have launched HSDPA-enabled laptops, most in partnership with mobile network operators (GSA, 2011).

As of March, 2011, the GSA, (2011) report a total of 526 UMTS900-HSPA devices availability. Eighty one (81) suppliers have launched the devices in the market. The device includes mobile phones, PC cards, USB adapters (dongles) and wireless routers. The availability of wide range of end-user devices (terminals) ensure a momentum towards deploying 3G/WCDMA-HSPA systems in the 900MHz band for mobile broadband services. The devices which can support UMTS900 are becoming mandatory in order to be destined in Europe, middle east, Africa, and Asia pacific market (Prieur, 2010). Figure 4.10, forecast terminal penetration, it shows that availability of UMTS900 terminals is closer to 100% in 2015 (Prieur, 2010). It is clearly shown that by the year 2015 devices that can support only GSM network will start to disappear in the market. On the other hand, this trend also shows the possibility of closing down GSM networks after 2015.

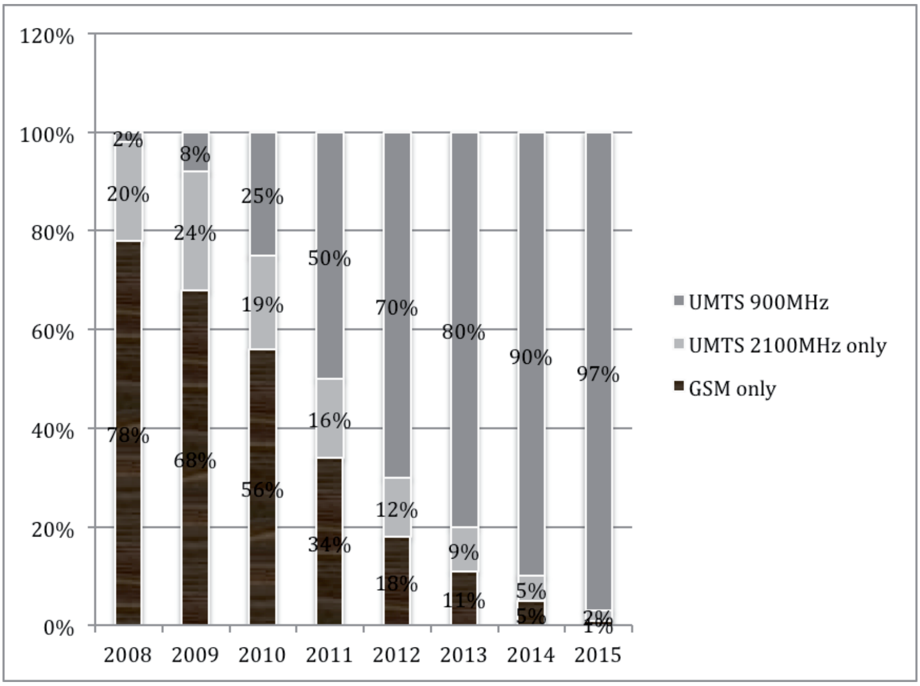


Figure 4.10: Forecast for terminal penetration (Prieur, 2010).

4.2.3.3 Applications and Contents

From the applications and contents value network elements, both 3G at 2100MHz and 3G at 900MHz had similar targets. They both aimed to provide the basic broadband Internet access to the mobile phone and laptops. Later due to innovation and expansion of service portfolio, some more services have emerged which encompass social or business communication and e-commerce transaction such as video calls/conferences, video streaming, online chatting etc. The two technologies were designed with the intention to have a capability for IP multimedia subsystems (IMS), hence capacity of both technologies is enough to deliver contents of the emerged applications. Table 4.10 summarizes the elements of the value networks supporting 3G at 2100MHz and 3G at 900MHz technologies.

Table 4.10: Players in the 3G at 2100MHz and 3G at 900MHz value network elements

3G at 2100MHz	3G at 900MHz
Components	
Network & terminal are manufactured by Ericsson, Nokia-Siemens Networks, Alcatel-Lucent, and Motorola.	Network & terminal are available from manufacturers such as Qualcomm, Ericsson and Nokia Siemens Networks.
Networks	
By Apr, 2011, a total number of 3G networks deployed worldwide was 801.	By March, 2011, there were 27 operational network deployed in 19 countries.
Terminals	
By Feb, 2011, there were 2,922 HSPA-enabled user devices comprises of PC cards, USB adapters (dongles), mobile phones, notebooks, wireless routers, personal media players, e-book readers, mobile tablets, and cameras.	By march, 2011, there were 526 UMTS900-HSPA devices. The devices includes mobile phones, PC cards, USB adapters (dongles) and wireless routers
Application and Contents	
Support broadband internet access and multimedia contents services.	Support broadband internet access and multimedia-based services.

From the value network viewpoint, both 3G at 2100MHz and 3G at 900MHz technologies are in a better position to provide the `whole product´ to the end users. The 3G at 900MHz ecosystem is coming up healthily while enjoying the benefit of its potential to provide cost effective solution to the rural areas. Generally, basing on the value network viewpoint, the two technologies are substitutive.

4.2.4 Policy and Regulations Viewpoint

Policy and regulations are considered as external factors having an effect on both the capabilities of the technologies, as well as the strategies and decisions of different players in the value network. According to Smura, (2006)´s framework, parameters that guide policy and regulations viewpoints are the (a) spectrum policy (b) service vs infrastructure-based competition.

4.2.4.1 Spectrum Policy

The 3G at 2100MHz operates at 2100MHz while 3G at 900MHz operate at 900MHz frequency bands. Both frequencies are available for use and can be allocated to operators by the responsible bodies (regulators or commissions). However, the 3G at 900MHz shares the 900MHz frequency band with the GSM networks. From the terminal penetration forecast, it is evident that there is a potential of closing down GSM networks at the point in time when all terminals become UMTS900 enabled (Prieur, 2010). This is because services provided by GSM networks can as well be provided by the 3G at 900MHz networks. This situation works in favor of the 3G at 900MHz network since frequency to be released by the closing GSM networks will be available for use by the 3G at 900MHz networks.

4.2.4.2 Service vs Infrastructure-based Competition

In communication network, service-based competition takes place when new entrant operators utilize the incumbent´s existing network infrastructure to offer services to end-users. In infrastructure-based competition, new entrants build and operate their own access network infrastructure, based on the same or alternative technologies as the incumbent. However for countries where an open access network is mandated and the wholesale prices are regulated, there are no incentives to invest in own network infrastructures. The potential for open access networks is evidenced where 3G at 900MHz network infrastructures are implemented to co-exist with GSM sites. This is a benefit to the 3G at 900MHz as there will be no interest to implement own 3G at 2100MHz network infrastructures while there is a possibility to re-use the existing GSM infrastructures to implement a network with similar 3G data capabilities (The 3G at 900MHz).

As a concluding remark, results from the four viewpoints of the conceptual framework show that, the two technologies target similar devices on more or less similar applications, so they are substitutive with regard to end user viewpoint. On the other hand, technology viewpoint reveals that both technologies have capabilities to support mobility and capacity for multimedia services, hence they are substitutive. The technologies are complementary when it comes to coverage. The coverage aspect of technology viewpoint reveals that, the 3G at 900MHz has an added advantage of having wide cell coverage. This characteristic implies wide network coverage with fewer base stations, hence reduced investment cost. Network operator can be attracted to this cost effective option and hence sustainability of the 3G at 900MHz technology.

From the value network viewpoint, the two technologies are substitutive, both have the capability to offer the `whole product` to the end users. Policy and regulation viewpoint show a potential for availability of frequencies for 3G at 900MHz technology. Due to the fact that, frequencies are the very scarce resources, releasing GSM frequencies for 3G at 900MHz is an added advantage to ensure sustainability of 3G at 900MHz in the market. Furthermore, the open access network infrastructure works in favor of 3G at 900MHz since it can co-exist with GSM networks. Which makes deployment of 3G at 900MHz cost-effective, fast and easier compared to when an operator is required to build a completely new infrastructure.

Generally the two technologies are substitutive, hence they will engage in the technological battle for technology dominance, which is referred to as technology sustainability in this thesis. However there are indicators forecasting 3G at 900MHz as a potential winner in this battle. The indicators are the cost-effectiveness of 3G at 900MHz due to wider coverage; potential to inherit subscribers (end user terminals) and frequency band from GSM networks; Open access and converged regulatory schemes, works in favor of the ability of 3G at 900MHz to co-exist with GSM, which is not the case with 3G at 2100MHz. It is envisioned that in this situation, there will be no incentive to build own network infrastructure, while there is a possibility to build on top of the existing ones. Therefore, operators are more likely to prefer the service-based competition rather than infrastructure based competition, which implies more deployments of 3G at 900MHz than 3G at 2100MHz. The results suggest dominance of 3G at 900MHz over 3G at 2100MHz.

4.3 Techno-economic Analysis to Identify a Cost Effective Technology

Cost required to deploy connectivity infrastructure, especially to the rural areas is one of the major challenges, therefore it is crucial to investigate cost aspect of the earmarked suitable and sustainable wireless broadband access technology for rural connectivity. This task was done by using the techno-economic analysis. In this thesis, a techno-economic analysis is used to justify the economic worth of re-using the existing second generation; GSM network, in the deployment of 3G network at 900MHz frequency band as a cost-effective and sustainable broadband access network for rural areas.

The 900MHz and 1800MHz bands have been widely used for GSM systems worldwide. However, deploying 3G systems in the 900MHz and 1800MHz bands does not mean the immediate replacement of GSM systems by 3G. It is envisioned that 3G networks can co-exist with GSM in the 900MHz frequency bands for some time in the future (Roskilde, 2006; Prieur 2010). It has been practically demonstrated that GSM and UMTS/HSPA networks can co-exist in the same frequency band without technical problems (NSN, 2010). Throughout this section, 3G at 900MHz and 3G at 2100MHz are referred to as UMTS900 and UMTS2100 respectively.

In this techno-economic analysis, the cost of the UMTS900 and GSM co-existence approach is compared with the cost of implementing a separate UMTS2100 networks. The comparison targets to investigate the cost aspects of 3G at 900MHz and 3G at 2100MHz. The techno-economic analysis is followed by a sensitivity analysis in order to identify the impact due to changes of the important cost parameters. The procedure followed during the techno-economic analysis is summarized in figure 4.11.

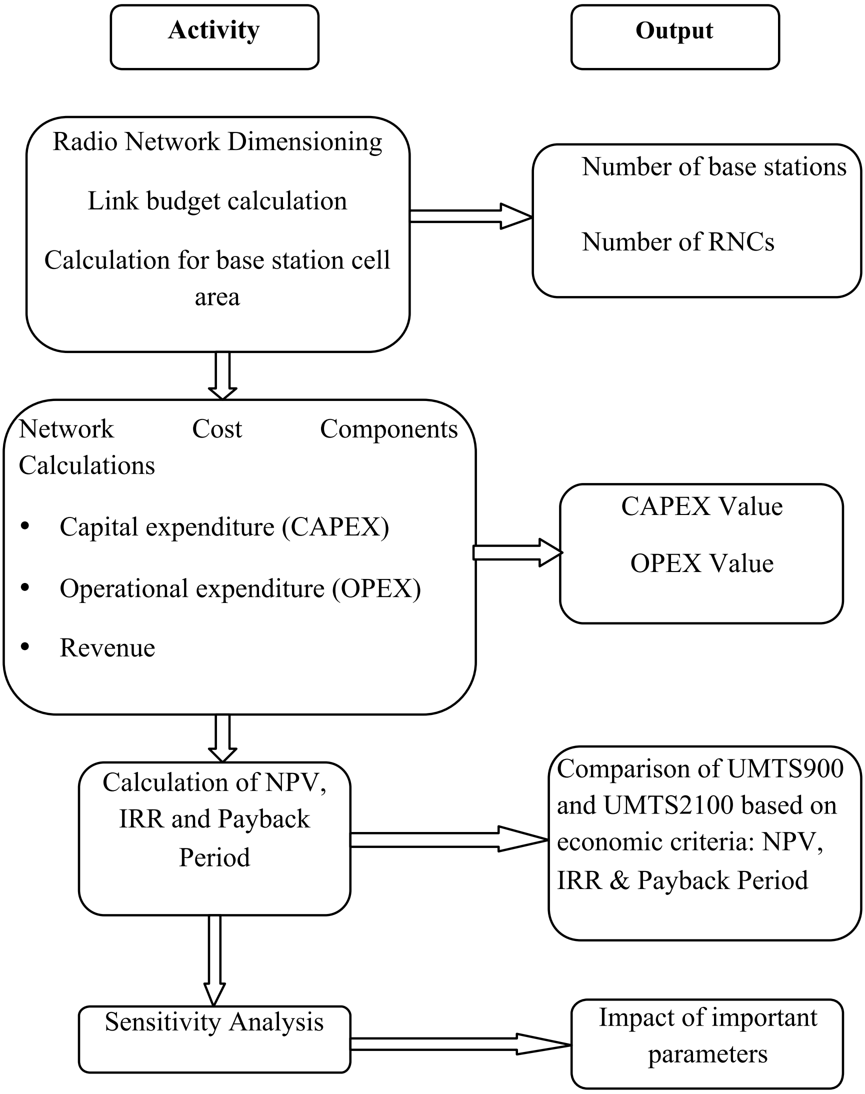


Figure 4.11: Activities/Steps taken during Techno-economic Analysis

In this thesis, the radio network dimensioning was performed to estimate the number of sites (base stations) required to provide coverage of the given geographical area. In order to get the required number of sites, link budget calculation was done for both UMTS900 and UMTS2100, in order to estimate the maximum allowed propagation loss in each case. The obtained propagation loss was used to estimate cell range by using the Cost 231 Hata propagation model. The cell range estimation depends on the number of sectors used in the site. Finally, the required number of sites was calculated as a ratio of total area to be covered over the site area.

4.3.1 Link Budget Calculation to Estimate the Maximum Propagation Path Loss

Propagation path loss is the difference (in dB) between the transmitted power and the received power. It represents signal level attenuation caused by free space propagation, reflection, diffraction and scattering (Holma & Toskala, 2004; Laiho et al., 2006). Link budget calculations based on 12.2 kbps voice service is shown in table 4.11. The link budget for mobile wireless networks is usually calculated (dimensioned) based on voice service with the assumption that voice service is the key business of the mobile network operators (Holma & Toskala, 2004; Chevallier et al., 2006). The parameter values for link budget calculation were taken from Holma & Toskala, (2004) for the UMTS2100 and values for UMTS900 were obtained from Ovum-Consulting, (2007).

Table 4.11: Link budget calculations based on 12.2 kbps voice service

	Values		**Formula**
Transmitter (Mobile)	**2.1 GHz**	**900MHz**	
Max. Mobile transmission power (W)	0.125	0.25	
Max. Mobile transmission power in dBm	21.0	24.0	a
Antenna Gain (dBi)	0.0	2.0	b
Body Loss (dB)	3.0	0.0	c
Equivalent isotropic Radiated power (EIRP) (dBm)	18.0	26.0	d = a+b-c
Receiver (Base Station)			
Thermal noise density (dBm/Hz)	-174.0	-174.0	e
Base station receiver noise figure (dB)	5.0	5.0	f
Receiver noise density (dBm/Hz)	-169.0	-169.0	g = e + f
Receiver noise power (dBm)	-103.2	-103.2	h = g + 10*log (3840000)
Interference margin (dB)	3.0	3.0	i
Total effective noise + interference (dBm)	-100.2	-100.2	j = h + i
Processing gain (dB)	25.0	25.0	k=10*log(3840/12.2)
Required signal to noise ratio Eb/No (dB)	5.0	3.1	l
Receiver Sensitivity	-120.2	-122.0	m = l - k + j
Base station antenna gain (dBi)	18.0	18.0	n

Cable loss in the base station (dB)	2.0	2.0	o
Fast fading Margin (dB)	0.0	5.0	p
Maximum path loss (dB)	**154.2**	**159.0**	**q = d - m +n - o - p**
Log-normal fading margin (dB)	7.3	10.0	r
Soft handover gain (dB), Multicell	3.0	3.0	s
In-car/indoor loss	8.0	10.0	t
Interference due to co-location with GSM 900MHz (dB)	0.0	3.0	v
Allowed Propagation Loss (dB)	**141.9**	**139.0**	**u = q - r + s - t - v**

The obtained maximum allowed propagation loss was used to estimate cell range by using the Cost-231 Hata radio propagation model. A radio propagation model, also known as the radio frequency propagation model, is an empirical mathematical formulation, which characterizes radio wave propagation as a function of frequency, distance and antenna heights. Created with the goal of formalizing the way radio waves are propagated from one place to another, such models typically predict the path loss along a link or the effective coverage area of a transmitter (Abhayawardhana et al., 2005). A model that is widely used for predicting path loss in mobile wireless system is the COST-231 Hata model (Kamboj et al., 2011; Ranvier, 2006). It was developed as an extension to the Hata-Okumura (Kamboj et al., 2011; Ranvier, 2006). The COST-231 Hata model is designed to be used in the frequency band from 500 MHz to 2000 MHz. The basic equations for propagation path loss in dB for urban environments and its corresponding correction factors for suburban and rural areas are shown in equation (4.1) to (4.10) (Ranvier, 2006; Ovum-Consulting, 2007).

For 900MHz Urban Area

$$L(R) = 69.55 + 26.16\log(f) - 13.82\log(h_B) + [44.9 - 6.55\log(h_B)]\log(R) - a(h_m) \quad (4.1)$$

Where,

$L(R)$ = maximum allowed path loss in dB

$a(h_m) = [1.1\log(f) - 0.7)]h_m - [1.56\log(f) - 0.8]$

h_b = base station antenna height in meters = 30m

h_m = is the user equipment (UE) antenna height in meters = 1.5m

f = used frequency in MHz = 920MHz

R = distance between BS and UE in km (i.e a cell radius)

Using the values provided, the formula simplifies into

$$L(R) = 35.2\log(R) + 126.6 \quad (4.2)$$

For 2100MHz - Urban Area

$$L(R) = 46.3 + 33.9\log(f) - 13.82\log(h_B) + [44.9 - 6.55\log(h_B)]\log(R) - a(h_m) \quad (4.3)$$

Where,

$L(R)$ = maximum allowed path loss in dB

$a(h_m) = [1.1\log(f) - 0.7)]h_m - [1.56\log(f) - 0.8]$

h_b = base station antenna height in meters = 30m

h_m = is the user equipment (UE) antenna height in meters = 1.5m

f = used frequency in MHz =1950MHz

R = distance between BS and UE in km (i.e a cell radius)

Using the values provided, the formula simplifies into

$$L(R) = 35.2\log(R) + 137.4 \quad (4.4)$$

Suburban environments

$$L(R)_{suburban} = L(R)_{urban} - 2\log^2(f/28) - 5.4 \quad (4.5)$$

for f = 920MHz

$$L(R)_{suburban} = 35.2\log(R) + 116.6 \quad (4.6)$$

for f = 1950

$$L(R)_{suburban} = 35.2\log(R) + 125.2 \quad (4.7)$$

Rural environments

$$L(R)_{rural} = L(R)_{urban} - 4.78\log^2(f) + 18.33\log(f) - 40.94 \quad (4.8)$$

for f = 920MHz

$$L(R)_{rural} = 35.2\log(R) + 98 \quad (4.9)$$

for f = 1950

$$L(R)_{rural} = 35.2\log(R) + 105 \quad (4.10)$$

Considering the rural area, which is a focus of this thesis, the cell ranges for both UMTS900 and UMTS2100 were calculated by using formula (4.9) and (4.10) respectively. From the link budget, the obtained values for the maximum allowed propagation path loss for UMTS900 and UMTS2100 were 139.0dB and 141.9dB respectively.

for *f* = 920MHz

$L(R)_{rural} = 35.2\log(R) + 98$

$139 = 35.2\log(R) + 98$

$R = 14.6 \text{ km} \sim 15\text{km}$

for *f* = 1950

$L(R)_{rural} = 35.2\log(R) + 105$

$141.9 = 35.2\log(R) + 105$

$R = 11.18 \text{ km} \sim 11\text{km}$

After, determined the cell radius R, then, the site area, which is a function of the base station sectorization configuration, was also calculated. For the three sectored antenna, the cell site coverage is calculated by using equation (4.11) (Ovum-Consulting, 2007).

$$\text{Cell site coverage } S_a = \frac{\sqrt[9]{3}}{8}R^2 \qquad (4.11)$$

For UMTS900, where cell range, R = 15km, then the site area is

$$S_a = \frac{\sqrt[9]{3}}{8} \text{ x } (15)^2$$

$$S_a = 31.7\text{km}^2 \sim 32\text{km}^2$$

For UMTS2100, where cell range, R = 11km, then the site area is

$$S_a = \frac{\sqrt[9]{3}}{8} \text{ x } (11)^2$$

$$S_a = 17\text{km}^2$$

Furthermore, the cell site coverage area was used to calculate the number of sites required to fulfill a given geographical coverage requirement. Number of sites was calculated as a ratio of total area to be covered over the site coverage area. Taking Tanzania as a cases study, which has a geographical area of about 945,087km2 and assuming coverage requirements of 80%, the remaining 20% is assumed to be water bodies such as lakes and rivers, then a total area to be covered is 756,070km2. With the site area of 32km2 and 17km2 for UMTS900 and UMTS2100 respectively, their respective number of sites are given by using equation (4.12).

$$\text{Number of Sites} = \frac{\text{Total Geographical Area to be Covered}}{\text{Site Coverage Area}} \quad (4.12)$$

$Sites_{900}$ = (756,070/ 32) = 23,627

$Sites_{2100}$ = (756,070/ 17) = 44,474

After obtaining the required number of sites, the following step was to find the number of required RNC to support the obtained number of NodeBs and equipments at the core network (i.e SGSN, GGSN, MSC, VLR & HLR) for both circuit switched and packet switched domains.

4.3.2 RNC Dimensioning

Number of the required RNCs was obtained by RNC dimensioning procedure. The purpose of RNC dimensioning is to find the number of RNCs needed to support the estimated traffic.

The following limitations on RNC capacity are to be taken into consideration, out of which the most demanding one (which needs largest number of RNCs) has to be selected in the process of RNC dimensioning (Laiho et al., 2006):

i. Maximum number of cells

ii. Maximum number of BSs under one RNC

iii. Maximum Iub throughput

iv. Amount and type of interfaces (such as E1, T1, or STM-1).

Although generally base station controllers (BSCs) are limited by the number of radio frequency (RF) network elements (such as sites, sectors, and transmitters) that can be supported, the capacity of an RNC tends to be traffic or throughput limited (Laiho et al., 2006; Chevallier et al., 2006). This is due to the fact that an RNC can be involved in traffic handling for base stations that it does not directly control. For example, an RNC can act as a serving RNC or drift RNC during soft handover. In such cases, the RNC may be handling traffic to/from a base station that it does not directly control. Thus, the number of controlled base stations becomes less important and the amount of traffic handled becomes more important to the capacity of the RNC. Unlike the situation for BSCs, it is more common for RNCs from a given vendor to be offered in a variety of configurations scenario. For example, the Iu interface might be offered using different transmission interface capacities (such as E1, T1, or STM-1). Table 4.12 shows the possible RNC´s configurations (Laiho et al., 2006).

Table 4.12: Possible radio network controller capacity configuration

		Iub Traffic Capacity		Other Interfaces	
Configurations	Iub throughput (Mbps)	BSs	Cells	STm-1	E1
1	48	128	384	4*4	6*16
2	85	192	576	4*4	8*16
3	122	256	768	4*4	10*16
4	159	320	960	4*4	12*16
5	196	384	1152	4*4	14*16

The following constraints/limitations were considered in the RNC dimensioning: maximum number of cells under one RNC, maximum number of BSs under one RNC, maximum Iub throughput, where number of RNCs were calculated by using equations (4.13), (4.14), (4.15) respectively.

Number of RNC according to limitation 1: maximum number of cells under one RNC:

Number of RNCs needed to connect a certain number of cells was calculated according to equation (4.13):

$$\text{numRNCs} = \frac{\text{numCells}}{(\text{cellsRNC x fillrate 1})} \tag{4.13}$$

Where,

numRNCs is the number of RNCs

numCells is the number of cells in the area being dimensioned

cellsRNC is the maximum number of cells that can be connected to one RNC

fillrate1 is the margin used as a backoff from the maximum capacity.

Number of sites (nodeBs) obtained for UMTS900 and UMTS2100 from equation (4.9) and (4.10) respectively were 23,627 and 44,474 sites respectively. Assuming that each site has three sectors with two frequency carrier used per sector and RNC configuration where a maximum capacity of cellsRNC = 1152 cells per RNC and 90% for fillrate 1, fillrate 2, fillrate 3, the number of RNCs needed are calculated as follows:

$UMTS_{900}$ = 23627 x 3 x2/ (1152 x 0.9)

= 137 RNCs

$UMTS_{2100}$ = 44474 x 3 x2/ (1152 x 0.9)

= 257 RNCs

Number of RNC according to limitation 2: maximum number of BSs under one RNC:

Number of RNCs needed according to the number of BSs to be connected was calculated by equation (4.14):

$$\text{numRNCs} = \frac{\text{numBSs}}{(\text{bsRNC x fillrate 2})} \qquad (4.14)$$

Where,

numBSs is the number of BSs in the area being dimensioned

bsRNC is the maximum number of BSs that can be connected to one RNC

fillrate2 is the margin used as a backoff from the maximum capacity

$UMTS_{900}$ = 23627 / (1152 x 0.9)

= 68 RNCs

$UMTS_{2100}$ = 44474 / (1152 x 0.9)

= 129 RNCs

Number of RNC according to limitation 3: maximum Iub throughput:

The number of RNCs to support Iub throughput was calculated using equation (4.15):

$$numRNCs = \left[\frac{(voiceTP + CSdataTP + PSdataTP)}{(tpRNC\ x\ fillrate.3)}\right] x\ numSubs \qquad (4.15)$$

Where,

tpRNC is the maximum Iub capacity

fillrate3 is the margin used as a backoff from the maximum capacity.

voiceTP = voiceErl x $bitrate_{voice}$ x (1 + SHO) is the throughput for voice.

CSdataTP = CSdataErl x bitratecsdata x (1 + SHO)) is the throughput for circuit switched data

PSdataTP = avePSdata/PSoverhead x (1 + SHO) is the throughput for packet switched data

voiceErl is the traffic of a single voice user;

CSdataErl is the traffic from a CS data user;

avePSdata is the average amount of PS data per user.

PSoverhead takes into account 10% of retransmission as well as 5% of overhead from the Frame

Protocol (FP) and L2 (RLC and MAC) overhead.

The different SHOs are the overhead per service produced by soft handover.

By assuming the following traffic profile:

Voice service: voiceErl = 25 mErl/subs, bitratevoice = 16 kbps,

CS data service1: CSdataErl = 10 mErl/subs, bitrateCSdata = 32 kbps,

CS data service2: CSdataErl = 5 mErl/subs, bitrateCSdata = 64 kbps,

PS data services: avePSdata = 0.2 kbps/subs, PSoverhead = 15%,

Tanzania Regulatory Authority report a sum of 21,158,364 voice subscribers and 462,514 mobile wireless internet subscribers (TCRA-Statistics, 2010). Then the total number of subscribers expected to be served by these networks is 21,620,878. Therefore the number of RNCs capable to handle traffic offered by these subscribers was calculated using equation (4.15), given a soft handover factor for all services of 30%, a maximum Iub capacity of tpRNC = 196Mbps and a fillrate3 of 90%. In this case, the UMTS900 and UMTS2100 are dimensioned to cover the same geographical area and serve the same number of subscribers, therefore it is assumed that given the same number of subscribers and their usage profile will generate similar traffic volume either in UMTS900 or in UMTS2100.

numRNCs = [(0.0025 x 16kbps + 0.010x32kbps + 0.005x64kbps+0.2kbps/0.85) x1.3x 21620878]/(196000kbpsx0.9)

numRNCs =[(0.04 + 0.32 + 0.32 + 0.24) x 601268]/176400

numRNCs = (0.94 x 28107141.4)/176400

numRNCs = 149.7 ~ 150

According to the RNCs dimensioning principles, the required number of RNCs is the maximum of the three results from equations (4.13)–(4.15). Therefore, for UMTS900 required number of RNC is 150 and for UMTS2100, the required RNCs is 257. The focus of this thesis is on the access network part, therefore it is assumed that costs and equipments for core networks part are the same in both cases and the operator have access to the core network, weather own or leased. Table 4.13 summarizes results of the radio network dimensioning (number of NodeBs and number of RNCs) for both $UMTS_{900}$ and $UMTS_{2100}$.

Table 4.13: Summary of equipments obtained from dimensioning

Equipment	**$UMTS_{900}$**	**$UMTS_{2100}$**
NodeB	23,627	44,474
RNC	150	257

4.3.3 Network Cost Components

The total costs of each connectivity technology is made up of initial investment costs called Capital Expenditure (CAPEX) and the ongoing Operational Expenditure, abbreviated as OPEX. In this section, the value of CAPEX, OPEX and revenue were calculated, which will later be used for calculation of Net Present Value (NPV) and Internal Rate of Return (IRR) economic criteria.

4.3.3.1 Capital and Operational Costs

Capital cost is the first time investment cost in the network deployment. The capital costs sometimes are referred to as the initial investment, which includes all the network equipment costs, installation and site rental charges. Operational costs are the recurring costs made up of network operational and maintenances costs. The value of OPEX was calculated as a twenty percent of the CAPEX costs. Values for equipment costs were taken from values of network equipment costs for the year 2011 forecasted by Ovum-Consulting, (2007). Spectrum license fee and network facility service operation fee were obtained from TCRA (TCRA-fees, 2010). Table 4.14 shows access network equipments, their respective unit and total costs, CAPEX and OPEX values.

Table 4.14: Equipments costs, CAPEX and OPEX values

Equipment Type	Required number ($UMTS_{900}$)	Required number ($UMTS_{2100}$)	Unit cost, $	Total cost, $ ($UMTS_{900}$)	Total cost,$ ($UMTS_{2100}$)
NodeB	23,627	44,474	75,000	1,772,025,000	3,335,550,000
NobeB installation and site acquisition	Once	Once	30,000	30,000	30,000
NodeB annual lease	-	-	20,000	20,000	20,000
RNC	150	257	1,000,000	150,000,000	257,000,000
Spectrum license fee	Once per year	Once per year	50	50	50
Network facility service operation fee	Once for 25 years	Once for 25 years	200	200	200
Capital Expenditure Subtotal				**1,922,075,250**	**3,592,600,250**
Network operational and maintenance costs (OPEX)			20% of capital Investments per year	**384,415,050**	**718,520,050**
CAPEX per Annum				**2,306,490,300**	**4,311,120,300**

4.3.3.2 Revenue

Revenue is defined as benefits generated by the investment. It is assumed that revenue are generated by selling voice, sms and internet-based services to individual and corporate customers. Number of customers in Tanzania that are subscribed to the mobile wireless internet services is 462,514 and voice subscribers are 21,158,364, making a total of 21,620,878 subscribers for the mobile wireless network operators (TCRA-Statistics, 2010).

TCRA provided an annual revenue per user (ARPU) per month for sms and voice services of 5,849 Tanzanian shillings (TShs) (TCRA-Statistics, 2010), which approximates to $6 ARPU/month. Therefore revenue generated from voice and sms services is 21,158,364 x $6 = $126,950,184/month. In one year, voice and sms service generate $126,950,184 x 12 = $1,523,402,208.

Taking an assumption that on average, corporate and individual users can buy 10GB of internet bundle at $270 per month for their internet related services (such as data, MMS, video, VoIP, etc). Then, revenue generated from mobile internet subscribers is 462,514 x $270 = $124,878,780/month. For a year, mobile internet subscribers generate $124,878,780 x 12 = $1,498,545,360. In total, voice, sms and internet services generate $1,523,402,208 + $1,498,545,360 =$ 3,021,947,568 per year.

It is worth to note that, the two connectivity options compared are suppose to provide coverage to the same size of a given geographical area. Therefore, it is expected that the total number of users served are the same for each technology and so is the total revenue generated.

4.3.4 Techno-economic Analysis

Deployment of UMTS900 and UMTS2100 networks represent two different connectivity models suitable for broadband access networks. It is obvious that initial investment and operational costs are likely to vary between the two options. This section aimed to provide the economic standpoint of each technology by using techno-economic analysis. Therefore, each technology was assessed according to three conventional economic criteria, NPV, IRR and payback period. Furthermore, sensitivity analysis was performed in order to study impact of uncertainties and risks. The main purpose of sensitivity analysis is to determine what are the important parameters and to what extent? (Ross et al., 2000).

4.3.4.1 Calculations of NPV and Payback Period

NPV is calculated as the sum of all the discounted cash flows during the economic life time of the investment or project (Ross et al., 2000). The discounted cash flow (DCF) is the value of a cash flow adjusted for the time value of money while cash flow (CF) is defined as the amount of cash flowing to/from a company or project during its economic lifetime. The net cash outflow is the summation of capital and operational costs per year while the net cash inflow in a year is obtained after deduction of operational costs, depreciation charges and income taxes from the revenue. Formulas to calculate DCF and NPV are given by equations 4.16 and 4.17, respectively.

$$DCF_t = \frac{CF_t}{(1+r)^t} \qquad (4.16)$$

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} \qquad (4.17)$$

Where DCF_t = Discounted cash flow for a given period of time

CF_t = Cash flow for a given period of time

r = Discount rate

t = a given period of time

NPV = Net Present Value

A fixed asset is considered depreciable if it will wear out or become obsolete over the years of its life period. The life that is assigned to an item depends on industry standards, management standards, or governmental regulations. Depreciation is defined as an accounting methodology that allows an organization to spread the cost of a fixed asset over the expected useful life of that asset. At the end of each period of the useful life of the asset, a part of the cost is expensed. Depreciation expenses are calculated by using either a straight-line depreciation method or an accelerated depreciation method. The straight-line method calculates depreciation by spreading the cost evenly over the life of the fixed asset. Accelerated depreciation methods such as declining balance and sum of years digits, calculate depreciation by expensing a large part of the cost at the beginning of the life of the fixed asset (White, 1977; Park, 1973; Ross et al., 2000).

In this thesis, depreciation charges were calculated according to the straight-line method. Therefore, the depreciation cost of each asset was calculated by dividing the asset cost by the number of years in the economic life time of the investment; five (5) years in this case. Table 4.15 shows depreciation costs of assets in $UMTS_{900}$ and $UMTS_{2100}$.

Table 4.15: Depreciation costs calculation

	$UMTS_{900}$			$UMTS_{2100}$	
S/N	Equipment	Total costs ($)	Depreciation cost ($)	Total costs($)	Depreciation cost ($)
1.	Node B (base station)	1,772,025,000	354,405,000	3,335,550,000	667,110,000
2.	RNC	150,000,000	30,000,000	257,000,000	51,400,000
Total Cost			384,405,000		718,510,000

Tax is charged after depreciation and operational costs have been deducted from the revenue. According to Tanzanian tax system, the income tax is charged at 30% of the revenues, (TRA, 2004). Then, the net cash inflow is what remains from the revenue after OPEX, depreciation and tax costs were deducted. Table 4.16 presents values of revenue, operational costs, depreciation costs, income tax charges and the net cash inflow for the two connectivity models.

Table 4.16: Values of revenue, operational costs, depreciation costs, tax and the net cash inflow

Connectivity Option	Revenue ($)	OPEX ($)	Depreciation ($)	Tax ($)	Net cash inflow ($)
$UMTS_{900}$	3,021,947,568	384,415,050	384,405,000	675,938,255	1,577,189,263
$UMTS_{2100}$	3,021,947,568	718,520,050	718,510,000	475,475,255	1,109,442,263

Table 4.17 shows values of DCF and NPV for both $UMTS_{900}$ and $UMTS_{2100}$ with the assumption that the economic lifetime is five (5) years. In calculating the NPVs, the value of discounted rate used was 10%, which is the industry benchmark rate-of-return (Ross et al., 2000). Discounted cash flows (DCF) were calculated by using equation (4.9) and NPV was calculated by using equation (4.10).

Table 4.17: Values of discounted cash flow and the net present value

Year	$UMTS_{900}$		$UMTS_{2100}$	
	DCF	**NPV**	**DCF**	**NPV**
0 (investment costs	-2,306,490,300	-2,306,490,300	-4,311,120,300	-4,311,120,300
1	1,433,808,421	-872,681,879	1,008,583,875	-3302536425
2	1,303,462,200	430,780,321	916,894,432	-2385641993
3	1,184,965,637	1,615,745,958	833,540,393	-1552101600
4	1,077,241,488	2,692,987,446	757,763,994	-794337606
5	979,310,444	3,672,297,890	688,876,358	-105,461,248
6			626,251,234	520,789,986

From the definition of payback period, which is a number of years to wait until the accumulated discounted cash flows from the investment equal or exceed the cost of investment (i.e when the NPV turns from negative to positive value), then the payback period for $UMTS_{900}$ is two (2) years, which implies that an annual cash return of 50%. For 5 years of investment, the NPV value of $UMTS_{900}$ connectivity model is positive, which means that the investment will be profitable; hence, this investment is a feasible one.

For the case of $UMTS_{2100}$, the payback period is six (6) years, implying that the annual cash return for this investment is less than 20%. Its NPV is still negative up to five years, which is the estimated economic lifetime of the investment. The payback period and NPV criteria suggest that $UMTS_{2100}$ investment is not a feasible option to cover the whole country.

4.3.4.2 Calculations of IRR

Common methods to calculate IRR are by using financial calculators, Microsoft excel software or by a manual trial and error calculations. The Microsoft excel software was used to calculate the IRR values in this thesis. Tables 4.18 and 4.19, show 57% and 1% values of IRR obtained for $UMTS_{900}$ and $UMTS_{2100}$, respectively. The calculated value of IRR for $UMTS_{900}$ is higher than the industrial benchmark of 10%, therefore, $UMTS_{900}$ has an acceptable value of IRR. The higher value of IRR implies that return of investment will be recouped much faster. On the other hand, the value of IRR for $UMTS_{2100}$ is 1%, which is much lower than the industrial benchmark. Based on IRR rule, the $UMTS_{2100}$ investment is suppose to be rejected.

Table 4.18: IRR for $UMTS_{900}$

Year	**Cash Flow**
0	-2,306,490,300
1	1,577,189,263
2	1,577,189,263
3	1,577,189,263
4	1,577,189,263
5	1,577,189,263
IRR =	**57%**

Table 4.19: IRR for $UMTS_{2100}$

Year	Cash Flow
0	-4,311,120,300
1	1,109,442,263
2	1,109,442,263
3	1,109,442,263
4	1,109,442,263
5	1,109,442,263
IRR =	**1%**

4.3.4.3 Sensitivity Analysis

Sensitivity analysis is a way to predict the outcome of a decision if a situation turns out to be different compared to the key prediction(s). It is the investigation of what will happen to the key decision criteria, when one of the variables is changed. Sensitivity analysis is useful in pinpointing variables that deserve the most attention. It points out where forecasting errors will do most damage, but it is worth to note that it does not tell what to do with the errors (Ross et al., 2000).

The IRR is sensitive to (affected by) changes in capital and operational costs. However, IRR is least sensitive to changes in the economic lifetime of the investment. On the other hand, NPV is sensitive to economic lifetime of an investment, the discount rate as well as to changes in capital and operational costs. Variables that are likely to change and they affect both IRR and NPV economic criteria, are capital and operational costs. In this case, sensitivity analysis investigates separately the impact due to changes in the capital costs and operational costs of the feasible connectivity model, the UMTS900.

For an increase of 25% CAPEX, new values for $UMTS_{900}$ are given in table 4.20, table 4.21 and table 4.22 show new values for NPV and IRR respectively.

Table 4.20: New values for a 25% increase in CAPEX

$UMTS_{900}$					
Revenue	**CAPEX**	**OPEX**	**Depreciation**	**Tax**	**Net Cash Inflow**
3,021,947,568	2,883,112,875	384,415,050	384,405,000	675,938,255	1,577,189,263

Table 4.21: New NPV

Year	$UMTS_{900}$	
	DCF	**NPV**
0 (investment costs)	-2,883,112,875	-2,883,112,875
1	1,433,808,421	-1,449,304,454
2	1,303,462,201	-145,842,253
3	1,184,965,637	1,039,123,384
4	1,077,241,488	2,116,364,872
5	979,310,444	3,095,675,316

Table 4.22: New IRR

Year	Cash Flow
0	-2,883,112,875
1	1,577,189,263
2	1,577,189,263
3	1,577,189,263
4	1,577,189,263
5	1,577,189,263
IRR =	**41%**

Results show a payback period of three (3) years, which means an annual cash return of about 33%, a positive NPV and an IRR of 41%. This connectivity model is still profitable even with 25% increase in capital expenditure. The only effect noted from the earlier prediction is a slight increase in the payback period of three years instead of the earlier two years.

For a decrease of 25% CAPEX, new values for UMTS900 are given in table 4.23, table 4.24.and table 4.25 show new values for NPV and IRR respectively.

Table 4.23: New values for a 25% decrease in CAPEX

$UMTS_{900}$					
Revenue	**CAPEX**	**OPEX**	**Depreciation**	**Tax**	**Net Cash Inflow**
3,021,947,568	1,729,867,725	384,415,050	384,405,000	687470707	1,604,098,316

Table 4.24: New NPV

Year	$UMTS_{900}$	
	DCF	NPV
0 (investment costs)	-1,729,867,725	-1,729,867,725
1	1,433,808,421	-296,059,304
2	1,303,462,201	1,007,402,897
3	1,184,965,637	2,192,368,534
4	1,077,241,488	3,269,610,022
5	979,310,444	4,248,920,466

Table 4.25: New IRR

Year	Cash Flow
0	-1,729,867,725
1	1,577,189,263
2	1,577,189,263
3	1,577,189,263
4	1,577,189,263
5	1,577,189,263
IRR =	**83%**

With 25% decrease in capital expenditure, the payback period is still two (2) years, implying a 50% annual cash return. The new NPV is positive and new IRR is 83%. New values still suggest an acceptable investment. For an increase of 25% OPEX, new values for UMTS900 are given in table 4.26, table 4.27 and table 4.28 show new values for NPV and IRR respectively.

Table 4.26: New values for a 25% increase in OPEX

$UMTS_{900}$					
Revenue	CAPEX	OPEX	Deprecia-tion	Tax	Net Cash Inflow
3,021,947,568	2,306,490,300	480,518,813	384,405,000	647107127	1,509,916,628

Table 4.27: New NPV

Year	$UMTS_{900}$	
	DCF	**NPV**
0 (investment costs)	-2,306,490,300	-2,306,490,300
1	1,372,651,480	-933,838,820
2	1,247,864,982	314,026,162
3	1,134,422,711	1,448,448,873
4	1,031,293,373	2,479,742,246
5	937,539,430	3,417,281,676

Table 4.28: New IRR

Year	Cash Flow
0	-2,306,490,300
1	1,509,916,628
2	1,509,916,628
3	1,509,916,628
4	1,509,916,628
5	1,509,916,628
IRR =	**54%**

Increasing 25% of operational expenditures, results into an IRR of 54%, a positive NPV and a payback period of two (2) years, which shows that this investment is still profitable.

For a decrease of 25% OPEX, new values for $UMTS_{900}$ are given in table 4.29, table 4.30 and table 4.31 show new values for NPV and IRR respectively.

Table 4.29: New values for a 25% decrease in OPEX

$UMTS_{900}$					
Revenue	**CAPEX**	**OPEX**	**Depreciation**	**Tax**	**Net Cash Inflow**
3,021,947,568	2,306,490,300	288,311,288	384,405,000	704,769,384	1,644,461,896

Table 4.30: New NPV

Year	$UMTS_{900}$	
	DCF	**NPV**
0 (investment costs)	-2,306,490,300	-2,306,490,300
1	1,494,965,360	-811,524,940
2	1,359,059,418	547,534,478
3	1,235,508,562	1,783,043,040
4	1,123,189,602	2,906,232,642
5	1,021,081,456	3,927,314,098

Table 4.31: New IRR

Year	Cash Flow
0	-2,306,490,300
1	1,644,461,896
2	1,644,461,896
3	1,644,461,896
4	1,644,461,896
5	1,644,461,896
IRR =	**61%**

Decreasing 25% of operational expenditures, results into an IRR of 61%, a positive NPV and a payback period of two (2) years, which implies that this investment is still profitable.

Table 4.32: Summarized sensitivity analysis results for UMTS900

Scenario	Parameter changes	New values	New IRR	New NPV
	No parameter changes	New Value	57% (Original IRR)	3,672,297,890 (Original NPV)
1.	25% increase in CAPEX	2,883,112,875	41%	3,095,675,316
2.	25% decrease in CAPEX	1,729,867,725	83%	4,248,920,466
3.	25% increase in OPEX	480,518,813	54%	3,417,281,676
4.	25% decrease in OPEX	288,311,288	61%	3,927,314,098

Results of the sensitivity analysis summarized in Table 4.32, shows that, neither increase nor decrease of 25% for CAPEX and OPEX costs had an effect to the UMTS900 investment. All the new IRRs lie well above the industrial benchmark and the NPVs are positive. The payback periods are two (2) to three (3) years, while the economic lifetime of the investment is estimated to be five (5) years. Therefore, in this case, the sensitivity analysis suggests that investment in UMTS900 is out of risk even with 25% forecast errors in capital or operational costs.

4.3.5 Concluding Discussion

This section provided a comparison between two connectivity models; UMTS900 and UMTS2100. Implementations of the two technologies have different requirements in terms of capital investments and operational costs. The comparison was done by using techno-economic analysis criteria to identify the economic feasibility of the two connectivity models.

The cost analysis results show that capital and operational costs of connectivity model with UMTS900 is cheaper than its counterpart, connectivity model with UMTS2100. Cost reduction on UMTS900 is due to its implementation strategy of re-using existing GSM network infrastructure. Re-using the existing infrastructure cuts down costs of civil work, site rental, administration and maintenances, which will otherwise be required, if one has to build a completely new site to host UMTS900. Another aspect that brings about cost efficiency on UMTS900, is its wider coverage compared to the coverage achieved by UMTS2100. The UMTS900 operates at lower frequency, 900MHz, hence results into a longer cell radius compared to the cell radius of a high frequency technology, the 2100MHz. This means, that the number of sites for UMTS900 needed are fewer than the number of sites for UMTS2100 to cover the same geographical area. Fewer sites imply cost efficiency in the capital expenditure and the opposite is true with more sites for UMTS2100.

Results from the economic criteria show that; investment in UMTS900 has a positive NPV and an IRR of 57%. It is in the acceptable range, that is above the industrial benchmark. It's payback periods is 2 years implying an annual cash returns of 50%. Furthermore, sensitivity analysis revealed that the investment is still stable within forecast errors of 25% on capital and operational costs. On the other hand, UMTS2100 investment showed negative NPVs within the estimated five years investment economic lifetime. Its payback period is six years, which means that, this investment had an annual cash return of less than 20%. The value of internal rate of return, IRR for UMTS2100 is 1%, which is far below the industrial benchmark. The result suggests that going for this investment will lead to a loss.

Basing on the techno-economic analysis, results revealed that the UMTS900 is a feasible investment, while UMTS2100 will be a loss-based investment. Furthermore, the connectivity model implemented by UMTS900 is free of risk even at 25% forecast errors. Therefore, this thesis concludes that connectivity model built from re-using existing GSM infrastructure to implement 3G network at 900MHz technology is a cost effective connectivity solution to provide broadband access network to the underserved community of rural areas of Tanzania.

CHAPTER FIVE
PERFORMANCE EVALUATION OF UMTS NETWORK FOR e-LEARNING APPLICATIONS

5.1 Introduction

This chapter presents performance evaluation of UMTS network in delivering e-learning applications. It explains development of a simulation model of the UMTS network. The developed model is used to evaluate quality of the delivered of e-learning applications. The general goal of performance evaluation is to understand the key performance parameters for the UMTS network configuration in order to deliver e-learning application with the required quality of service. Performance parameters are defined in terms of Quality of Service (QoS) metrics in a network. The QoS metrics can be categorized into two groups: network related QoS metrics and applications or user relevant QoS metrics.

The most common network related QoS metrics are packet end-to-end delay, delay variation (jitter), packet loss ratio, and link utilization. The end-to-end delay refers to the delay of transmitting a packet through a network domain. It contains delay components from packet processing, segmentation and reassembling, transmission, propagation, and queuing delays. Packet loss ratio is defined as the ratio of discarded packets to the total amount of transported packets. Packet loss ratio is supposed to be controlled to be reasonably low in order to avoid retransmission, which on the other hand will lead to end user application performance degradation. Link utilization is an appropriate link-specific QoS metric. It is expressed as a percentage of the achieved throughput over the link to the given link bandwidth. Applications or user oriented QoS is the quality of service relevant to the user with regard to the application performance. The QoS perceived by the user is sometimes referred to as Quality of Experience (QoE). From users´ perspective; typical relevant metric for applications QoS is the application response time. The factors that contribute to application response time include:

i. Delays due to contention on servers (server processing time)

ii. Delays due to contention on the client (client processing time)

iii. Delays due to contention with "other" traffic at the various intermediate devices (queuing delays)

iv. Delays due to contention with traffic of the same application from other users at the intermediate devices (queuing delays)

v. Network delays (transmission and propagation)

vi. Delays due to protocol effects (TCP retransmissions, windowing etc.)

The application performance evaluation in this chapter takes into consideration metrics from both the network relevant QoS and applications relevant QoS metrics. The metrics considered are those that can influence/impact users perceived QoS.

5.2 Definition of e-Learning Applications

e-Learning is basically teaching and learning that is facilitated and supported via Information and Communications Technology (ICT). It is simply a medium for delivering learning materials and it covers a wide array of activities from supported learning, to blended or hybrid learning (the combination of traditional and e-learning practices), to learning that occurs 100% online. However, there are number of other terms used to describe this mode of teaching and learning; they include online learning, virtual learning, distributed learning, networked learning and web-based learning. Fundamentally, they all refer to educational processes that utilize information and communication technologies to facilitate asynchronous as well as synchronous learning and teaching activities. As the definition of the term e-learning varies widely and so is its applications. There is a wide variety of applications that are used to facilitate delivery of e-Learning services. They includes static or dynamic web pages with text, diagrams or pictures, auto-corrected quizzes for self assessment, distance lecturing, video clips, narrated slide shows, instant messaging and video conferencing.

In this work, e-learning applications are categorized into two major groups, namely light-media applications and rich-media applications. The categorization is based on the nature of an application, and its requirements for network capacity. Light-media are the less bandwidth-greedy applications such as static or dynamic web pages with text, diagrams and pictures or images, narrated slide shows such as power point presentation with embedded audio explanations, autocorrected quizzes for self assessment and online chatting (instant messaging). The rich-media applications encompass distance lecturing which consists of audio and multimedia contents, streaming video clips, and video conferencing.

5.3 Application Performance Parameters and their Acceptable Range of Metrics (Values)

There are two standardization bodies, the International Telecommunication Union - Telecommunication Standardization (ITU-T) and the Third Generation Partnership Project (3GPP) that have defined parameters and their respective values to quantify performance of applications delivered through networks. The ITU-T sector is responsible for the creation of telecommunications standards, which are published as ITU-T recommendations. Recommendations are developed by technical groups known as study groups, each of which is responsible for a specific technical area. For example the ITU-T Study Group 12, abbreviated as ITU T SG 12, is the lead study group to work on performance and Quality of Service (QoS). The 3GPP and ITU-T Recommendation G.1010 provided a summary indication of suitable performance targets for data application as shown in table 5.1, 5.2, and 5.3.

Table 5.1: Performance Targets for Conversational/Real-Time Services (3GPP-TS-23.107, 2009; ITU-T Rec-G.1010, 2001).

Medium	**Application**	**Degree of Symmetry**	**Typical Data rates /Amount of data**	**Key performance parameters and target values**		
				End-to-end one way delay	Delay variation within a cell	Information loss
Audio	Conversation voice	Two-way	4 - 64 kbps	<150 msec preferred <400 msec limit	<1 msec	< 3% packet loss
Video	Videophone	Two-way	16 - 384 kbps	<150 msec preferred <400 msec limit		< 1 % packet loss
Data	Telemetry (Two-way control)	Two-way	< 28.8 kbps	<250msec	NA	Zero
Data	Interactive games	Two-way	< 1KB	<250msec	NA	Zero
Data	Telnet	Two-way (Asymmetry)	< 1KB	<250msec	NA	Zero

Table 5.2: Performance Targets for Interactive Services (3GPP-TS-23.107, 2009; ITU-T Rec-G.1010, 2001).

Medium	**Application**	**Degree of Symmetry**	**Typical Data rates /Amount of data**	**Key performance parameters and target values**		
				One way delay (Response Time)	Delay variation within a cell	Information loss
Audio	Voice messaging	Primarily one-way	4 - 32kbps	<1 sec for playbacks <2 sec for records	<1 msec	< 3% packet loss
Data	Web Browsing	Primarily one-way	~ 10 KB	< 4 sec/page	NA	Zero
Data	Transaction services - high priority (e.g e-commerce. ATM)	Two-way	< 10 KB	< 4 sec	NA	Zero
Data	E-mail (server access)	Primarily one-way	< 10 KB	< 4 sec	NA	Zero

Table 5.3: Performance Targets for Streaming Services(3GPP-TS-23.107, 2009; ITU-T Rec-G.1010, 2001).

Medium	**Application**	**Degree of Symmetry**	**Typical Data rates / Amount of data**	**Key performance parameters and target values**		
				Start up delay	Transport delay variation	Packet loss at session layer
Audio	Speech, mixed speech and music Medium to high quality music	Primarily one-way	5 - 128bps	< 10 sec	<1 msec	< 1% packet loss ratio
Data	Movie clips, surveillance, real time video	Primarily one-way	16 - 384 kbps	< 10 sec	<1 msec	< 1% packet loss ratio

Data	Bulk data transfer/retrieval Layout and synchronization information	Primarily one-way	10 KB - 10 MB	< 10 sec	NA	Zero
Data	Still image	Primarily one-way	< 100 kB	< 10 sec	NA	Zero

5.4 UMTS Network Modeling and Simulation

In order to evaluate e-learning application performance over UMTS network, the following simulation modeling steps were done:

i. Develop a simulation model of UMTS network by using OPNET modeling environment.

ii. Configure source traffic models to represent e-learning applications.

iii. Define the Service Level Agreements (SLAs) that the e-learning applications performance are suppose to comply with.

iv. Run a simulation with one user accessing e-learning applications, record results obtained for end-to-end delay, cell downlink throughput, application page response time and link utilization. This simulation is done for verifying if the model is correctly developed.

v. Increase number of users in the model as long as the SLAs still holds. Identify maximum number of users that can be served by a single cell with the required QoS (i.e. SLAs are not violated). This is done to validate the model, in order to know if it behaves as the real world network it represents.

vi. Configure the light-media and heavy-media e-learning applications and run simulation to establish the application´s performance baseline (best case) data in terms of page response time.

vii. Configure the contending traffic in the model. Run simulations to establish the real world scenario application performance data.

viii. Study the impact of traffic differentiation: configure priority scheduling, run simulation to study impact of traffic differentiation in providing different applications' QoS requirements.

ix. Perform confidence analysis calculations to get confidence intervals in order to establish credibility of simulation results.

The simulation modeling for application performance evaluation steps are summarized in the workflow figure 5.1.

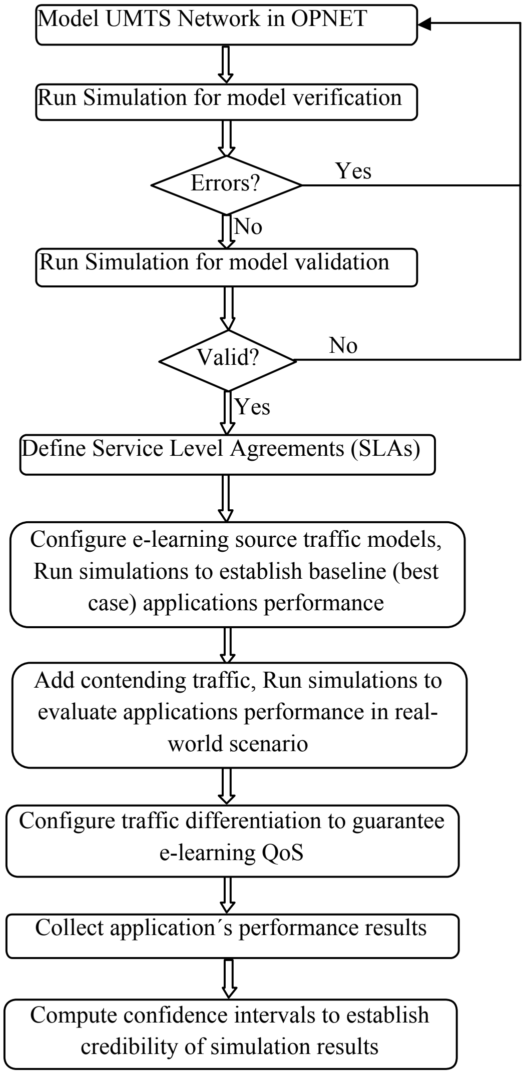


Figure 5.1: Performance Evaluation Simulation Modeling Workflow

5.4.1 Defining Parameters and Values for Service Level Agreement (SLA)

Service level agreements are the defined thresholds of acceptable application performance. These agreements are made between a customer and a service provider. The SLAs are usually used to gauge performance status of an application. Table 5.4 show parameters and values defined for SLAs of e-learning applications used during simulations. The defined SLA are inline with the accepted performance parameters and values of web based application.

Table 5.4: Parameters and values defined for Service Level Agreements (SLAs).

Application	Application response time (sec)	End-to-end delay (sec)	Packet loss (%)	Link utilization (%)
Web browsing	2 preferred - 4 limit (2-< 4)	1- < 4	0	< 100
Online-Learning	2 - < 4	1- < 4	0	< 100
Test & Quiz	2 - < 4	1- < 4	0	< 100

5.4.2 Defining Parameter and Values for Applications' Source Traffic Models

Source traffic models are the representation of an application behavior in a network. They are designed to generate an input load for evaluation, either analytically or by simulation (Svoboda, 2008). In addition to performance evaluation; source traffic models are also useful in the process of network planning (Staehle et al., 2001). The light-media and rich-media e-learning applications defined earlier are both web based applications. Therefore, it is necessary to define the source traffic model, which will represent characteristics of web based traffic. The term web traffic comprises all HTTP traffic generated during a session with a typical web browser in a particular web based application.

Choi & Limb, (1999) derived a model for web traffic, which represents activities of a user surfing the web as shown in figure 5.2. The model of a web user is based on an ON/OFF type process, where the ON state represents the activity after accepting a web request and the OFF state represents a silence period after all objects in a web request are retrieved. The duration of ON state and OFF state correspond to the page loading time and viewing time, respectively. The web user can thus be in the following states:

i. Web request: represent arrival process of web page request.

ii. Loading and viewing (HTTP ON): This is the time for fetching all objects belonging to one web request. The user is waiting for objects to be loaded; he can start viewing the already arrived objects while waiting the others. Alternatively, the user can interrupt the loading process (e.g. by clicking on appearing links) and thus start another web request.

iii. Viewing (HTTP OFF): Viewing time is the inactive interval between two web requests. A new web request is considered to be immediately generated after expiration of the viewing period.

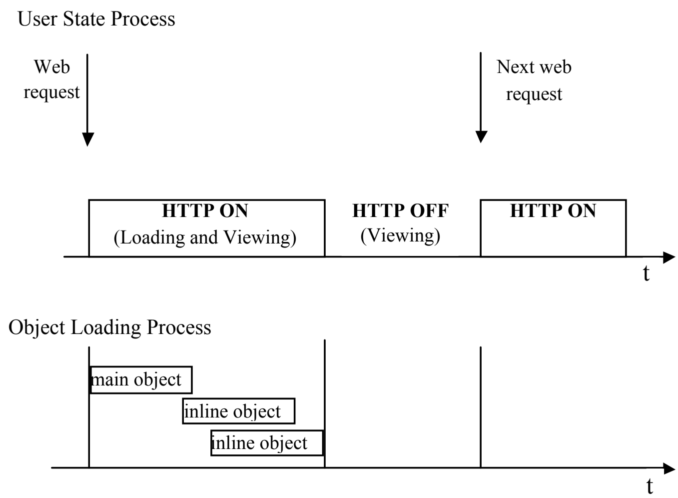


Figure 5.2. Web Traffic Behavioral Model (Choi & Limb, 1999)

Parameters and their respective values for the web (http) traffic derived by Choi & Limb, (1999) are given in table 5.5.

Table 5.5: Parameters and their respective values for web (http) traffic by Choi & Limb, (1999)

Web based Source Traffic Model			
HTTP ON			**HTTP OFF**
Main object size	**Inline object size**	**Number of inline objects**	**Viewing (Inter-request time)**
Lognormal Mean = 10kB Median = 6kB Stddev = 25kB	Lognormal Mean = 7.7kB Median = 2kB Stddev = 126kB	Gamma Mean = 5.5 Median = 2 Stddev = 11.4	Weibull Mean = 39.5s Median = 11s Stddev = 92.6s

The OPNET modeler has built-in standard source traffic models representing different applications such as FTP, email, http, remote login, database, print, voice and video conference. Parameters used to characterize the built-in http model in OPNET are inline with those of the http model developed by Choi & Limb, (1999). Therefore, in this work, the standard built-in http model in OPNET was used to generate http traffic into the network model for simulation. The selected http model for Online-Learning and Quiz & Tests types of e-learning applications is heavy browsing and light browsing respectively. The configured parameters and values for the Online-Learning and Quiz & Tests http traffic models are shown in table 5.6.

Table 5.6: Parameter and Values Specified for HTTP Traffic Model

Attribute	Value	
Online_Learning (Heavy Browsing)		
HTTP Specification	HTTP 1.1	
Page Inter-arrival Time	Exponential (60)	
Page Properties	***Objects Size***	***Objects per Page***
	Constant (1000)	Constant (1)
	Medium image	Constant (5)
Server Selection	***Initial Repeat Probability***	***Page per Server***
	Browse	Exponential (10)
RSVP Parameter	None	
Type of Service	Interactive multimedia	
Quiz & Tests (Light Browsing)		
HTTP Specification	HTTP 1.1	
Page Inter-arrival Time	Exponential (720)	
Page Properties	***Objects Size***	***Objects per Page***
	Constant (500)	Constant (1)
	Small image	Constant (5)
Server Selection	***Initial Repeat Probability***	***Page per Server***
	Browse	Exponential (10)
RSVP Parameter	None	
Type of Service	Interactive multimedia	

For Online-Learning, the page inter-arrival times are exponentially distributed with mean 60 seconds. Each page has 1000 bytes of text and 5 “medium images” each randomly picked with a uniform distribution. For Quiz & Tests, page inter-arrival times are exponentially distributed with mean 720 seconds. Each page has 500 bytes of text and 5 “small images” each randomly picked with a uniform distribution.

5.4.3 UMTS Network Modeling

The UMTS network model was developed by using the OPNET’s UMTS specialized model in the OPNET modeler 16.0. The modeler is a discrete event simulator, which provides environment to support modeling of communication systems. The simulated system level UMTS model is as shown in figure 5.3. It represents multiple users (UEs) accessing web based e-learning applications from an application server, abbreviated as TanSSeL server via the UMTS network.

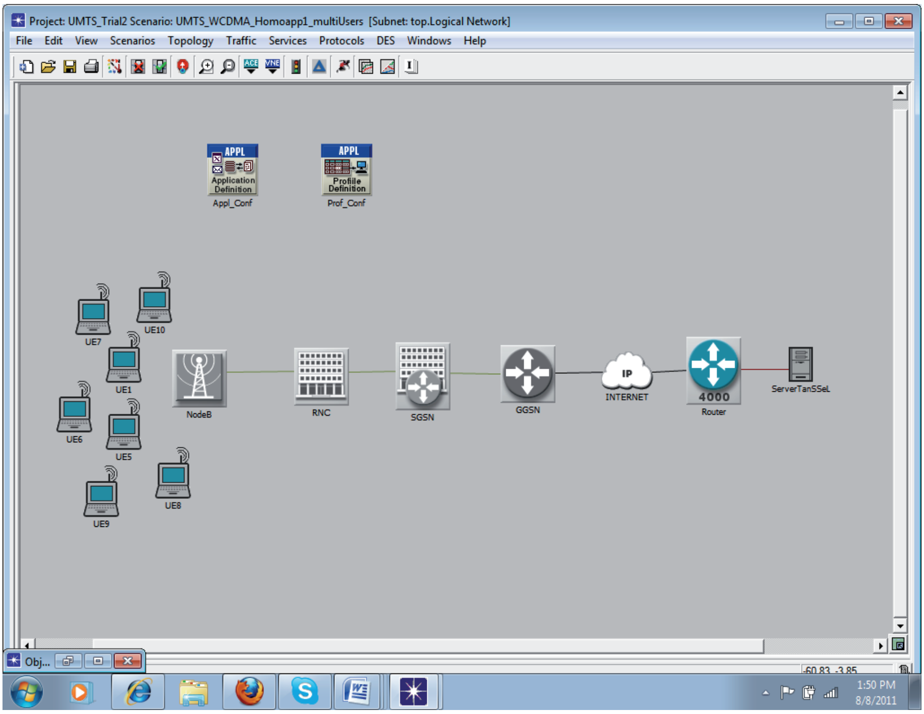


Figure 5.3: The simulated model of UMTS network

5.4.4 Simulation Scenarios

Simulations for e-learning application performance were performed in different scenarios. The scenarios were configured according to the workflow presented in figure 5.1. Scenario 1 was meant to verify if the developed model operated as it was intended to. Model verification is the process of determining, if the simulated model is correctly implemented as well as if it functions correctly. This was accomplished by running the scenario 1 simulation in the OPNET´s simulation debugger mode. Statistics were collected to check, if there were no errors, which means that the model was correctly implemented and functioning properly.

Scenario 2 was for model validation. This is to investigate, if the simulated model behaves as the real system it represents. Model validation is the process of determining if a simulation model correctly represents the real system. A simulation model can be validated by being examined by experts (expert intuition), by comparing simulation results with measurements results from a real system, or by comparing simulation results with theoretical results. Among the three methods, comparing simulation outputs and measurements from a real system is the most reliable way of validating a simulation model and it was the primary validation method used in this work. Real network measurement results were taken from the work of Holma & Toskala, (2004), who conducted capacity measurement field trial from a single cell of UMTS network configured to offer 384kbps packet data rate in the downlink direction. In this thesis, the network model was as well simulated to represent a single cell configured to offer 64/384kbps data rate at uplink/downlink respectively.

Scenario 3 aimed to establish baseline (best case) data of e-learning application performance. This is a simulation of only e-learning applications in the network without any other traffic. The two e-learning applications were defined and their respective source traffic models were configured. The configured parameter values for the e-learning source traffic models are as shown in table 5.6 in section 5.4.2. Simulation scenario 4 presents impact of contending traffic to the e-learning traffic. This scenario represents a real world situation in which e-learning applications will be sharing the same network resources with other users as well. In this work, contending traffic was modeled as database application, which downloads updates for the database automatically in the background. Presence of background traffic affects performance of explicit (e-learning) traffic by inducing additional delays. The background traffic results in queue build-up at intermediate devices, hence causes delays based on the queue length at any given time. The final scenario 5 aimed to study the impact of configuring traffic differentiation and priority scheduling in a network in order to guarantee the required QoS for e-learning applications. e-Learning application traffic was assigned higher priority than contending traffic. From users´ perspective, page response time is the relevant metric for web-based applications QoS. Therefore, it was used as a key performance parameter.

Simulation results of page response time, which is the key performance metric for e-learning applications as perceived by users, were presented graphically followed by results´ confidence analysis, which shows average value of page response time for each user in a scenario, confidence intervals and correlation of values obtained from simulation results.

A confidence interval is a range around a measurement that conveys how precise the measurement/simulation result is. Confidence intervals can be presented based on different levels of significance, such as 90 percent, 95 percent or 99 percent. Level of significance is a statistical term for how willing an author of the measurement or simulation results is to be wrong, for example, with a 95 percent confidence interval, the author has a 5 percent chance of being wrong. To be more specific, this means the value to be estimated can be found outside the confidence interval at a chance of 5%.

Confidence interval tells about the possible range around the estimated value and how reliable the estimate is? A reliable estimate is one that would be close to the same value if the measurements or simulations were repeated while an unreliable estimate is one that would vary from one sample to another. Wider confidence intervals in relation to the estimate itself indicate large variation of the results, and consequently, a significant degree of uncertainty. On the other hand, narrow confidence intervals in relation to the estimate show that the estimated value is relatively stable. Confidence intervals are calculated based on the standard error of a measurement. The standard error is a calculation, which shows how well the sample point estimate can be used to approximate the true value. Generally, the larger the number of measurements made, the smaller the standard error and narrower the resulting confidence intervals. Once the standard error is calculated, the confidence interval is determined by multiplying the standard error by a constant that reflects the level of significance desired, based on the normal distribution. The rounded constants for 90%, 95% and 99% confidence intervals are 1.645, 1.96 and 2.576 respectively.

Confidence intervals for the estimated mean μ with 95% confidence level is calculated by using the formula below:

$$\bar{x} - 1.96 \frac{s}{\sqrt{n}} < \mu < \bar{x} + 1.96 \frac{s}{\sqrt{n}} \quad (5.1)$$

Where,

n = Sample size

s = Standard deviation

$\bar{x}$ = Estimated mean

μ = True mean

During the confidence analysis, correlation values were also calculated. Correlation means a measure of ties or similarity between values. Positive correlation means neighboring values tends to lie on the same side of the average value while negative correlation means neighboring values tends to lie on different sides of the average value. Ideally, the xi values used in estimating the average value should be independent. However, some few percentages of positive or negative correlations are in general acceptable and unavoidable. The reason for this flexibility is that, even though small correlation might exist, its effect on the confidence interval is negligible. Correlation calculations in this thesis were done by using formulas for lag 1-autocorrelation between neighboring values.

5.5 Simulation Results and Discussions

5.5.1 Scenario 1: Results for Model Verification

Simulation results were collected for end-to-end delay, cell downlink throughput, application page response time and link utilization as shown in figure 5.4 - figure 5.7. Results from the discrete event simulation log table show that the implemented UMTS model runs successful without errors as shown in figure 5.8. This is verification that the UMTS model is correctly implemented.

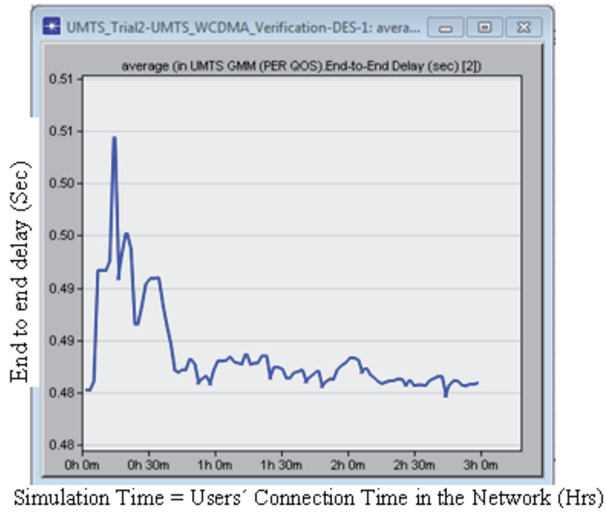


Figure 5.4: End to end delay

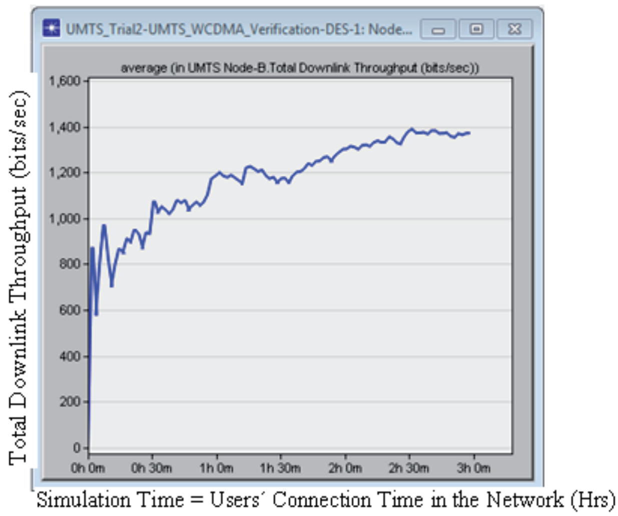


Figure 5.5: Total downlink Throughput

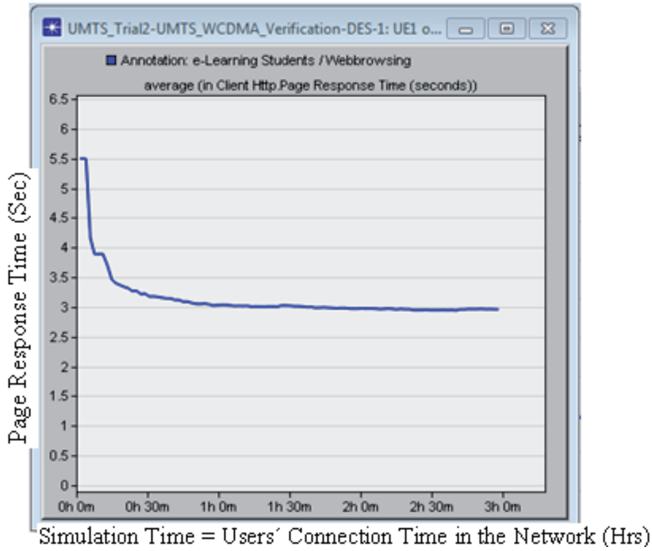


Figure 5.6: Page response time (Average)

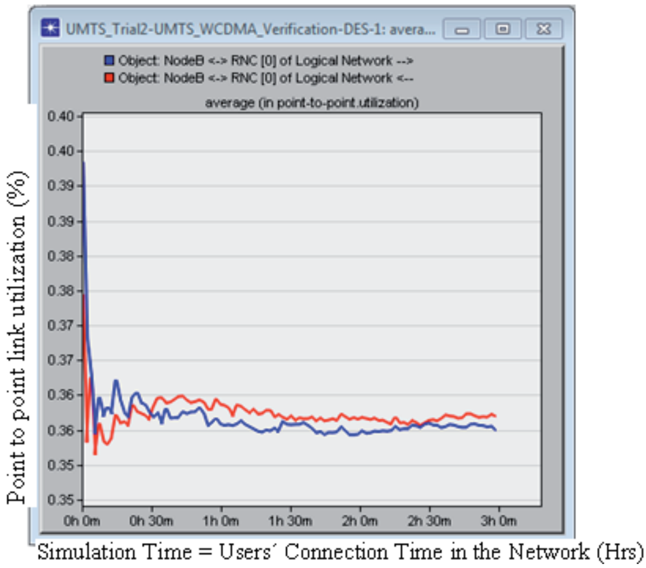
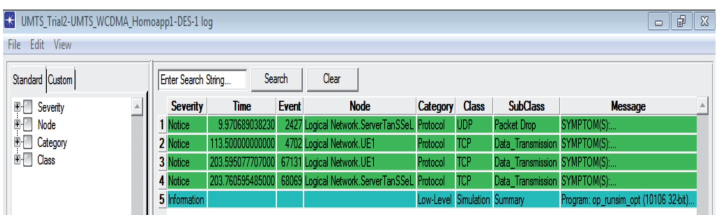


Figure 5.7: Link utilization



	Severity	Time	Event	Node	Category	Class	SubClass	Message
1	Notice	9.970689038230	2427	Logical Network.ServerTanSSeL	Protocol	UDP	Packet Drop	SYMPTOM(S):...
2	Notice	113.500000000000	4702	Logical Network.UE1	Protocol	TCP	Data_Transmission	SYMPTOM(S):...
3	Notice	203.595077707000	67131	Logical Network.UE1	Protocol	TCP	Data_Transmission	SYMPTOM(S):...
4	Notice	203.760595485000	68069	Logical Network.ServerTanSSeL	Protocol	TCP	Data_Transmission	SYMPTOM(S):...
5	Information				Low-Level	Simulation	Summary	Program: op_runsim_opt (10106 32-bit)...

Figure 5.8: Discrete event simulation log entries showing no errors

5.5.2 Scenario 2: Results for Model Validation

Results of measurements presented in Holma & Toskala, (2004) from the real world operational networks show that a single cell configured to offer 384kbps data rate in the downlink direction can only serve seven (7) simultaneous users. Therefore more than seven users shall experience much longer delays as the cell is already at its maximum power. The pole capacity is always limited by the maximum downlink power of the cell, as the data rate is asymmetrical.

The simulated network model was developed to represent a single cell of the UMTS network offering web based e-learning application. Users were added to the model one at a time up to the optimal number where value of the page response time was at maximum (4 seconds) according to the threshold set for acceptable performance of a web browsing application, which is also defined as one of the SLAs. Figure 5.9 and 5.10 show results of a page response time in actual values and as average respectively, for seven users in a cell, as a performance metric for users' perceived quality of service. Confidence analysis of the results is presented in table 5.7.

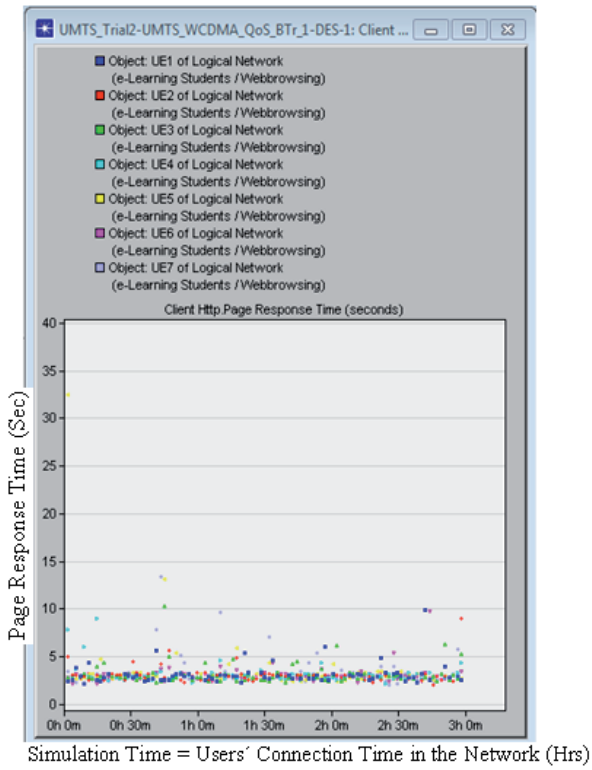


Figure 5.9: Web based e-learning application´s page response time for seven users (actual values)

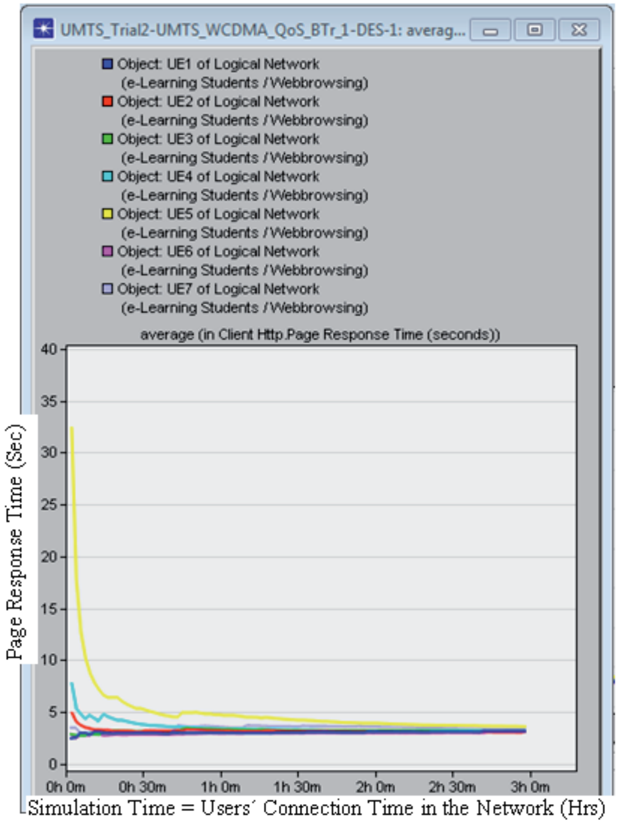


Figure 5.10: Web based e-learning application´s page response time for seven users (average)

Table 5.7: Confidence Analysis (Seven Users)

End user	EU1	EU2	EU3	EU4	EU5	EU6	EU7
Page response (s)	3.166478	3.126119	3.186807	3.13418	3.610767	3.105586	3.385106
Std Dev	1.063838	0.8836	1.102472	0.973502	3.586206	0.868672	1.672903
Confidence	0.208508	0.173182	0.216081	0.190803	0.702883	0.170256	0.327883
Upper bound (s)	3.374987	3.299301	3.402887	3.324983	4.31365	3.275843	3.712989
Lower bound (s)	2.95797	2.952936	2.970726	2.943377	2.907883	2.93533	3.057223
Correlation	-11.96%	0.21%	5.51%	-5.80%	4.42%	-1.83%	14.69%

These results show a 95% confidence that the average page response time of a web-based application for each end user EUi is between the lower bound Lbi and upper bound Ubi. Where i = 1,2,3,4,5,6,7. Confidence analysis shows a narrow confidence intervals in relation to the estimated (average) page response times, hence a reliable simulation results. There are small percentages of positive and negative correlations for most users, which imply negligible effects on the confidence intervals.

When the eighth user was added, page response time violated the required application performance target, hence breach SLAs as shown in figure 5.11 and figure 5.12. Confidence analysis of the results is presented in table 5.8. In other word, it explains that the cell was already at its maximum pole capacity, hence the delay that causes SLAs violations. Results are inline with field measurement done by Holma & Toskala, (2004).

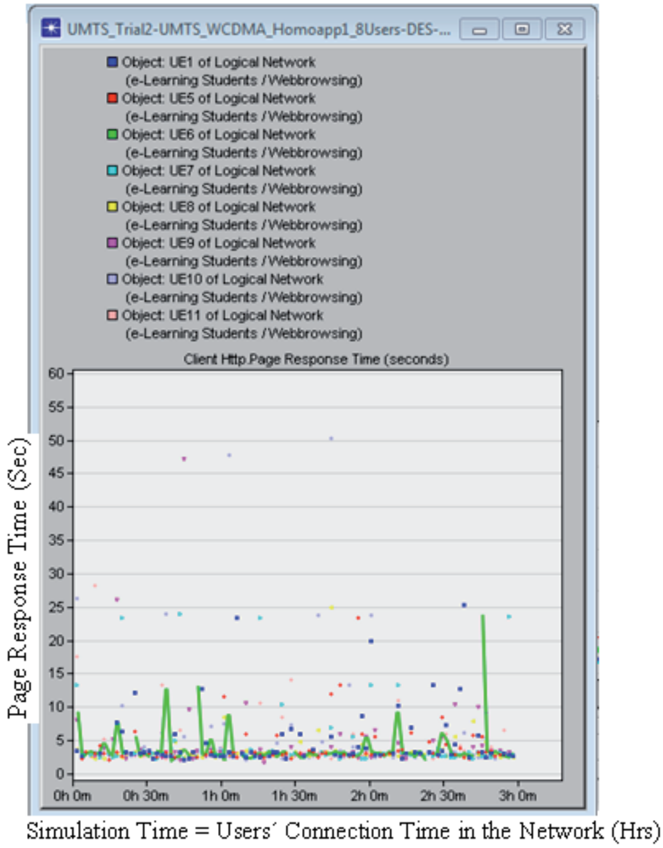


Figure 5.11: Web based e-learning application´s page response time for eight users (actual values)

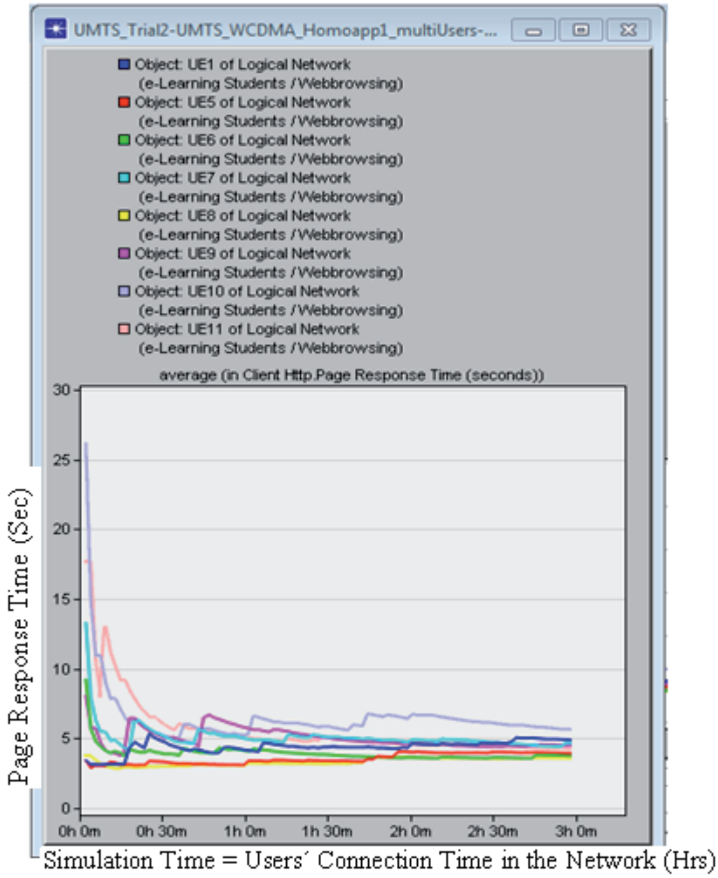


Figure 5.12: Web based e-learning application´s page response time for eight users (average)

Table 5.8: Confidence Analysis (Eight Users)

End User	EU1	EU2	EU3	EU4	EU5	EU6	EU7	EU8
Page response (s)	4.878831	3.932987	3.753295	4.662841	3.570481	4.498436	5.635363	4.280122
Std Dev	4.439659	2.907555	2.906645	5.032903	2.617444	5.568773	8.345968	3.874842
Confidence	0.870157	0.56987	0.569692	0.986431	0.51301	1.091459	1.63578	0.759455
Upper bound (s)	5.748988	4.502857	4.322987	5.649272	4.08349	5.589895	7.271142	5.039577
Lower bound (s)	4.008674	3.363117	3.183603	3.676411	3.057471	3.406976	3.999583	3.520667
Correlation	-0.04%	10.95%	-8.36%	-9.71%	-3.33%	4.92%	-3.26%	-3.71%

These results show a 95% confidence that the average page response time of web-based application for each end user EUi is between the lower bound Lbi and upper bound Ubi. Where i = 1,2,3,4,5,6,7,8. Majority of the average values are larger than 4 seconds and none of the upper bound confidence interval values keep the SLAs. These imply that eight users cannot be served within the agreed SLAs or the required web based applications performance targets.

Confidence analysis shows a narrow confidence intervals in relation to the estimated (average) page response times, hence a reliable simulation results. There are small percentages of positive and negative correlations, which imply negligible effects on the confidence intervals. Table 5.9 shows comparison between measurements and simulation results. The comparison displays that simulation results tally properly with measurement results, hence the model is a valid representation of the UMTS single cell network configured to offer 64/384kbps data rates in uplink/downlink respectively.

Table 5.9: Comparison of measurements and simulation results for model validation

	Measurements Results	**Simulation Results**
Configured data rate (UL/DL)	64/384 Kbps	64/384 Kbps
Maximum number of users served	7	7

5.5.3 Scenario 3: Baseline (Best Case) e-Learning Application Performance Results

The simulated model was configured to serve two e-learning applications in a best effort basis and there were no contending traffic introduced in the model. Results of e-learning page response time (actual and average values) in this scenario are shown in figure 5.13 and 5.14 respectively. Confidence analysis of the results is presented in table 5.10.

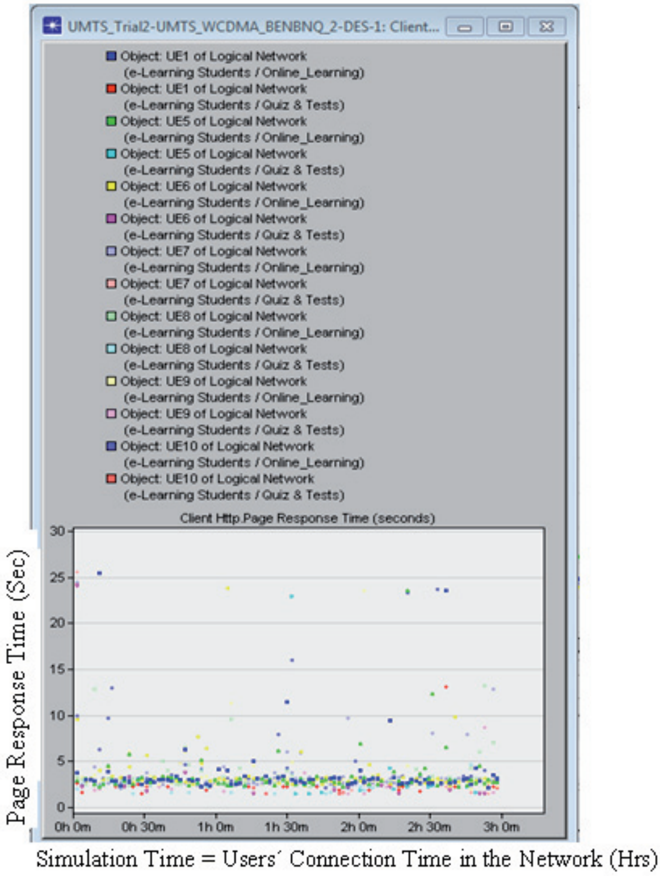


Figure 5.13: Page Response Time (actual values)

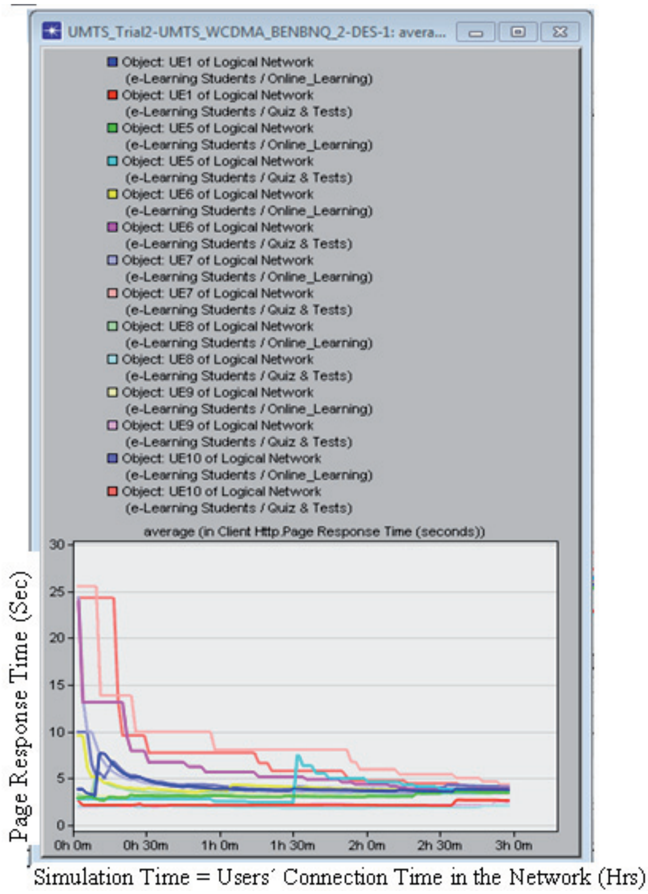


Figure 5.14: Page Response Time (Average)

Table 5.10: Confidence Analysis (Best case)

End user	EU1	EU1	EU2	EU2	EU3	EU3	EU4	EU4	EU5	EU5	EU6	EU6	EU7	EU7
Application	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2
Page response (s)	3.77	2.63	3.47	3.59	3.64	3.49	3.47	4.34	3.55	2.18	3.33	2.49	4.11	3.91
Std Dev	3.54	1.53	2.73	2.42	2.75	2.53	2.91	2.61	2.29	0.85	2.63	1.18	3.82	2.51
Confidence	0.69	0.30	0.53	0.47	0.54	0.50	0.57	0.51	0.45	0.17	0.52	0.23	0.75	0.49
Upper bound (s)	4.46	2.93	4.00	4.06	4.18	3.98	4.04	4.86	4.00	2.34	3.85	2.72	4.86	4.40
Lower bound (s)	3.07	2.33	2.93	3.12	3.11	2.99	2.90	3.83	3.10	2.01	2.82	2.25	3.36	3.42
Correlation (%)	-6.22	1.04	0.18	3.82	-9.67	20.07	-2.76	-5.32	4.78	8.34	0.71	-5.15	3.61	-1.72

These results show a 95% confidence that the average page response time of web-based e-learning applications: Online_learning (eApp1), Quiz & Tests (eApp2) without any other traffic in UMTS network configured in best effort basis for each end user EUi is between the lower bound Lbi and upper bound Ubi, where i = 1,2,3,4,5,6,7. The average of almost all users in both applications keep the SLAs except only 2. The confidence intervals are narrow in relation to the average values and the correlations are the small negative and positive percentages.

5.5.4 Scenario 4: Results with the Presence of Contending Traffic

Within a network cell vicinity (coverage) in the real world situation, e-learning applications will be sharing network resources with other applications such as the conventional telephone (voice) services, short messaging services (sms) and other web based data services. In order to represent this scenario, the simulated network model is configured to serve both e-learning and contending traffic (background traffic of automatic database updates) in a best effort basis. Page response time results (actual and averages) of the e-learning services in this scenario are shown in figure 5.15 and 5.16 respectively. Confidence analysis is shown in table 5.11.

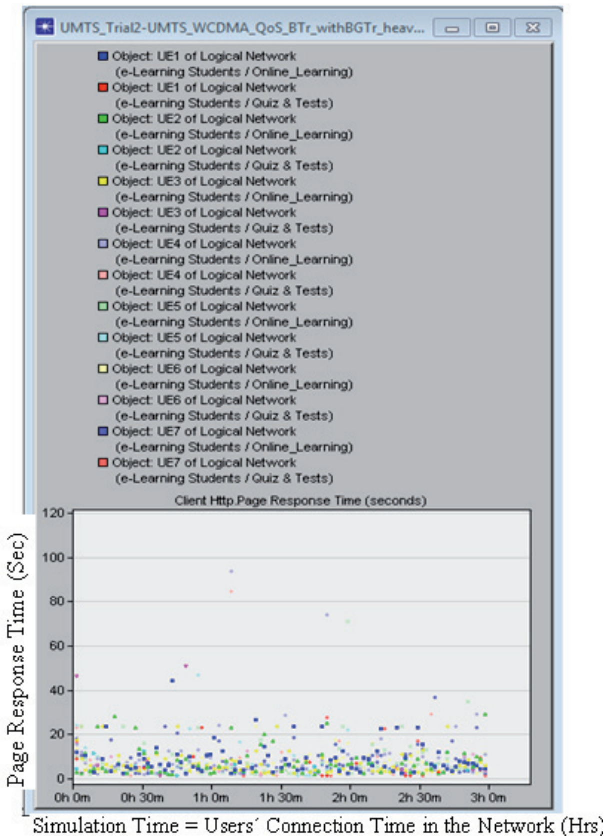


Figure 5.15: Page response time (Actual values)

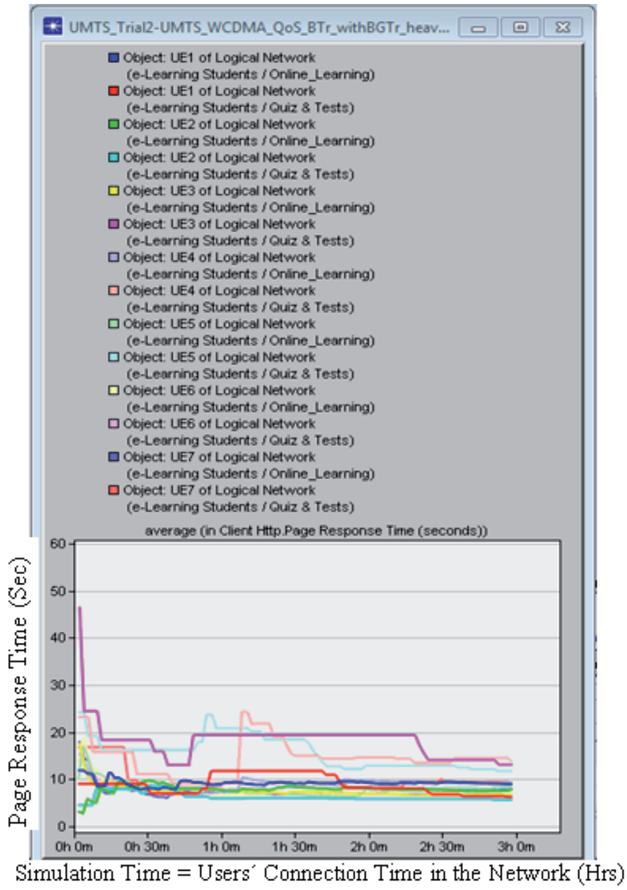


Figure 5.16: Page response time (Average)

This result shows an increase in the page response time from the best case (baseline) data. This increase in delay is a result of the presence of background traffic. Page response time is more than four seconds (4 seconds), which is out of acceptable performance target values.

Table 5.11: Confidence Analysis (e-learning applications with contending (background) application)

End user	EU1	EU1	EU2	EU2	EU3	EU3	EU4	EU4	EU5	EU5	EU6	EU6	EU7	EU7
Application	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2
Page response	8.91	6.23	7.85	5.65	6.70	13.12	9.31	13.80	8.23	11.72	6.99	6.53	7.41	8.99
Std Dev	7.21	2.90	6.50	2.11	5.00	6.99	12.35	9.54	9.18	6.60	4.69	2.87	6.23	4.63
Confidence	1.41	0.57	1.27	0.41	0.98	1.37	2.42	1.87	1.80	1.29	0.92	0.56	1.22	0.91
Upper bound	10.32	6.79	9.12	6.06	7.68	14.49	11.73	15.67	10.03	13.02	7.91	7.10	8.63	9.90
Lower bound	7.50	5.66	6.57	5.23	5.72	11.75	6.89	11.93	6.44	10.43	6.07	5.97	6.19	8.09
Correlation(%)	-8.06	-5.79	3.35	-8.55	-9.68	0.68	-1.13	-4.77	11.21	-9.29	7.49	9.36	-6.68	-1.90

These results show a 95% confidence that the average page response time of web-based e-learning applications: Online_learning (eApp1), Quiz & Tests (eApp2) with presence of background traffic due to automatic database updates in UMTS network configured in best effort basis for each end user EUi is between the lower bound Lbi and upper bound Ubi. Where i = 1,2,3,4,5,6,7. Both average values and upper bound confidence intervals are more than 4 seconds (outside the acceptable performance target). Confidence intervals are narrow with respect to the average values and there are small positive and negative percentages of correlation.

5.5.5 Scenario 5: Results with Traffic Differentiation

Page response time (actual and average) results of e-learning applications performance in a network configured with traffic differentiation as a mechanism to guarantee quality of service are presented in figure 5.17 and figure 5.18 respectively. Simulation results with traffic differentiation mechanism showed an improvement in the page response time. The results` confidence analysis is presented in table 5.12.

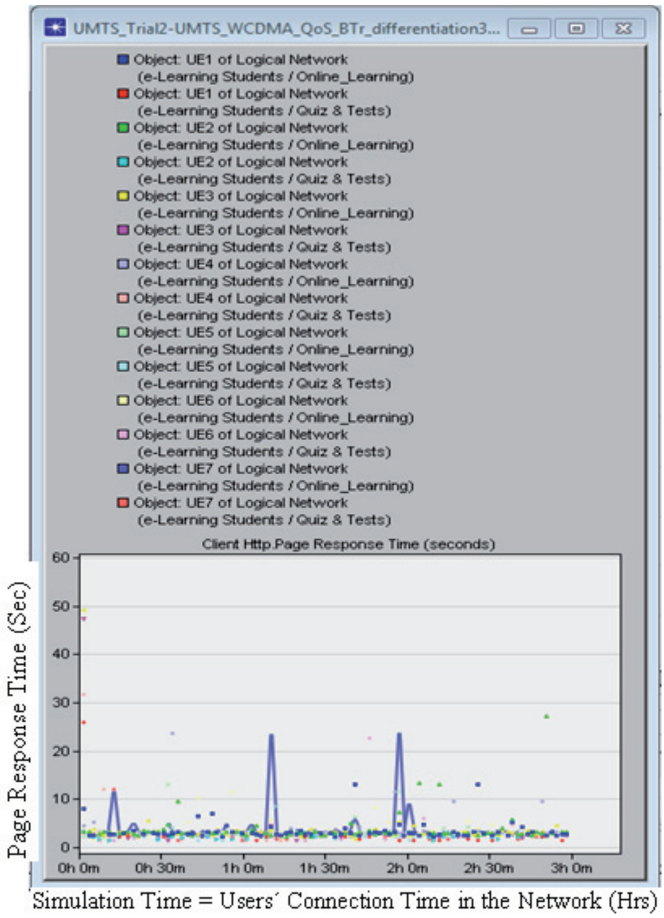


Figure 5.17: Page response time (Actual values)

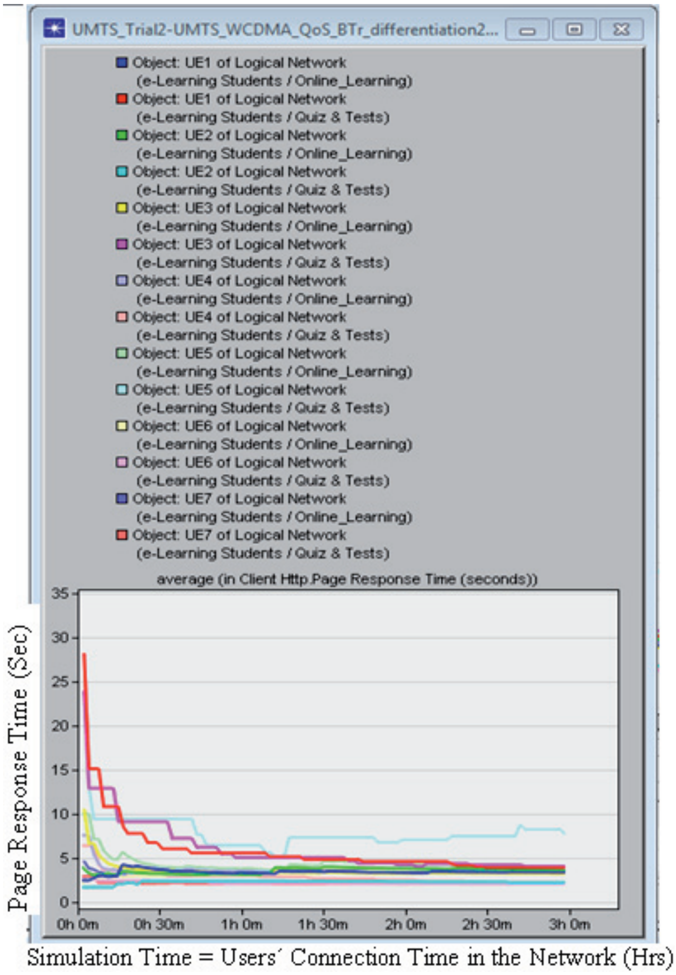


Figure 5.18: Page response time (Average)

Table 5.12: Confidence Analysis (UMTS network configured with traffic differentiation and priority scheduling)

End user	EU1	EU1	EU2	EU2	EU3	EU3	EU4	EU4	EU5	EU5	EU6	EU6	EU7	EU7
Application	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2	eApp1	eApp2
Page response (s)	3.38	3.91	3.55	2.23	3.24	4.06	3.36	2.25	4.00	7.79	3.46	2.08	3.58	2.10
Std Dev	2.20	2.92	2.88	0.81	1.68	2.63	1.93	0.95	3.68	4.21	2.62	0.78	2.14	0.77
Confidence	0.43	0.57	0.57	0.16	0.33	0.52	0.38	0.19	0.72	0.83	0.51	0.15	0.42	0.15
Upper bound	3.81	4.48	4.11	2.39	3.57	4.57	3.74	2.44	4.72	8.62	3.97	2.23	4.00	2.25
Lower bound	2.95	3.34	2.98	2.07	2.91	3.54	2.98	2.07	3.28	6.97	2.94	1.93	3.16	1.94
Correlation(%)	-11.90	21.88	2.45	-5.25	2.55	7.45	-16.18	2.69	-4.79	1.12	-9.34	-9.50	1.96	-16.66

These results show a 95% confidence that the average page response time of web-based e-learning applications: Online_learning (eApp1), Quiz & Tests (eApp2) with presence of background traffic due to automatic database updates in UMTS network configured with traffic differentiation and priority scheduling for each end user EUi is between the lower bound Lbi and upper bound Ubi. Where i = 1,2,3,4,5,6,7. Majority of the average values as well as upper bound keep the SLAs. There are narrow confidence intervals and majority of correlation values are small positive and negative percentages.

5.6 Concluding Remarks

This chapter presented simulation modeling of the UMTS network. The simulated model was used to evaluate performance of e-learning applications. Results showed that performance of e-learning applications delivered in network on best effort basis with presence of contending background traffic was out of the acceptable values. Introduction of traffic differentiation showed improvement in the applications performance. This result suggests that in order to deliver e-learning application with the required QoS, then mechanisms to guarantee QoS are to be configured in a network. The simulation model can further be used as a test-bed for conducting applications` performance evaluation studies.

CHAPTER SIX
MODEL FOR PROVISION OF SUSTAINABLE BROADBAND RURAL CONNECTIVITY

This chapter explains different models used to implement ICT projects in rural areas. Three projects are selected as case studies to understand the best practices in implementing sustainable projects. The chapter further examines the readiness of Tanzania to provide rural connectivity in terms of availability of ICT infrastructure and institutional frameworks (policies, legislations (Acts) and regulations) supporting rural connectivity in the country. With the existing ICT infrastructures, institutional frameworks and experience from selected best practice projects implementation, a sustainable broadband rural connectivity model adapting public private people's partnership (PPPP or 4Ps) implementation strategy is proposed.

6.1 Models for Implementing ICT Projects in Rural Areas

Rural areas are often characterized by highly spaced population consists of low-income communities, where individuals can rarely afford costs of ICT services. Therefore, shared access is the model commonly used to deliver ICT services in rural areas (Siochrú, 2005). Implementation of the shared access ICT facilities for rural areas differs widely ranging from donor funded projects, in which the project management remains under local community at the end of the donor funding time, franchise business model, Public-Private Partnership (PPP) and Public-Private People´s Partnership (PPPP). Brief descriptions of the mentioned models are given in the forthcoming paragraphs.

Donor funded project is a type of project where almost all resources for project implementation are provided by the donor. Most of the donor-funded projects are of the form of pilot projects. They often use a “top-down” implementation approach, which at the end of the donor funding time, local community may not have enough capacity or knowledge to manage and maintain the project. Therefore, their sustainability is always questionable. Hence, most of the donor funded projects are usually unsustainable after donor funding time. A franchise is a business system in which private entrepreneurs purchase the rights to open and run a similar or part of a big business. Nokia Siemens Network (NSN) village connection (NSN, 2008), n-logue´s rural connectivity model (Jhunjhunwala et al., 2004) and Grameens public payphone (Cohen, 2001) are examples of franchising models implementing ICT projects in rural areas. A characteristic of a franchising model is to push delivery and management of services closer to the end users. The NSN village connection is a solution that enables the GSM network operators to extend their network reach to accommodate remote villages, where traditional technology and commercial business model would not be profitable. The NSN village connection is implemented in partnership with local entrepreneurs, who are familiar with potential customers and who can run the local operations. In this model, the entire village customer acquisition and care are handled locally, reducing overall sales and marketing expenses to the operator (franchisor). The n-logue´s rural connectivity model employes a three-tier franchise model to implement village-level kiosk, that provides Internet and telephone access to local population. In this model, the n-Logue company is at the top level, responsible for overall management of the network. Local Service Providers (LSPs) are on the second tier, responsible for managing the project at the local level. In coordination with n-Logue, the LSPs invest in setting up an access center that provides last-mile access to subscribers in the project area. On the bottom tier are the local entrepreneurs that are recruited by the LSP to invest in setting up Internet kiosks in their villages. The kiosk owners purchase computer equipment through n-Logue, who also provides training, support and technical assistance (Paul, 2004 ; Jhunjhunwala et al., 2004). The locally owned franchises offer a variety of Internet and computer-based services to the rural market. Partners of this model further developed relevant local content and services using the local language aimed at making kiosks useful to the rural society. Another example of franchise model for rural ICT is the Grameen public payphone. The Grameen public payphone aimed to connect rural areas of Bangladesh through provision of public shared-access, where the entrepreneurs provide telephone services to local communities for fee. The project is implemented by a partnership of the GSM network operator and stationary phones in the villages owned and operated by local entrepreneurs (Cohen, 2001). Franchise model in implementing ICT projects is not widely deployed due to low level of ICT literacy and low income of the rural community. It is rarely to find an entrepreneur with both skills and financial capacity to operate ICT projects in rural areas. It is obvious that providing connectivity to rural areas is not financially viable to commercial operators. Therefore, government intervention is required for rural connectivity viability. This requirement scenario resulted into the Public-Private Partnership (PPP) model gaining popularity, especially in developing countries, where governments prioritized rural connectivity.

PPP means collaboration of public sector such as government joining forces with private sectors to implement projects. In this collaboration, Governments have been intervening by providing financial support in terms of subsidies, often from universal access funds initiatives. While PPPs have potentials to run investments in rural areas, it has been experienced that many developing countries do not have enough administrative and regulatory capacities to run PPP projects efficiently. Typical example is vandalization or poor maintenance of equipments especially those intended for ICT projects. This problem is also partly attributed to lack of beneficiary sense of ownership and inclusion (Spio-garbrah, 2010). This shortcoming was taken as an opportunity to consider involving beneficiaries of the project in the PPP model, which eventually lead to the public-private people's partnership (PPPP) model, sometimes abbreviated as 4Ps.

The PPPP model is based on the concept that for projects – especially in the rural areas – to be sustainable, the beneficiaries must feel a sense of ownership and inclusion (Spio-garbrah, 2010). In literature, PPPP is defined as a strategic cooperative relationship between public sector, private sector and community (people), who agree to share responsibility for achieving some specific goals (Siochrú & Girard, 2005; Spio-garbrah, 2010). The partnership emphasizes greater involvement of the communities that will eventually benefit from the outcome of the cooperative relationship. In a PPPP, the ownership of the activity under cooperation such as a project is shared. The heart of a PPPP is therefore sharing of risks and benefits. The schematic diagram of the 4Ps model is shown in figure 6.1.

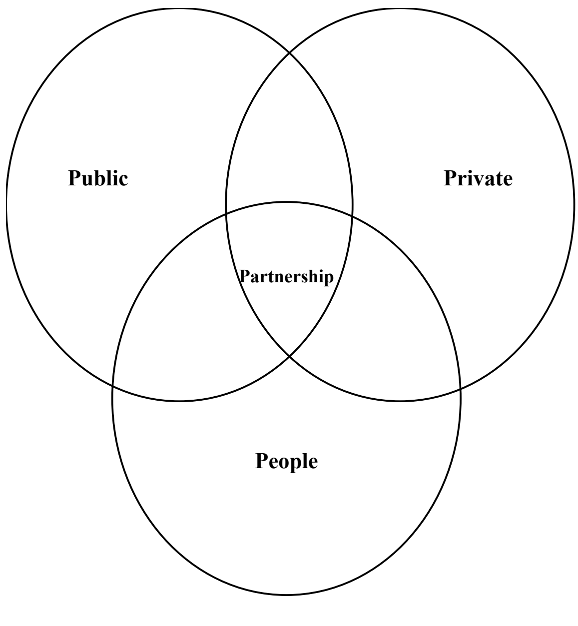


Figure 6.1: Schematic Diagram of Public-Private Peoples Partnership (PPPP or 4Ps)

It is evident that, most of ICT projects, which are implemented in collaboration with the community they serve, seem to be sustainable. Examples are the winning projects, which were selected as the most successful community-based rural ICT projects in the final report of the Commonwealth African Rural Connectivity Initiative (COMARCI). All of the selected projects were developed in partnership with the community they serve (Calindi et al., 2008; Spio-garbrah, 2010). Therefore, such a selection supports the recommendation that a PPPP is a suitable formula for implementation of projects that are unlikely to be profitable in rural areas, if owned and managed either by the public sector alone, the private sector alone or a combination of public and private sector partners (Spio-garbrah, 2010).

6.2 Selected Case Studies of Best Practices for Sustainable Project Implementation

The public private peoples partnership (PPPP) is recommended as a sustainable model for implementation of ICT-based projects in rural areas (Spio-garbrah, 2010; Calindi et al., 2008; Roman, 2009). Also, it has been noted that, partnership with the community to be served is essential for the project success and sustainability (Calindi et al., 2008; Roman, 2009). Out of the many projects documented in the literature, the following three projects: rural wireless broadband networks in Peru, rural broadband connectivity project in Dominican republic and sanitary intervention project in Nigeria, were selected as examples of best practices in implementation of the PPPP model, in order to understand the role of different actors and how collaboration/partnership takes place.

6.2.1 The Rural Wireless Broadband Network in Chancay-Huaral Valley District in Peru

The Chancay-Huaral Valley is a coastal district of Peru with many small farms. Farmers of Huaral were unable to capitalize on the great economic potential of their fertile land, abundant water and proximity to the nearby markets within Peru. A major challenge has been farmers' inability to adjust agricultural production to market fluctuations due to poor communications. Poor communications has also resulted into inefficient management of the river waters for irrigation (Saravia, 2005).

A rural wireless broadband network was established to make agricultural information available to farmers. The specific objectives were (1) To train farmers in the effective use of agricultural information, (2) To develop an agricultural information system that efficiently provides information via the internet to the farmers, (3) To strengthen local capacity for obtaining, distributing and using agricultural information (Saravia, 2005). The project deployed a wireless network that connects 13 telecenters. The interconnection of the 13 locations was done by using WiFi 802.11g technology in the 2.4 GHz frequency band, which covers a distance of up to 25km. All thirteen locations were sharing a 512 Kbps broadband connection contracted for the project. The project has been deployed with active participation of the local farmers' association, responsible for management of water and irrigation. Technical assistance has been provided by a Non-Governmental Organization (NGO) called CEPES (the Peruvian Center of Social Studies / the Centro Peruano de Estudios Sociales). The NGO provided ICT training to young people who later took ICT jobs (Saravia, 2005). A remarkable strength that provided sustainability in this project is the collaboration climate that has been created. Existing institutions in the valley pull together their forces and resources to plan and execute this project. Services offered in this project were the agricultural information via internet and Voice over Internet Protocol (VoIP). The VoIP service was not a target in the initial project planning; however, it later came up as a specific demand from project beneficiaries. This shows that the local community was pro-active to maximize the project capabilities.

Management in the project was divided into two parts: management of the services that the project is providing and management of the equipment and the physical aspects of the network. Service management was taken care by administrators of the thirteen communication centers, who have been trained for that. On the other hand, the CEPES technical team handled management of the equipment, configuration, maintenance and technical support. Twelve local people were trained to use the network, to identify connection errors, routine maintenance, to manage, configure and administer the network. Upon training completion, they were expected to take charge of network administration tasks form CEPES. There was also a plan for the project economic sustainability. It was planned that revenue from the internet and telephone services will be used to cover costs of interconnection with the public network and for paying technicians responsible for network maintenance and technical supports in each location.

6.2.2 Rural Broadband Connectivity Project in Dominican Republic

INDOTEL, the Dominican Republic communications regulatory authority launched the rural broadband connectivity project as part of the government's e-Dominican strategy in 2007. The project objectives were to provide telephone services through public call centers and broadband internet service through internet cafes to 508 localities throughout the country (Roman, 2009). This project also aimed at providing training to both end users and entrepreneurs in the use of the telephones and computers as well as in managing public call centers and cyber cafés. The project included a program to develop web pages with important information about each community, such as location, how to reach it, tourist attractions and products made by the local community. In order to promote entrepreneurship, the Internet access and public call centers were encouraged to be owned and managed by local entrepreneurs.

The project implementation started with establishing the status of telecommunications infrastructure in the area and consultations were made to all stakeholders in order to secure their support and involvement in the project. It was established that there were existing small entrepreneurs who uses satellite and wireless technologies to install local telecenters, cyber cafes and public call centers, where the local population pay to use the services. Consultation exercise involved stakeholders such as public institution and local entities, telecommunication operators, service providers and NGOs.

During consultations with public institutions and local entities, the Ministry of Education, the Ministry of Health, and local municipalities were consulted in order to understand the status of infrastructure available and to assess the need for telecommunications, especially Internet services. In addition, the local governments were invited to actively participate in the project (Roman, 2009). The regulator (INDOTEL) sent invitation for consultation with operators and service providers to chief executive officers (CEOs) of all of the major operators. At least one representative of each operator attended the meeting. Discussions about deploying broadband infrastructure throughout the country and the reasons for its absence in rural areas took place during the meeting and operators were encouraged to plan expanding their networks to the rural areas (Roman, 2009).

Establishing contacts with civil society agencies and NGOs was a strategic move, since most of them consider internet access as a working tool and would use it to communicate with their distant offices or staffs located in rural areas. For this reason, rural broadband connectivity projects are attractive to civil society agencies and NGOs. Before launching the full scale project, the regulator did a pilot implementation in a small community called Los Botados, to confirm if the rural broadband connectivity project was economically and technically viable (Roman, 2009).

In the Dominican Republic, the rural broadband project was financed by using the Universal Access Funds (UAF) through tender processes supervised by the regulator. In this process, potential investors (telecommunication operators companies) are given a certain time to prepare their bids, which are evaluated according to tender procedure. The company with a bid that meets all the technical specifications and asks for the least amount of subsidy from the fund is awarded the project to carry out commercial network roll out (Roman, 2009). In this case study, the regulator played a vital role in ensuring provision of rural connectivity.

6.2.3 Sanitary Intervention Project in Nigeria

This was a project aimed at finding a long-term solution to finance a sanitary intervention project. The mission was to promote safe sanitary and hygiene practices through hygiene education and provision of public convenience facilities that are modern, functional and well maintained (Asabia, 2009). The target areas for provision of sanitary convenience facilities were motor parks, markets, open spaces, central business areas, commuter points and high density areas. The model adopted to finance sanitary intervention was called public-social private partnership (Asabia, 2009). This is basically a 4Ps model where the unmentioned people´s P is represented by the social component of the model. Roles and responsibilities of partnership in the sanitary intervention project were mentioned as follows (Asabia, 2009):

State and local government were responsible to provide sites to locate the public convenience facilities and to provide an enabling environment for project implementation.

The facilities construction costs were financed by the private sector; an NGO. The NGO took lead in engaging local community and other stakeholders located in the sites earmarked for construction of public conveniences to ensure support and ownership of the project. Community and other stakeholders were educated about basic health and hygiene requirements and the link between diseases and unsafe sanitary practices with the ultimate aim of bringing about behavior change. To ensure project sustainability, the NGO runs and maintains the facility for an interim period of two years. After which a memorandum of understanding was signed, to enable the community or stakeholders in the target area to take over the management and ownership of the facility through a governing council comprising of key stakeholder representatives. The facilities were operated on a pay and use system. Revenue generated from usage was used to pay cleaning staff wages and to cover maintenance costs.

There are four (4) lessons that can be drawn from the projects presented as case studies of the PPPP modeling. The first lesson learned is that: presence of a Governmental will can make a project move fast as in the case of Dominican Republic, where the regulator took a lead in all steps required for a rural broadband project to take off viably. However, it is not a rule of thumb that the Government/regulators are the ones to lead the PPPP initiatives. Any of the partnership stakeholders can lead, especially the people (local community or local entrepreneurs), because, they are the ones, who properly know their needs. This was very evident in Peru´s and Nigeria's projects. Another lesson learned is the importance of local community participation in all project phases in order to deliver relevant and useful services. This aspect is more evident in the case study from Peru, where local community was able to demand relevant services. On the other hand, all case study projects demonstrated the usefulness of nurturing project ownership by the local communities/local entrepreneurs for both technical and economical sustainability. Having gained experience from the selected best practices to implement sustainable projects, the following section investigates readiness of Tanzania to deploy PPPP model for implementation of broadband rural connectivity.

6.3 Readiness of Tanzania to Deploy PPPP Model for Broadband Rural Connectivity

The following section investigate availability of supporting environment for rural connectivity, such as status of telecommunication infrastructures, institutional framework (policies, regulations, strategies and legislations) and initiatives for infrastructure development which can be used to gauge readiness of Tanzania to deploy PPPP model for broadband rural connectivity.

6.3.1 Telecommunication Infrastructures

Tanzania's economy relies heavily on agriculture, which accounts for nearly half of Gross Domestic Product (GDP) and employs 80% of the workforce. However, the telecommunication sub-sector of ICT was one of the fast growing industries in the country over the last 10 years (2000 - 2010). Statistics show that, the subsector contributed 2.5 % to the GDP in 2009 up from 2.1% in 2008. The historical development of telecommunication in Tanzania can be traced back to 1993, when the then Tanzania Postal and Telecommunication Company (TPTC) was resolved to form three entities: (1) the telecommunication regulator, called Tanzania Communication Commission (TCC) (2) The Tanzania Telecommunication Company Limited (TTCL), an operator offering telecommunication services, and (3) The Tanzania Postal Corporation (TPC), a regulator offering postal and courier services. In the same year (1993), the Tanzania Broadcasting Commission (TBC) was also established to regulate radio and television broadcasting. Tanzania is also on a global trend of switching from analogue to digital broadcasting. Due to convergence of technology and services, TCC and TBC were merged in 2003 to form the Tanzania Communication Regulatory Authority (TCRA) to regulate telecommunication, broadcasting and postal sectors.

Part of responsibilities of TCRA is to license and enforce license conditions of broadcasting, postal, and telecommunication operators, manage radio frequency spectrum and establish standards for regulated goods and services. In addition to the mentioned responsibilities, TCRA require all operators to expand their services up to rural areas in their license obligations.

In 2005, TCRA introduced a converged licensing framework, which is technology- and service - neutral framework. The converged framework ensures efficient utilization of network resources, in such a way that an individual network can be used to provide a broad range of ICT services. The converged licensing regime allows leasing of excess capacity of communications infrastructures owned by utility companies in order to provide communication services to customers after acquiring the necessary licenses from the Authority. Moreover, it provides a framework for all communication service providers to build a nationwide backhaul and interconnect to each other.

TTCL, the then incumbent telecommunication operator was licensed to provide fixed line telecommunication services during the period of 2001 - 2005 when the telecommunication market was liberalized. There are currently two operators, TTCL and Zanzibar Telecommunication Company Limited (Zantel) licensed to provide fixed-line telecommunication services, network services and facilities throughout the country (Tanzania mainland and Zanzibar). The wireless mobile communication technology enters the Tanzanian market in 1994, when the then Mobitel Company, currently branded as Tigo, was first registered as the only privately owned wireless mobile network operator. Currently there are seven wireless mobile operators, namely Tigo, Vodacom, Zain, TTCL, Zantel, Benson and Sasatel. Their respective quarterly (Jan -March, 2011) subscription market share is shown in figure 6.2.

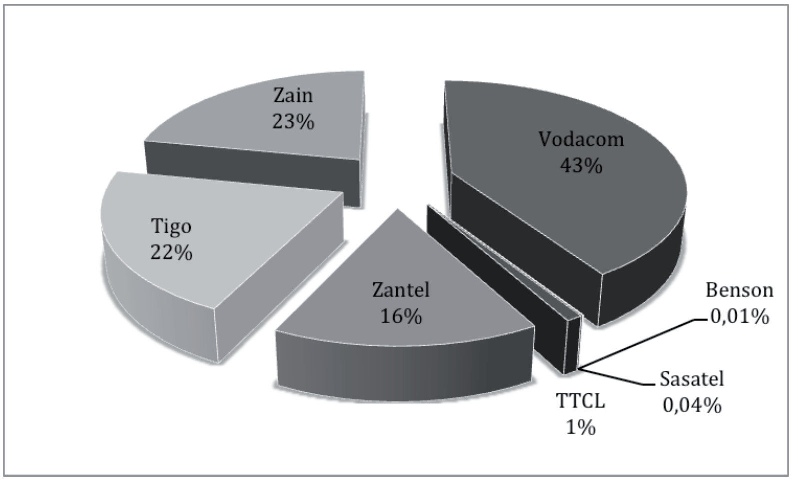


Figure 6.2: Quarterly Operator's Subscriptions Market Shares (Jan-March, 2011)

The Tanzania communication regulatory authority, by the year 2011, has licensed 18 network facilities (NF) operators for provision of ICT infrastructure services ranging from wired as well as wireless solutions. The network facilities operators are expected to provide any element or combination of elements of physical infrastructure used principally for, or in connection with, the provision of network services. Network coverage of fixed-line network operators is mainly up to levels of regional or district headquarters. Apart from wired network, the wireless infrastructures are also in place from mobile wireless cellular networks operators, which provide voice as well as broadband data and internet (multimedia) services. With wireless operators, coverage for voice services is almost the whole country while for broadband multimedia services; the coverage is on urban areas and in cities. Furthermore, the TCRA, which is responsible to allocate radio frequency to telecommunication networks and ICT services operators, has strategically reserved the extended GSM spectrum for operators aiming to deploy broadband network coverage in suburban and rural areas of Tanzania. So far there is an operator, called Rural NetCO, which is allocated the extended GSM spectrum and is dedicated to extend coverage of broadband mobile wireless network to rural areas in the country. During the time of writing this thesis, the network was not yet operational, it was under development. This network is based on 3G UMTS at 900MHz frequency band. It is a shared network, in which its design strategy is to re-use existing infrastructures such as sharing network base station sites with other telecommunication operators. With the current status of both wired and wireless technologies, the rural areas of Tanzania are still unconnected in regards to broadband network capacity.

6.3.2 Initiatives for Broadband Infrastructure Development in Tanzania

There are efforts in Tanzania that aim to develop broadband ICT infrastructures. Upon their successful implementation, the communities underserved by ICT services will be one the beneficiaries. Typical example of such efforts is the National ICT Broadband backbone (NICTBB) infrastructure project. This is a construction of a terrestrial national-wide ICT backbone by using optic fibre cable technology to cover all regions and district headquarters in Tanzania mainland and Zanzibar. The implementation strategies of national ICT backbone project is to use existing networks segments from multiple utility companies such as Tanzania Electric Supply Company (TANESCO), Tanzania Railways Corporation (TRC), Songo Songo Gas Company (SONGAS), Tanzania Zambia Railways Authority (TAZARA) and Tanzania Telecommunication Company Limited (TTCL) as shown in figure 6.3. The national ICT backbone aims to establish three main rings, namely northern, western and southern rings to form a carrier of carriers network which can be leased to network services or content providers. In addition, the backbone is aimed to provide cross border connectivity to the neighboring countries: Kenya, Uganda, Rwanda, Burundi, Democratic republic of Congo (DRC), Zambia, Malawi and Mozambique. Phase 1 of the NICTBB project, which includes utilization of existing optic fiber cable over pylons owned by TANESCO and construction of new direct buried fiber system along routes of missing links, was completed in April, 2010.

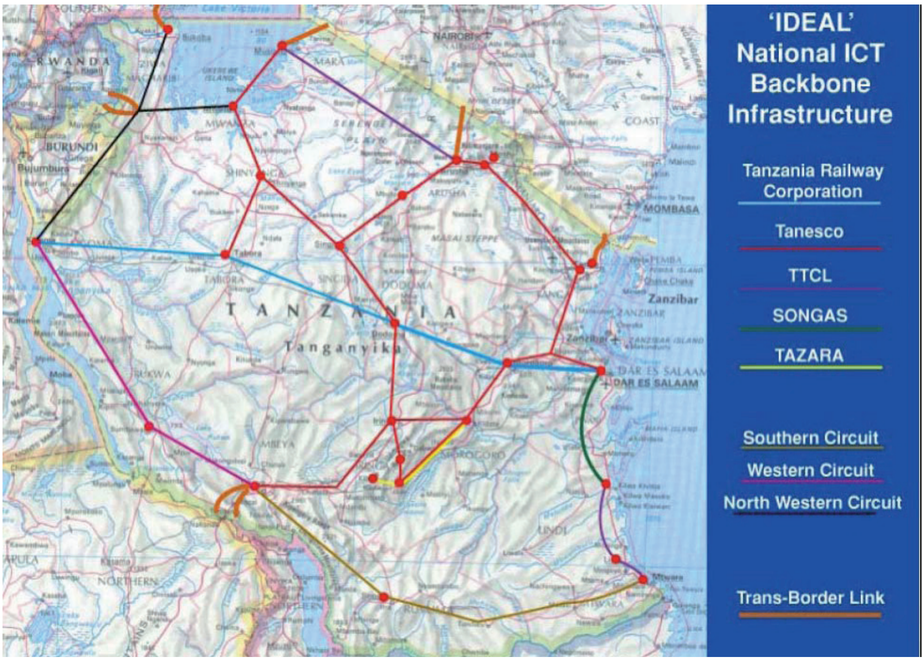


Figure 6.3: The National ICT Backbone in Tanzania (Source: Pehrson & Ngwira, 2006)

Tanzania is also connected to the rest of the world by using submarine cables, in addition to satellite systems. Examples of such submarine cables is the SEACOM and the Eastern Africa Submarine Cable System (EASSY) along the east African coast as shown in figures 6.4. The SEACOM cable was launched on 23rd July 2009 and has an high capacity of 1.28Tb/s (terabits per second). EASSY has a capacity of 1.4 Tbps and was launched in 7 April, 2010.

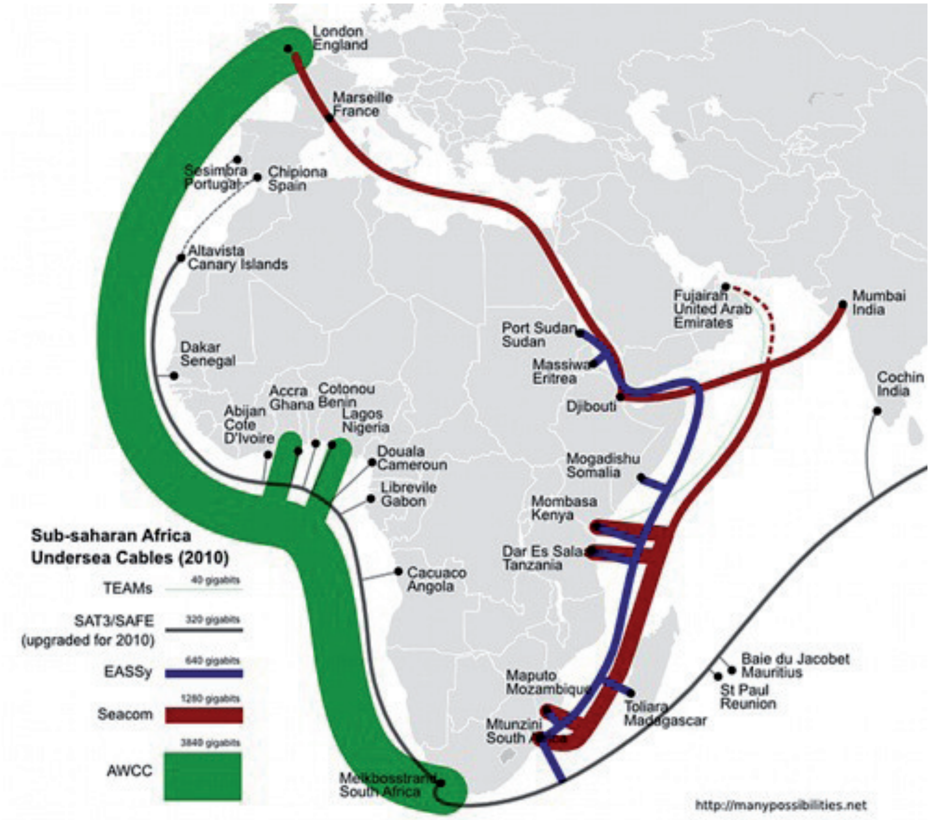


Figure 6.4: SEACOM and EASSY Submarine cables in Tanzania (Source: Adam, 2009)

The current status (2011) of broadband infrastructure, both terrestrial (NICTBB) and submarine cables in Tanzania is shown in figure 6.5.

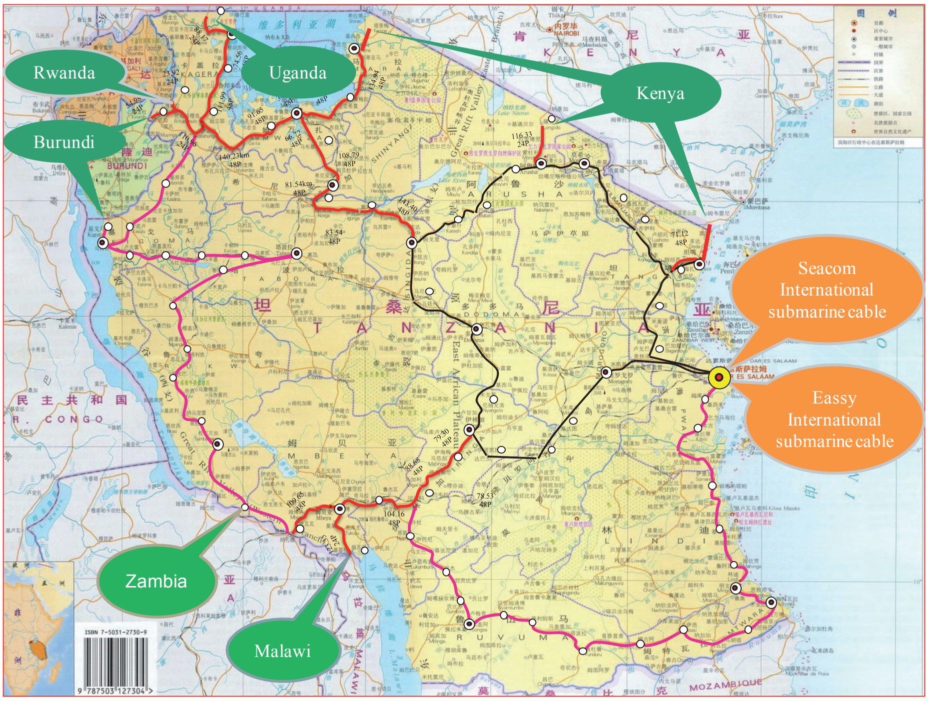


Figure 6.5: Tanzania national ICT backbone and Submarine Cables (Source: MCST[1])

6.3.3 Institutional Frameworks

This section explores institutional framework such as policies, regulations, Acts and strategies that support rural connectivity in Tanzania. Existence of such frameworks is a useful tool to foster and enforce implementation of rural connectivity projects.

i. *Tanzania National Development Vision 2025*

The national development vision aims at a Tanzania of 2025 to be a nation imbued with five main attributes: (1) High quality livelihood (2) Peace, stability and unity (3) Good governance (4) A well educated and learning society (5) A competitive economy capable of producing sustainable growth and shared benefits. The objective of this development vision is to awaken, co-ordinate and direct people's efforts, minds and national resources towards the five main attributes. Upon achievement of the five attributes, Tanzania is envisioned to be an active participant in the global competitive economy of the 21st century, which is characterized by advanced technology, high productivity, modern and efficient transport and communication infrastructure with highly skilled and innovative manpower (Vision-2025, 2000).

1 MCST – Ministry of Communications, Science and Technology, Tanzania.

ii. National ICT Policy

In 2002, Tanzania set off a multi-stakeholder ICT policy development initiative that led to the development of a national ICT policy and its adoption by the Government in 2003. The policy is currently (2011) under review for improvement. The policy articulates ten focus areas drawn from the aspirations of Tanzania's Vision 2025. One of the focus area is the ICT infrastructure, with an objective of establishing mechanisms that will result in least cost access to bandwidth for institutions or individuals in Tanzania. The National ICT Policy stipulates that, "Tanzania should have a universally accessible broadband infrastructure and ICT solutions that enhance sustainable socio-economic development and accelerate poverty reduction national-wide; become a hub of ICT Infrastructure regionally and be a full participant in the global information society" (ICT-PolicyTz, 2003).

To achieve these objectives, the Government is committed to ensure that a reliable state of the art ICT infrastructure, of adequate capacity, high-speed and countrywide coverage is developed. Under this policy, the government is committed to support, through incentives and directives, bona fide institutions actively involved in the development and application of ICT infrastructure and services (ICT-PolicyTz, 2003). Another focus area of ICT policy is the universal access, where the Government is committed to reduce the ICT access gap between the rural and the urban areas by activating the universal communications access fund, offering special incentives to investors in rural ICT provisions, supporting the construction of rural telecentres and involving local government authorities in ICT utilization and promotion. The Government also committed to encourage financial institutions to give particular support to investors in rural ICT services (ICT-PolicyTz, 2003). As part of implementation of the national ICT policy and a converged licensing regime, Tanzania embarked on an initiative for development of an open national ICT backbone network in 2005.

iii. The National Strategy for Growth and Reduction of Poverty (NSGRP)

Introduced in 2005, this strategy, which is popularly known as MKUKUTA in Swahili, was revised in 2010 into MKUKUTA II. Among other objectives, the strategy aims to promote use of PPP model for developing and operating ICT infrastructures. It also looks for efforts to support increase access and application of ICT, which will eventually increase productivity in government, business, education and Small To Medium Enterprises (SMEs) development (NSGRP, 2005; NSGRP II, 2010).

iv. National Rural Development Strategy (RDS)

The strategy came into existence in the year 2001with the aim to promote introduction of ICT in rural areas through developing telecentres. The telecentres are responsible for providing ICT services such as voice, fax, e-mail, internet access, distance education , telemedicine, news distribution, access to information on market and weather condition (RDS, 2001).

v. *Universal Communications Service Act 2006*

The Act established a fund responsible for promoting ICTs in rural and underserved urban areas by subsidizing operators investing in rural areas (UCS-Act Tz, 2006; Pehrson & Ngwira, 2006). The fund receives contributions from TCRA, development partners and telecommunication operators who contribute 0.3% from their annual growth turn over.

vi. In 2005, Tanzania prepared different communication regulations which in one way or another support provision of broadband connectivity. The selected regulations are the Tanzania communication regulations for: broadband services, quality of service, access and facilities, interconnection, and radio communication and frequency spectrum.

The previous section presents existence of telecommunication infrastructures, institutional frameworks and initiatives for broadband connectivity in the country. ICT for education projects and the governmental will are explained in chapter 1, section 1.1.3. Collectively, all these efforts demonstrate readiness of Tanzania for rural connectivity. The following section proposes implementation strategies in order to build a sustainable broadband rural connectivity in Tanzania.

6.4 The Proposed Model for Provision of Sustainable Broadband Rural Connectivity

Availability of broadband infrastructures, institutional frameworks, ICT for education projects and the governmental will are the potential enabling tools for PPPP implementation in Tanzania. Having the tools and by borrowing ideas and implementation strategies from the best practice projects implemented based on PPPP model, a sustainable model for broadband rural connectivity suitable for Tanzanian context is proposed as shown in figure 6.6. Roles of different actors in the model are explained in the forthcoming sections.

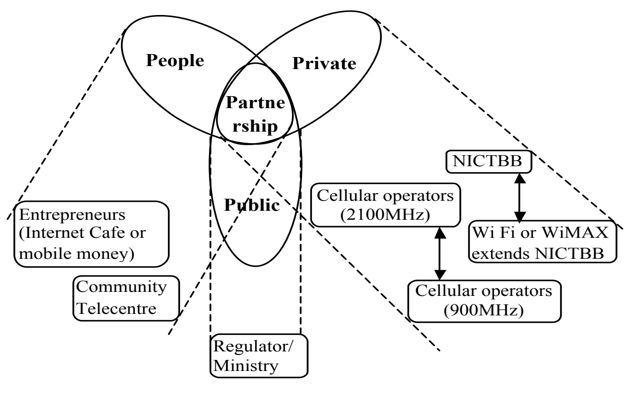


Figure 6.6: The 4Ps Model of Rural Broadband Connectivity in Tanzania

6.4.1 Public Sector

The public sector can be made up by the communication regulatory authority and/or the Ministry responsible for communications, science and technology. The main roles of the public sector are to:

i. Create and enforce enabling policy and regulatory frameworks for PPPP.

ii. Train the local community in basic computers literacy, Internet use as well as services and applications delivered by broadband networks.

iii. Enforce as well as contribute the subsidy funding for universal communications access fund to private sectors in order to facilitate ICT infrastructure and service deployment to rural areas.

iv. Encourage private sectors for commercial network rollout in rural areas.

v. Coordinate formation of the 4Ps.

6.4.2 Private Sector

The private sector in this context is proposed to have two (2) tiers; the upper tier also known as the backbone tier and the lower tier known as access network tier. Architecture of the private sector in the Tanzanian 4Ps model is shown in figure 6.7. The upper tier (backbone tier) is composed of cellular mobile operators. These are the operators that have wide coverage in the urban areas, but their network are not extended to reach rural areas, due to high cost associated with network roll out and maintenance in rural areas. Another candidate for backbone tier is an operator managing the NICTBB infrastructure. Objective of the backbone tier is to provide local and international connections to the access network tier that is made up of operators who have infrastructures in rural areas. The access network tier is responsible to provide broadband network capacity in the rural areas. In this context, the access network tier can be made up of Wi Fi or WiMAX wireless operators extending the coverage of the NICTBB. The access network tier can as well be made up of a wireless cellular mobile operator of 3G broadband access network at 900MHz frequency band to extend coverage of the existing 3G at 2100MHz broadband mobile wireless network.

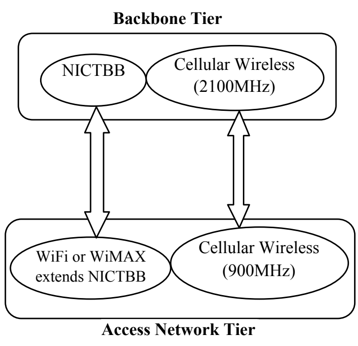


Figure 6.7: The two (2) Tiers of Private Sector in the 4Ps Model for rural connectivity in Tanzania

Different roles of the two tiers are as follows:

Backbone Tier

i. Provide local and international connections to the access network tier

ii. Develop and offer value added services

iii. Create environment for franchise business model with access network tier

iv. Train the access network operators for potential business opportunities

v. Train the local community in basic computer literacy, Internet use as well as services and applications delivered by broadband networks.

Access Network Tier

i. Roll out the commercial broadband access network infrastructure

ii. Develop and offer value added services

iii. Create environment for franchise business model with local entrepreneurs

iv. Train local entrepreneurs for potential business opportunities

v. Train the local community in basic computer literacy, Internet use as well as services and applications delivered by broadband networks.

6.4.3 People´s Sector

People or local community can be the local government or management responsible for a shared local telecommunication service such as telecentres where applicable. Another potential local partner to represent the people's part is the existing entrepreneurs in rural communities who are already providing some forms of telecommunication services such as internet cafes or mobile money transfer to others in the community. The 4Ps model can benefit from the ICT-based local entrepreneurs from their ICT literacy and experiences. Roles of the people's part in the partnership can be:

i. Make in-kind contribution to set - up network, for example provides land, labor and site security.

ii. Train the local community in computers and Internet use.

iii. Strive for participation and local ownership of the rural broadband connectivity, which will lead to sustainability and service relevance.

iv. Demand and maximize use of the value added services.

6.4.4 Sustainability

Definition of sustainability as provided by the International Fund for Agricultural Development (IFAD) Strategic Framework 2007-2010 is that "Sustainability means *ensuring that the institutions supported through projects and the benefits realized are maintained and continue after the end of the project"* (IFAD, 2011). By adopting the above definition, the following paragraphs present sustainability aspects of the proposed 4Ps model for broadband rural connectivity in Tanzania. Sustainability in this case is considered into three aspects: financial, technological and the partnership (stakeholders working together) sustainability.

In addition to the subsidies offered by the public sector and revenue collected from the main intended service to be offered, such as e-learning services in this case, other value added services relevant to the local community can contribute to the rural connectivity project financial sustainability. Providing need-driven services that are affordable to the local community, which also inspire social-economic development at the community level will generate revenue that in turn contribute to the financial sustainability of the project.

Technological sustainability is another important component in the overall sustainability of the broadband rural connectivity solution. From the comparison of technologies using the conceptual framework done in chapter 4, the technologies proposed to provide connectivity in the 4Ps model for rural connectivity in Tanzania showed to be sustainable in the market.

The training component appears to be a role for all actors in the proposed 4Ps model due to the fact that capacity building to the local community is essential to ensure sustainability of the project. People in the community have to understand the usefulness and potential of broadband Internet as well as of the services and applications that it can deliver. Otherwise, they will neither adopt the broadband project nor use its services or applications. If the local community feels empowered by the broadband rural connectivity projects, they will participate more actively in seeking ways to keep it running. Therefore, it is necessary for the people to be trained to become customers of the service and thereby ensure the project's sustainability. Training for potential business opportunities between backbone tier, access network tier and local entrepreneurs is essential in order to foster business partnership climate and sustainability. Capacity building by formal training is not the only ingredient for sustainability. Awareness creation to the community about services to be provided by the broadband network and how to access and use them can also add to the sustainability of the rural broadband connectivity. In order to enhance sustainability, the partnership should strive to nurture local community involvement/inclusion and ownership throughout all the implementation phases of rural broadband connectivity projects.

Participatory action research is a practical approach which involves all participants affected by the issue under study (Rydhagen, 2002). Active participation of actors, which can be brought about by the participatory approach, strengthens partnership and trust among the stakeholders. Due to the requirement of PPPP model to maintain the strategic partnership in all phases and throughout the project, participatory approach is recommended in the process of nurturing partnerships, because it can build a climate where rural communities feel a sense of inclusion and ownership. Furthermore, having the existing policies, legislations, strategies and regulatory framework supporting rural connectivity will protect, promote and support its development and existence, hence its sustainability.

CHAPTER SEVEN
CONCLUSION AND DIRECTION FOR FURTHER RESEARCH

7.1 Research Findings / Research Results

Different research approaches were employed to achieve the set research objectives. Results received were published in either conference proceedings or journals. The papers objectives and their contributions in achieving research objectives are briefly summarized in this section.

Paper I: Simba, F., Trojer, L., Mvungi, N.H., Mwinyiwiwa, B.M. and Mjema, E.M. *"Strategies for Connectivity Configuration to Access e-Learning Resources:Case of Rural Secondary Schools in Tanzania"*. Published in the Proceedings of World Academy of Science, Engineering and Technology, Vol. 54, Pp 789 – 794. The paper was presented in ICOLDE 2009: "International Conference on Open Learning and Distance Education ", held in Paris, France on 24 – 26, June, 2009.

Tanzania has a challenge to have a well educated and learning society by the year 2025. This paper presents an earmarked strategy to address the challenge. The strategy is to integrate ICT in education through e-learning. However, e-learning initiatives are also challenged by limited or totally lack of connectivity to majority of secondary schools, especially those in rural and remote areas. This paper explores the possibility of rural secondary schools to access online e-Learning resources from a centralized e-Learning

Management System (e-LMS). Different connectivity configurations have been proposed according to the ICT infrastructure status of the respective schools.

Paper II: Simba, F., Trojer, L., Mvungi, N.H., Mwinyiwiwa, B.M. and Mjema, E.M. *"Rural Connectivity Technologies Cost Analysis"*. Published in the Proceedings of World Academy of Science, Engineering and Technology, ISSN 2070- 3724, Vol. 59, Pp 125 – 131. The paper was presented in ICCNMC 2009: "International Conference on Communications, Networking and Mobile Computing", held in Bali, Indonesia on 25 – 27, Nov, 2009.

One of the limitations for connectivity problems in rural areas of Tanzania is the high cost of establishing infrastructures for IP-based services. This paper presents development of software system to calculate cost of connectivity to rural areas of Tanzania. The system is developed to provide easy access to connectivity costs from different technologies and different operators. This is due to the fact that the cost of connectivity varies from one technology to the other and at the same time the cost is also different from one operator (service provider) to another within the same country. Development of the calculator followed the V-model software development lifecycle. The calculator is used to evaluate the economic viability of different technologies considered as being potential candidates to provide rural connectivity.

Paper III: Simba, F., Trojer, L, Mvungi, N.H., Mwinyiwiwa, B.M. and Mjema, E.M. *"Broadband Access Technologies for Rural Connectivity in Developing Countries"*. Published in the International Journal of Research and Reviews in Computer Science, ISSN: 2079-2557. Vol. 2, No. 2. April, 2011 Issue. pp 312 - 318.

Rural areas especially those of the developing countries provide challenging environment to implement communication infrastructure for data and Internet based services. The main challenges are the high cost of network implementation and lack of customer base, as rural areas are characterized by low income, highly scattered and low population density. This situation drives network operators to establish network infrastructures in urban/city centers leaving rural areas as underserved community. This paper surveys the available connectivity technologies with potentials to offer broadband access network to rural areas. The scope of this survey is on wireless access technologies, because they are efficient in terms of cost, time of deployment and network management for rural environment. It presents comparison of the surveyed technologies in terms of their capacity (data rates) and coverage. Further, it also discusses the current deployment of WiMAX and 3G technologies in Africa, which is a home to most of the developing countries. The survey results indicate potential broadband access technologies for rural areas of the developing countries.

Paper IV: Simba, F., Trojer, L, Mvungi, N.H., Mwinyiwiwa, B.M. and Mjema, E.M. *"Techno-Economic Analysis of UMTS900 and UMTS2100 for Rural Connectivity in*

Tanzania". Accepted for oral presentation and thereafter publication in the proceedings of 14th IEEE International Conference on Communication Technology (ICCT 2012), to be held in November 9th-11th, 2012 in Chengdu, China.

Rural areas of the developing countries lack Information and Communication Technology (ICT) infrastructures such as access network, also known as last mile connectivity, to deliver ICT services. The lack of connectivity is due to high cost of implementing ICT infrastructures. Wireless technologies are envisioned as candidates for rural connectivity. They are not only easier and faster to deploy but also cheaper than the wired technologies. This paper presents a techno-economic analysis of two wireless technologies in Tanzania, called third generation (3G) implemented at 900MHz and at 2100MHz frequency bands. Objectives of techno-economic analysis are to investigate economic feasibility and to determine a cost effective option between the two connectivity options. Results show that, 3G at 900HMz is a feasible and cost - effective connectivity technology in Tanzania. These results can be generalized to other developing countries, since rural areas pose similar characteristics with regard to ICT infrastructure development.

Paper V: Simba, F; Trojer, L and Yonah, Z. O. *"Sustainable Broadband Connectivity Model for Rural Areas of Tanzania"*. Submitted for publication in the African Journal of Science, Technology, Innovation and Development (AJSTID).

One of the reasons for lack or limited ICT infrastructures in rural areas of developing countries in general and Tanzania in particular, is the lack of strategies to implement already established policies, regulations and legislations that support roll-out of such ICT infrastructures. Other factors are high cost of connectivity, lack of energy, low ICT literacy and shortage of local contents. Despite the presence of eighteen (18) licensed network facilities service providers in the communication market in Tanzania, rural areas are still unconnected. However, there is a government initiative to build a countrywide terrestrial fiber optic broadband backbone with penetration presence down to the level of district headquarters. This is a commendable initiative; however, areas that are far from district headquarters will still be disadvantaged. The Public Private Peoples´ Partnership (PPPP) is recommended as a sustainable model for rural connectivity. This paper investigates the readiness of Tanzania to deploy the PPPP model for rural broadband connectivity. Furthermore, it recommends a sustainable model for rural connectivity in Tanzania by adapting the PPPP model and borrowing best practices from existing PPPPs projects implementations.

Paper VI: Simba, F., Trojer, L, Mvungi, N.H., Mwinyiwiwa, B.M. and Mjema, E.M. *"Performance Evaluation of e-Learning Applications in UMTS Network"*. Submitted for presentation and thereafter publication in the proceedings of the 8th International Conference on Broadband Communications, Networks and Systems (BROADNETS), to be held in Limassol, Cyprus, November 19-21, 2012.

The aim of this paper is to study the effect of traffic differentiation and priority scheduling in providing Quality of Service (QoS) for e-learning applications in Universal Mobile Telecommunication System (UMTS) networks. A simulation model of the UMTS network has been developed and used to study performance of e-learning applications as perceived by users. Priority scheduling is used to prioritise traffic between e-learning and other conventional users according to their QoS requirements. Simulation results show that a UMTS network configured with traffic differentiation and priority scheduling can deliver e-learning services with page response time of less than 4 seconds. This performance is within the acceptable values of applications´ quality of service.

Contributions of different papers in achieving the research objectives as well as in answering research questions are presented in figure 7.1.

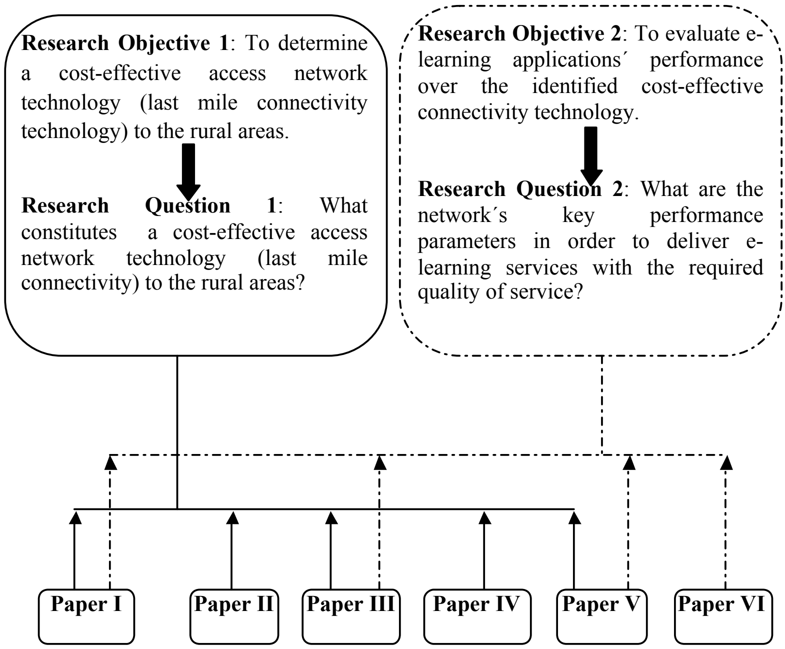


Figure 7.1: Contribution of published papers in answering research questions and achieving research objectives.

7.2 Summary of Answers to Research Questions

This research was developed based on the general objective of determining a cost-effective and performance efficiency connectivity solution for rural secondary schools in Tanzania in order to access e-learning resources. The research work was guided by two research questions, targeting cost and performance of a connectivity technology for rural areas. A summary of answers to research questions is presented hereunder:

Research Question 1: What constitutes a cost-effective broadband access network technology (last mile connectivity) to the rural areas?

Summary of the Answer: A sustainable technology with broadband capacity, low capital expenditure (CAPEX) and low operational expenditure (OPEX) is a cost-effective solution for last mile rural connectivity. During the research period, capabilities of different broadband wireless technologies with the potential to provide rural connectivity were identified and surveyed. The criteria used were capacity (data rates) and coverage. The coverage and capacity of broadband access technologies are summarized in table 4.5 in chapter 4. Mobile cellular wireless technology was identified as the most suitable option among the five surveyed technologies (fixed and mobile WiMAX, 3G at 2100MHz, 3G at 900MHz and hybrid network of fiber optic extended by WiMAX). The research further used a conceptual framework to analyze a competition between the two variant of mobile cellular wireless technology (3G at 2100MHz and 3G at 900MHz) for sustainability. Thereafter, a techno-economic analysis of 3G at 2100MHz and 3G at 900MHz was conducted to identify a cost-effective option in terms of CAPEX and OPEX. Results of the techno-economic analysis presented in chapter 4 show that 3G at 900MHz is a cost-effective connectivity technology for rural areas. The cost efficiency came from its low frequency, which results into a wider cell coverage accommodating the sparsely rural population. Another aspect that brings cost-efficiency is the implementation strategy of 3G at 900MHz, which is a co-existence of 3G and GSM in the same base station. The co-existence cut down base station civil work and site rental charges. The wider network cell coverage and co-existence with GSM technology translates into reduced CAPEX as well as OPEX.

Research Question 2: What are the network´s key performance parameters in order to deliver e-learning services with the required quality of service?

Summary of the Answer: UMTS network, which has been identified as a cost-effective connectivity technology, is capable of delivering triple play services i.e basic voice, data, multimedia streaming and video conferencing. Through simulation modeling, this research identified, that UMTS network configured in best effort basis is not capable to guarantee delivery of e-learning applications with acceptable QoS. In order to deliver e-learning applications in UMTS networks with acceptable QoS, mechanisms to guarantee QoS are required. This research examined use of traffic differentiation through priority scheduling to guarantee QoS of e-learning applications. By using traffic differentiation through priority scheduling, UMTS networks were capable to deliver e-learning applications with the acceptable QoS.

7.3 Research Contributions

Six (6) papers were published during the time of this research. Two (2) papers were published in journals and the remaining four (4) were conference papers, presented in their respective International conferences and thereafter published in the conference proceedings. Summary of the papers and their objectives are found in section 7.1. The papers are the scientific and academic contribution to the body of knowledge.

Survey of the broadband wireless technologies with the potential to provide rural connectivity done in chapter 4 is a collection of technical information about strengths and weaknesses of the different wireless technologies with emphasis on capacity (data rate) and coverage. Putting together technical information of five (5) technologies in a single document is a contribution to learners and researchers, which will ease information retrieval.

Another contribution is a simulation model of UMTS network for applications performance evaluation. It is a contribution to network operators, service providers and academia (researchers). The model can be used as a laboratory tool for testing performance of applications before they are deployed to the real world UMTS network. Furthermore, the proposed 4Ps model for providing sustainable broadband connectivity to rural areas is a contribution to Tanzanian Government (policy makers and planners), development partners and researchers to support decisions for rural connectivity solution.

7.4 Concluding Remarks

This thesis presents a research work for determining a cost-effective and performance efficiency connectivity solution for rural secondary schools to access e-learning resources. Identifying a cost-effective connectivity technology is not a straight forward task taking into account the fast evolution/development of information and communication technologies. It should be noted that, the cost-efficiency aspect of a technology is not entirely means the financial requirements, other aspects such as sustainability and implementation strategies are also important. This thesis presents a scientific procedure to determine a cost-effective connectivity technology. By following the procedure, the 3G mobile cellular wireless technology operating at 900MHz frequency was determined to be the cost-effective technology to offer broadband connectivity to rural areas.

The research identified that Tanzania is equipped with enough requirements to provide rural connectivity. There is availability of institutional frameworks (policies, regulations, strategies and legislations), Governmental will and telecommunication infrastructures (though their coverage are still urban-based) to support rural connectivity. Due to the fact that providing rural connectivity is not profitable to commercial operators, then collaboration of different stakeholders is required for rural connectivity viability. Therefore, the Public Private People's Partnership (PPPP or 4Ps) model was proposed as a sustainable implementation strategy for rural connectivity solution. This model has the potential to bring together stakeholders and enforce implementation of already established institutional frameworks for rural connectivity. The implementation approach of the 4Ps model, which is based on the concept of partnership, is also proposed to be nurtured through mode 2 and participatory action researches in order to build trust and strengthen the partnership climate. Deployment of the proposed 4Ps model is envisioned to bring social-economic development, increase ICT literacy and capacity development in the country.

This research identified that UMTS networks configured on best effort basis will not guarantee QoS for e-Learning applications. These results suggest that in order to deliver e-learning application with the required QoS, then mechanisms to guarantee QoS, such as traffic differentiation through priority scheduling, are to be configured in the network used.

7.5 Direction for Further Research Work

This research will be fully exploited, when there exist an implementation of the proposed PPPP model for sustainable broadband rural connectivity. The earmarked approach is to conduct mode 2 research as well as develop participatory action research, which will bring together public, private and peoples sectors in an effort to implement broadband rural connectivity.

After determining a cost-effective and performance efficiency connectivity technology suitable for rural areas, the research looks forward to find security solution for multimedia e-learning services in order to keep the integrity and prevent any unauthorized access. In addition to security, a further research work is required to find solutions for network performance monitoring to ensure e-learning service reliability.

On the other hand, a further research work is needed to expand the simulated UMTS network model to be able to evaluate performance of all four UMTS traffic classes. Moreover, the research work can be expanded to identify wireless (3G - 4G) networks´ parameters that can be re-configured (network optimization) in order to enhance/guarantee QoS of e-learning applications.

Connectivity to rural areas is still challenged by lack of electrical power to run telecommunication systems. It will be useful and interesting to find a solution of electrical power for rural areas. The earmarked approach is the integration of renewable energy technologies with the wireless telecommunications systems for rural areas.

Another area of interest for further research is to develop open source industrial-standard software for access network components of a broadband technology for rural connectivity. If software parts of connectivity technology get developed and hence be available (obtained) as free and open source software, it will make the technology to be more cost-effective.

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APPENDICES

APPENDIX A: Configuration of UMTS Modeling and Simulation Scenario

This appendix section provides description and values of parameters configured during UMTS network modeling and simulation.

A1. UMTS Model´s nodes and links description

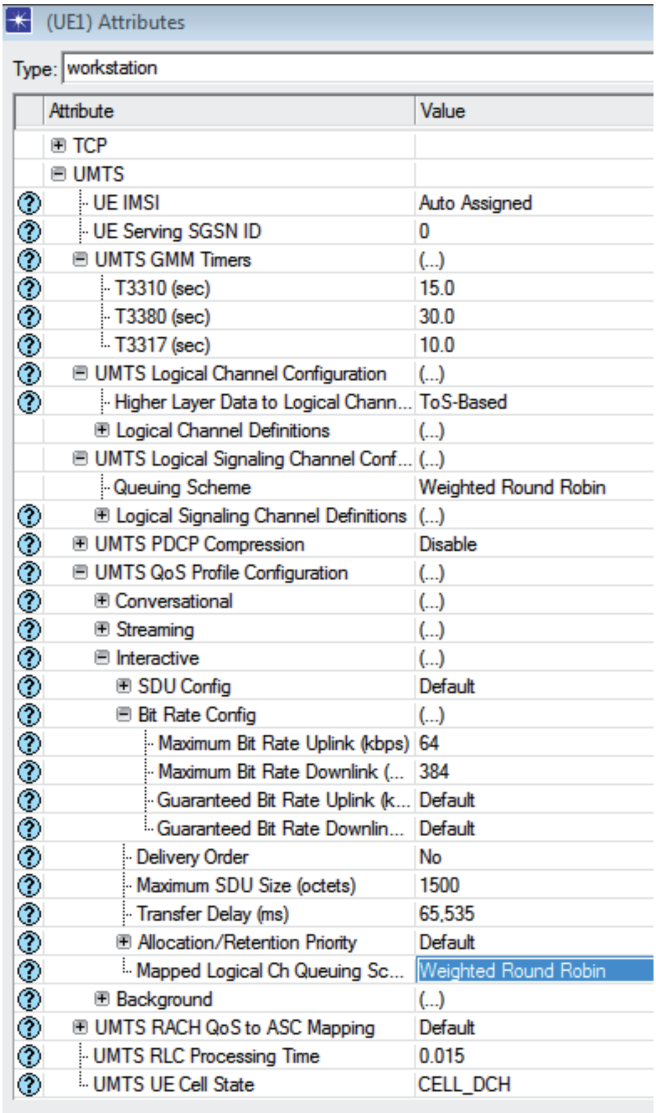
S/N	Equipment	Description
1	User Equipment (UE)	Device Name: umts_wkstn_adv node Represents a UMTS workstation with client-server applications running over TCP/IP and UDP/IP. The workstation supports one underlying W-CDMA connection.
2	NodeB	This node model serves as a Node-B node that handles the connection of the UEs in its own cell with RNC and the rest of the UMTS network. Its general function is to provide radio interface services for UEs camping in the cell. Protocols supported are UMTS (W-CDMA) and ATM.
3	RNC	Device Name: umts_rnc_ethernet2_atm2_slip2_adv This model serves as a UMTS Radio Network Controller. (RNC) of a UTRAN participating in a UMTS network. It has the ability to support and manage up to 8 Node-Bs on the ATM interface and an unlimited number of Node-Bs on the IP interface. Each connection to a Node-B will run either over an ATM stack or an IP stack. IP (PPP), ATM and Ethernet interfaces are available for connectivity with the UMTS SGSN node. Protocols supported are ATM, UMTS (RANAP, RLC, RRC, NBAP, RNSAP.
4	SGSN	Device Name: umts_sgsn_ethernet_atm9_slip_adv This node models represents an UMTS Serving GPRS Support Node (SGSN) node and supports the following technologies: ATM, Ethernet and SLIP.

5	GGSN	Device Name: The umts_ggsn_atm8_ethernet8_slip8_adv This node represents an UMTS Gateway GPRS Support Node (GGSN), supporting 8 ATM interfaces, 8 Ethernet interfaces and up to 8 serial line interfaces at a selectable data rate. The various IP interfaces are used for connection with SGSN nodes via UMTS core network as Gn interfaces.
6	Internet	The ip32_cloud node model represents an IP cloud supporting up to 32 serial line interfaces at a selectable data rate through which IP traffic can be modeled. IP packets arriving on any cloud interface are routed to the appropriate output interface based on their destination IP address.
7	Router	The CS_4000_3s_e6_fr2_sl2_tr2 model represents the following device: Vendor = Cisco Systems, Product = CISCO4000, Device Class= Router. A typical use of this device is to route data between two Ethernet LAN segments connection via an IP network. Supported protocols are Ethernet (IEEE 802.3), Token Ring (IEEE 802.5), Internet Protocol (IP), Routing Information Protocol (RIP), User Datagram Protocol (UDP), Open Shortest Path First (OSPF), Frame Relay (ANSI T1.618).
8	TanSSeL Server	The ethernet_server model represents a server node with server applications running over TCP/IP and UDP/IP. This node supports one underlying Ethernet connection at 10 Mbps, 100 Mbps, or 1 Gbps. The operational speed is determined by the connected link's data rate.
9	Application configuration	The "Application Config" node can be used to specify applications using available application types.
10	Profile configuration	The "Profile Config" node can be used to create user profiles. The user profiles can then be specified on different nodes in the network to generate application layer traffic.
11	Link (NodeB & RNC)	The ATM_E3 link with 34,368,000 bps data rate, it can connect ATM switches, gateways, workstations, servers and station nodes.
12	Link (RNC & SGSN)	The ATM_E3 link with 34,368,000 bps data rate, it can connect ATM switches, gateways, workstations, servers and station nodes.
13	Link (SGSN& GGSN)	The ATM_E3 link with 34,368,000 bps data rate, it can connect ATM switches, gateways, workstations, servers and station nodes.
14	Link (GGSN & Internet)	Is a point to point link with 34,368,000 bps data rate, it connects two nodes running IP.
15	Link(Internet &Router)	Is a point to point link with 34,368,000 bps data rate, it connects two nodes running IP.

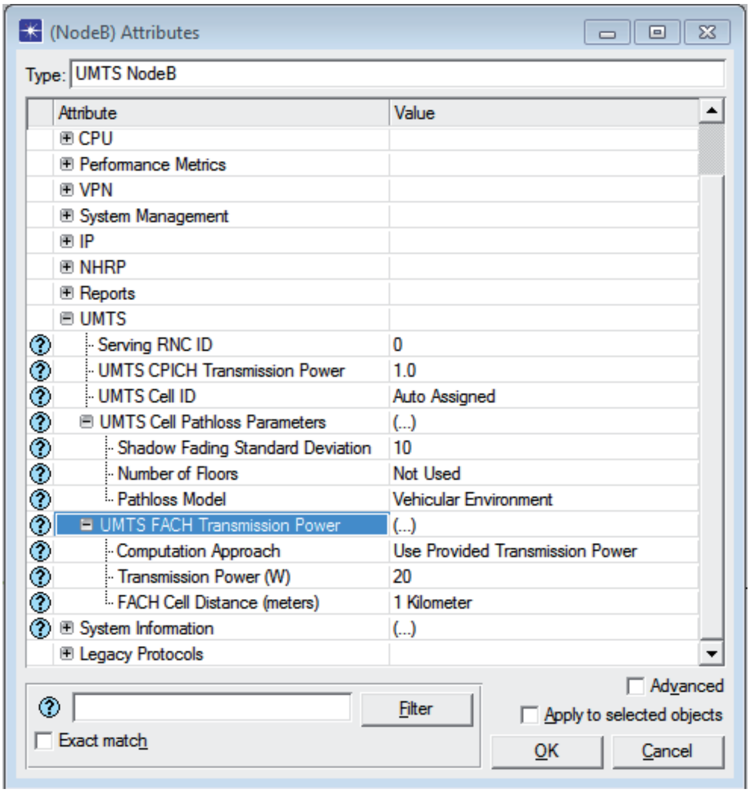
16	Link (Router&Server)	The 100BaseT duplex link represents an Ethernet connection operating at 100 Mbps. It can connect any combination of the following nodes (except Hub-to-Hub, which cannot be connected): 1) Station 2) Hub 3) Bridge 4) Switch 5) LAN nodes

A2. Best Effort UMTS Model´s Configuration

a. User Equipment (UE)



b. NodeB


(NodeB) Attributes
Type: UMTS NodeB
Attribute
Value
CPU
Performance Metrics
VPN
System Management
IP
NHRP
Reports
UMTS
Serving RNC ID
0
UMTS CPICH Transmission Power
1.0
UMTS Cell ID
Auto Assigned
UMTS Cell Pathloss Parameters
(...)
Shadow Fading Standard Deviation
10
Number of Floors
Not Used
Pathloss Model
Vehicular Environment
UMTS FACH Transmission Power
(...)
Computation Approach
Use Provided Transmission Power
Transmission Power (W)
20
FACH Cell Distance (meters)
1 Kilometer
System Information
(...)
Legacy Protocols
Filter
Exact match
Advanced
Apply to selected objects
OK
Cancel

c. Radio Network Controller (RNC)

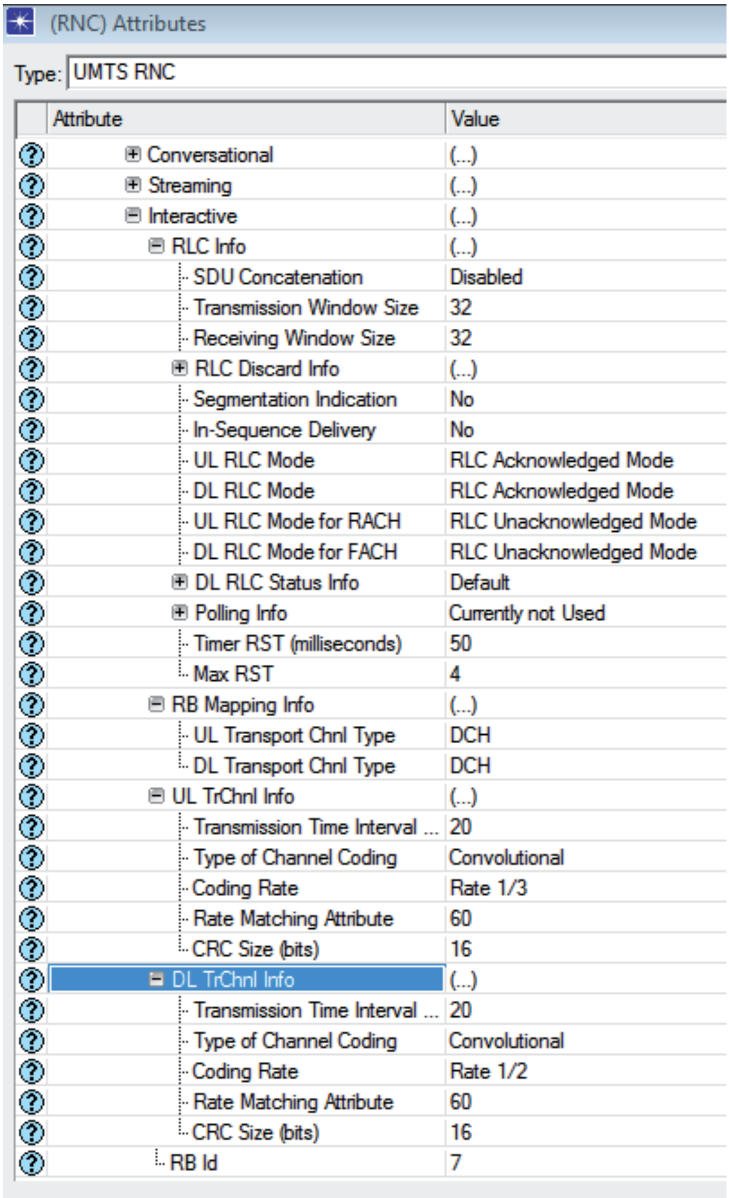
i. Signaling channel configuration

(RNC) Attributes

Type: UMTS RNC

Attribute	Value
name	RNC
⊟ UMTS RNC Parameters	
⊞ Admission Control Parameters	(...)
⊟ Channel Configuration	(...)
⊟ Signaling Channel Config	(...)
⊟ RLC Info	(...)
Transmission Window Size	8
Receiving Window Size	8
⊞ RLC Discard Info	Default
Segmentation Indication	No
In-Sequence Delivery	No
UL RLC Mode	RLC Unacknowledged Mode
DL RLC Mode	RLC Unacknowledged Mode
⊞ DL RLC Status Info	Default
⊞ Polling Info	Currently not Used
Timer RST (milliseconds)	50
Max RST	4
⊟ RB Mapping Info	(...)
UL Transport Chnl Type	DCH
DL Transport Chnl Type	DCH
⊟ UL TrChnl Info	(...)
Transmission Time Interval (m...	20
Type of Channel Coding	Convolutional
Coding Rate	Rate 1/3
Rate Matching Attribute	256
CRC Size (bits)	16
⊟ DL TrChnl Info	(...)
Transmission Time Interval (ms)	20
Type of Channel Coding	Convolutional
Coding Rate	Rate 1/3
Rate Matching Attribute	256
CRC Size (bits)	16
RB Id	3
⊞ Data Channel Config (Per QoS)	(...)

ii. Data channel configuration

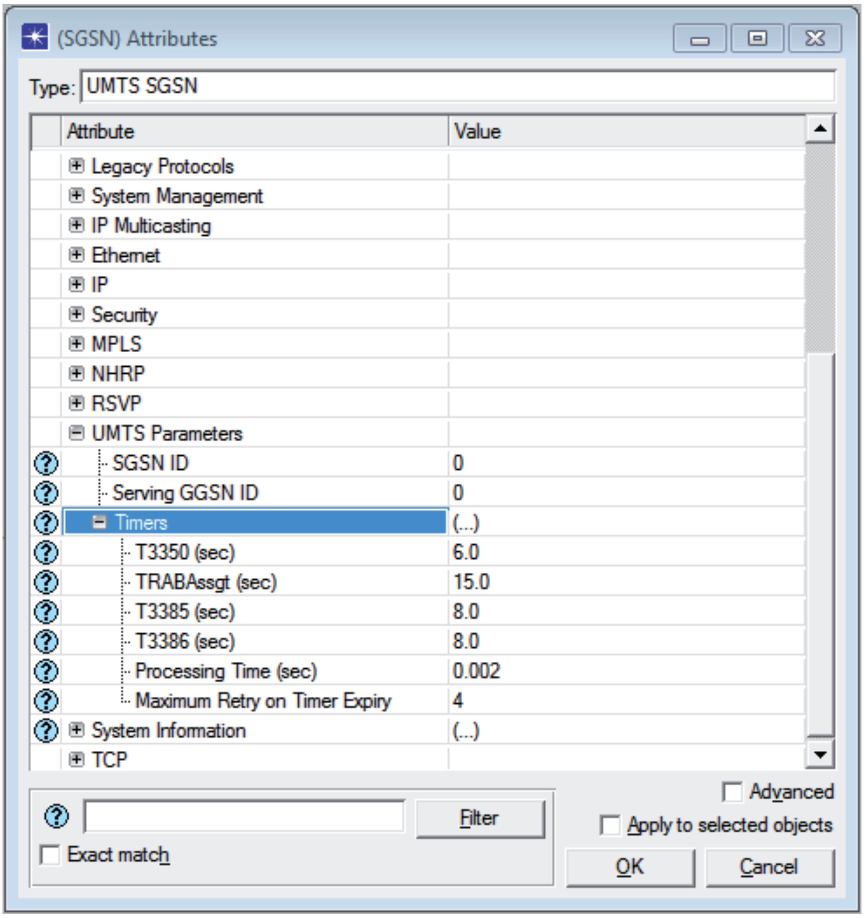


(RNC) Attributes

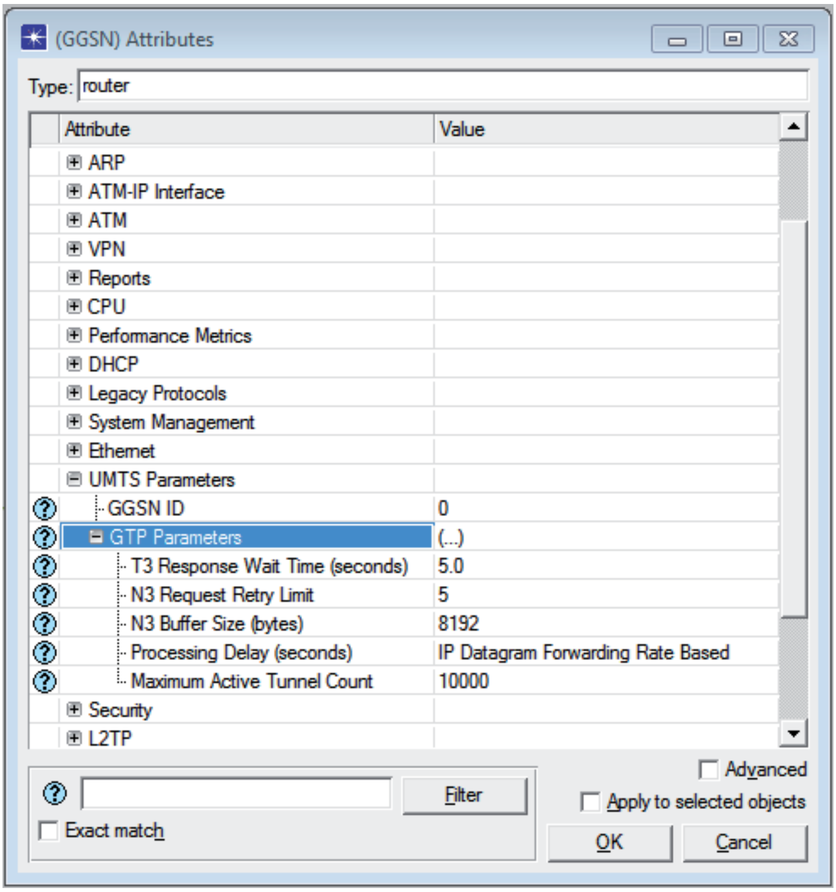
Type: UMTS RNC

Attribute	Value
Conversational	(...)
Streaming	(...)
Interactive	(...)
RLC Info	(...)
SDU Concatenation	Disabled
Transmission Window Size	32
Receiving Window Size	32
RLC Discard Info	(...)
Segmentation Indication	No
In-Sequence Delivery	No
UL RLC Mode	RLC Acknowledged Mode
DL RLC Mode	RLC Acknowledged Mode
UL RLC Mode for RACH	RLC Unacknowledged Mode
DL RLC Mode for FACH	RLC Unacknowledged Mode
DL RLC Status Info	Default
Polling Info	Currently not Used
Timer RST (milliseconds)	50
Max RST	4
RB Mapping Info	(...)
UL Transport Chnl Type	DCH
DL Transport Chnl Type	DCH
UL TrChnl Info	(...)
Transmission Time Interval ...	20
Type of Channel Coding	Convolutional
Coding Rate	Rate 1/3
Rate Matching Attribute	60
CRC Size (bits)	16
DL TrChnl Info	(...)
Transmission Time Interval ...	20
Type of Channel Coding	Convolutional
Coding Rate	Rate 1/2
Rate Matching Attribute	60
CRC Size (bits)	16
RB Id	7

d. Serving GPRS Support Node (SGSN)

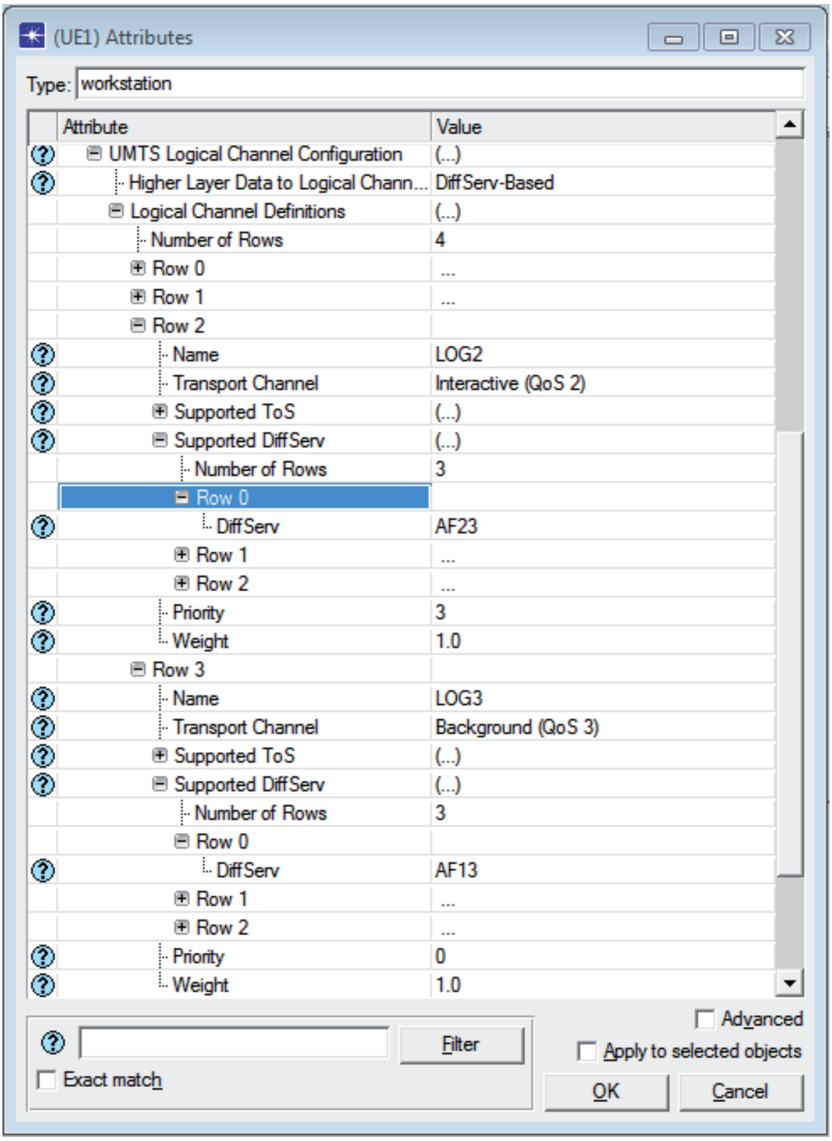


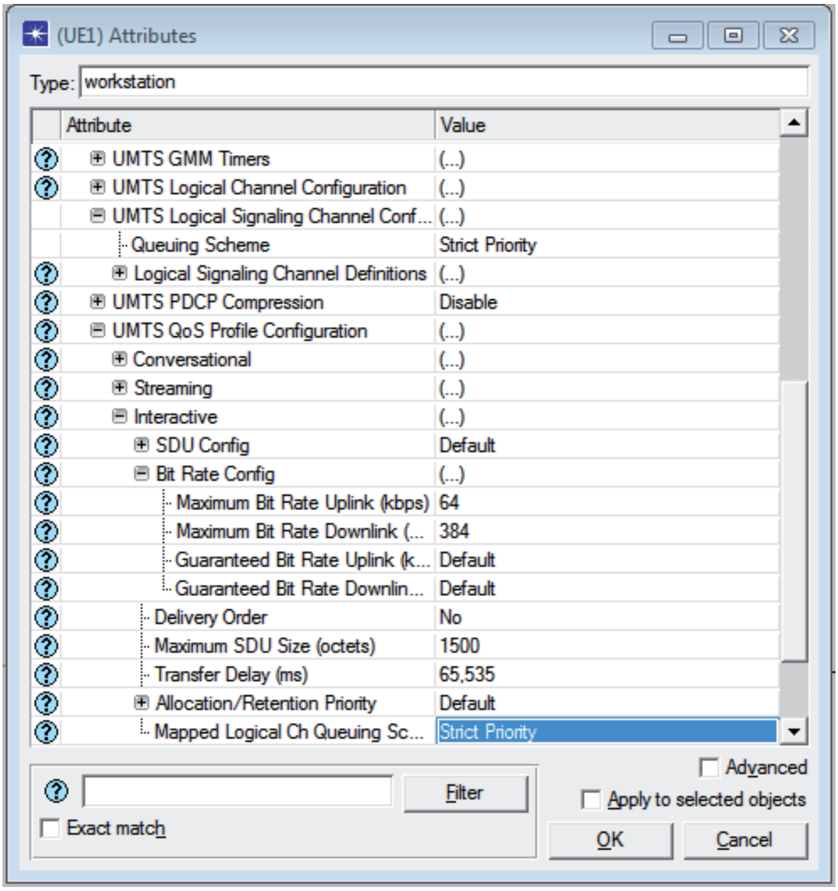
e. Gateway GPRS Support Node (GGSN)



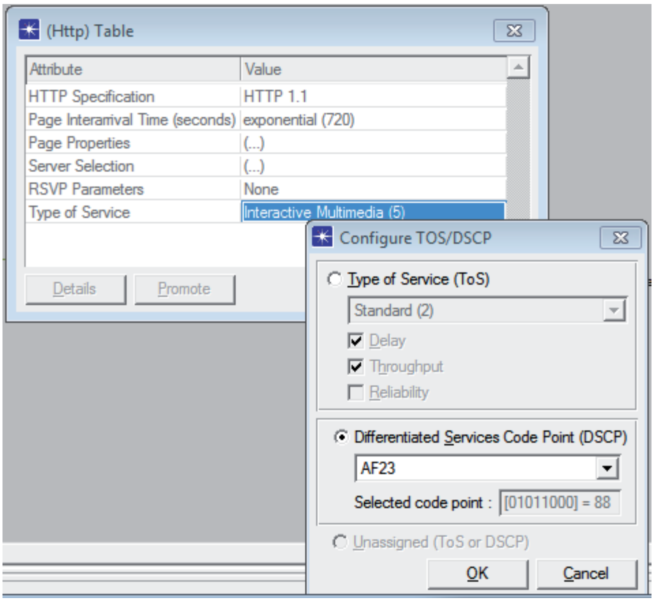
A3. Configuring Traffic Differentiation in the UMTS Model

a. Configuration in the UE

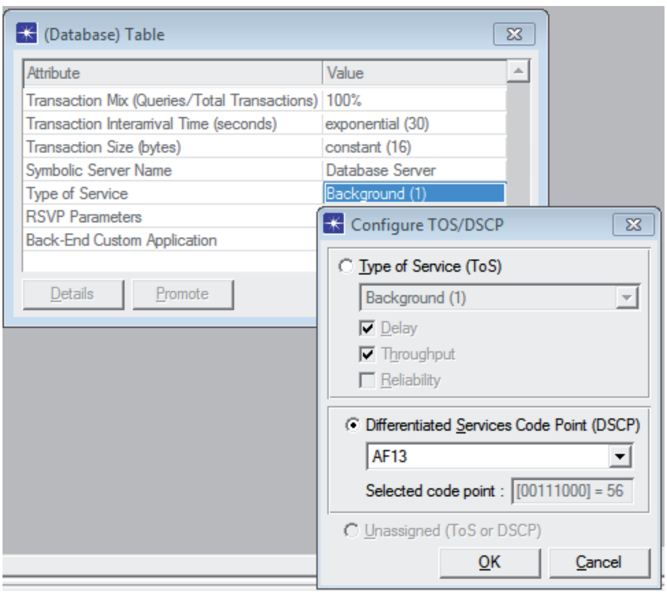



(UE1) Attributes
Type: workstation
Attribute
Value
UMTS GMM Timers
(...)
UMTS Logical Channel Configuration
(...)
UMTS Logical Signaling Channel Conf...
(...)
Queuing Scheme
Strict Priority
Logical Signaling Channel Definitions
(...)
UMTS PDCP Compression
Disable
UMTS QoS Profile Configuration
(...)
Conversational
(...)
Streaming
(...)
Interactive
(...)
SDU Config
Default
Bit Rate Config
(...)
Maximum Bit Rate Uplink (kbps)
64
Maximum Bit Rate Downlink (...
384
Guaranteed Bit Rate Uplink (k...
Default
Guaranteed Bit Rate Downlin...
Default
Delivery Order
No
Maximum SDU Size (octets)
1500
Transfer Delay (ms)
65,535
Allocation/Retention Priority
Default
Mapped Logical Ch Queuing Sc...
Strict Priority
Filter
Exact match
Advanced
Apply to selected objects
OK
Cancel

b. HTTP Source traffic model parameters

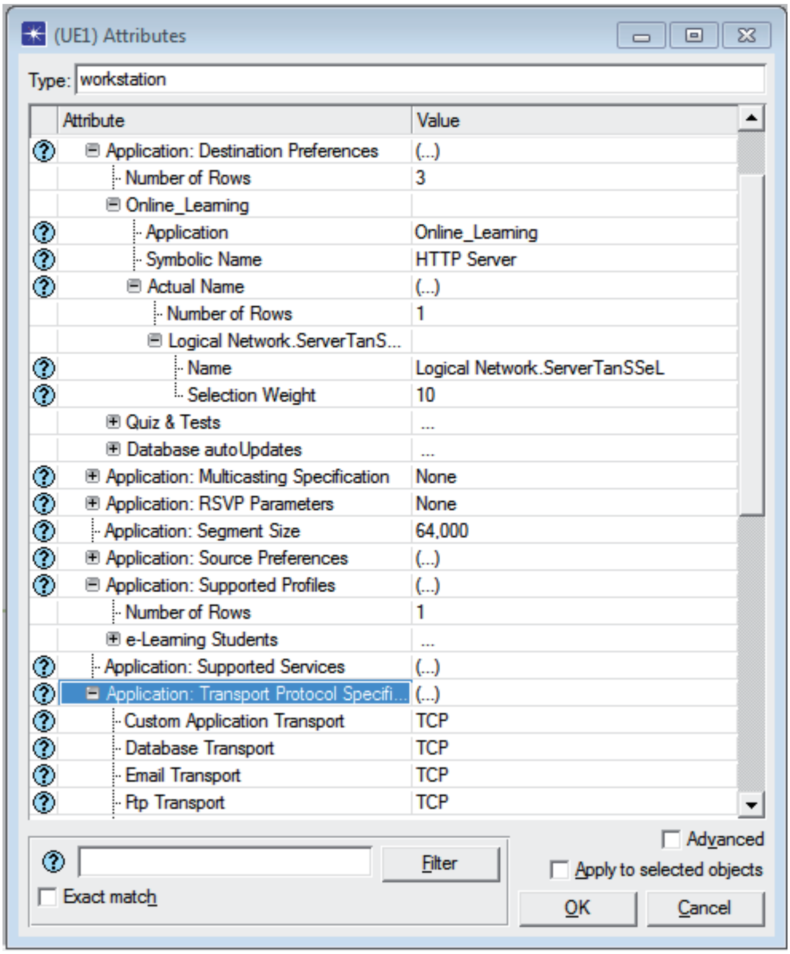


c. Database Source traffic model parameters

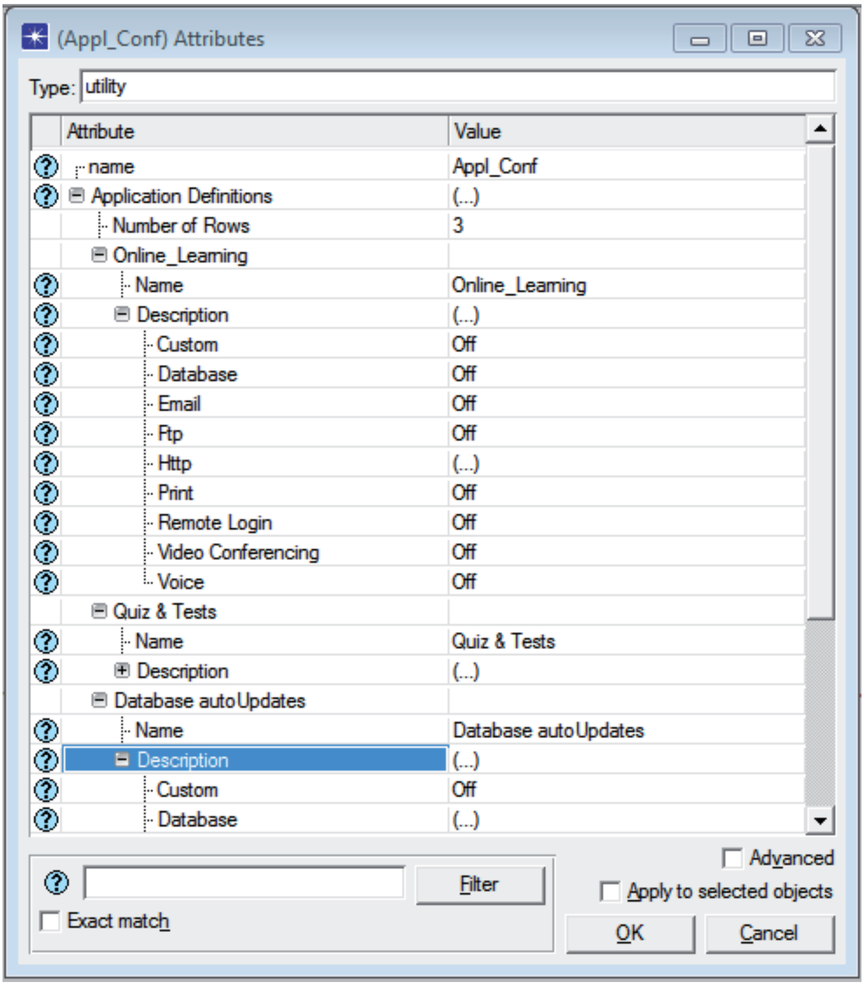


A4. Application Configuration in UMTS Network Model

a. Configuration in the UE



b. Application definition in the appl_config node



i. Parameters and values for HTTP traffic models (Online_learning and Quiz & Tests)

(Http) Table

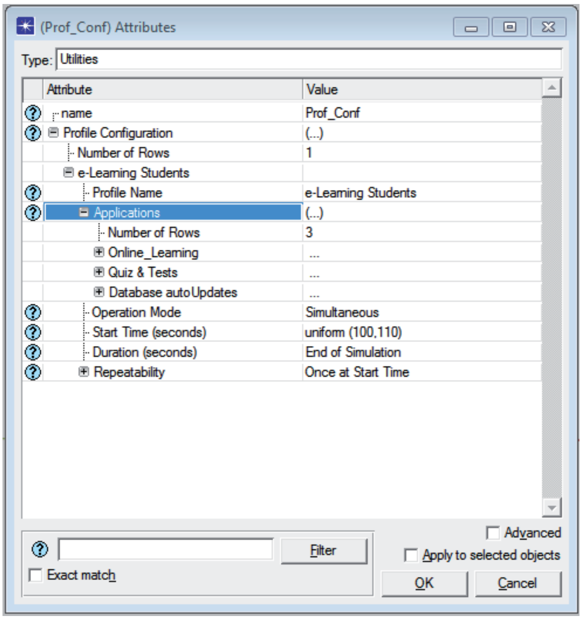
Attribute	Value
HTTP Specification	HTTP 1.1
Page Interarrival Time (seconds)	exponential (720)
Page Properties	(...)
Server Selection	(...)
RSVP Parameters	None
Type of Service	Interactive Multimedia (5)

ii. Parameters and values for database traffic model

(Database) Table

Attribute	Value
Transaction Mix (Queries/Total Transactions)	100%
Transaction Interarrival Time (seconds)	exponential (30)
Transaction Size (bytes)	constant (16)
Symbolic Server Name	Database Server
Type of Service	Background (1)
RSVP Parameters	None
Back-End Custom Application	Not Used

c. Profile definition in the Prof_Conf node



d. Configuration in the server node