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Towards Sustainable Broadband Communication in Under-served Areas : A Case Study from Tanzania

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Abstract

The problem discussed in this thesis is how to establish sustainable broadband markets in under-served areas. The purpose is to improve people's living conditions by promoting efficient service delivery in education, health, and governance and alleviating poverty. Due to the high-perceived risks, the market forces have failed to bring ICT in these areas. The business community is reluctant to take on the supplier role.

Earlier efforts through development partners have been focusing on connecting under-served areas to the global Internet via telecentres. However, most implementations could not operate beyond the initial funding for various reasons, especially the lack of understanding of the local needs where most technical solutions were imported from the developed world, not optimized to work under local conditions.

We propose the creation of community or municipal owned "broadband islands", defined as high speed communication broadband networks that do not depend on external connections for their operations. Using an Action Research participatory approach, we are emphasizing multi-stakeholder partnerships, and engaging the local community to contribute infrastructure, technical solutions and leadership. Our proposal is validated through the design and deployment of two pilot sites in rural areas of Tanzania. Our original contributions include 1) An overall model on how to establish and sustain broadband markets in under-served areas, making it scalable and reproducible. 2) technical innovations, especially the design and implementation of a low cost, low power-consuming, and robust router with integrated power management. 3) Organizational innovations by establishing institutional mechanisms at a local level in public-private-community partnership. 4) Innovative funding mechanisms by identifying partners who can pay on behalf of the end users and cut down costs through resource sharing schemes.

The government of Tanzania has shown interest to use the pilot sites as models for extending the national backbone into other municipal. Also, discussions are underway to organize similar pilots in East Africa.

Acknowledgements

First, I would like to thank my advisor, now retired, Professor Björn Pehrson who gave me the opportunity to join KTH and introduced me to a wider academic networking community. My special thanks go to Associate Professor Peter Sjödin for becoming my main advisor for these last few months. I thank you for your comments and feedback, especially on the difference between Engineering and Science. Thanks to co-advisor, Associate Professor Björn Knutsson for being there to discuss various solutions we could deploy in under-served areas as well as for showing me how to use bubbles to structure ideas when writing papers. Thank you Associate Professor Terrence Brown for being my co-advisor during the initial registration process. I thank you for discussions on business and entrepreneurship, especially the difference between the business model and the canvas tool as applied in business.

I would like to thank my colleagues at TSLab for their willingness to help in their different capacities. A special thanks go to the families of Nuru Kisome, Faraja Makwasa, and John Nkondora who have been supportive in many ways since I arrived in Stockholm.

There are many individuals and institutions in Tanzania who facilitated the experiments carried out as part of this thesis. My special thanks go to Prof. John Kondoro, principal at Dar Es Salaam Institute of Technology (DIT); Theophilus Mlaki, a retired director at the Tanzania Commission for Science and Technology (COSTECH); Dr. Hassan Mshinda, director general at COSTECH; and Robhi Machaba, CEO of Juasun Ltd.

Last but not least, my thanks go to my wife and children. From the depths of my heart, I would like to thank my wife Mary for her support and love during my long student term life. Thanks to my kids Lucy, Lucas and Samuel. A special thanks to my father, Dr. Samwel Kitugi Nungu for his endless support and encouragement, especially when I was about to give up during the MSc level where this journey started. Thank you Gerd Holmedahl Nungu for your love, support and understanding. Thanks to my aunts, uncles and siblings Emmanuel, Wictor, Sandra and Magori.

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Definitions

First Mile: This is the link from a user to point of presence of service providers. This link is often owned by the user.

Last Mile: This is the final leg of delivering connectivity from a communications provider to a customer. The actual distance of this leg may be considerably more than a mile, especially in rural areas, but can also be shorter. This link is mostly owned by the service provider.

Anchor Customers: Are established institutions with a steady income, such as the public sector (school, health, and governance), military, tourist service providers and conference centers.

Universal Service Policies: These are policies focusing on promoting or maintaining "universal" availability of connections by individual households to a public network facilities and services at affordable prices.

Universal Access: Refers to a situation where every person has a reasonable means of access to publicly available network facilities and services. Universal Access is typically provided through pay telephones, community telecentres, community Internet access terminals and similar means.

Open Access to Communication: Refers to a situation where anyone can buy services at any lower layer at reasonably cost related tariffs and provide services on any higher level in the layered hierarchy.

Digital Divide: Defined as the gap between those individuals and communities that have, and do not have, access to the information technologies that are transforming people's lives.

Included Papers

This thesis includes, summarizes and discusses the results presented in eight papers, listed below. These will be referred to as Paper A - H.

Paper A Amos Nungu, Björn Pehrson, "Interconnection of Broadband Islands in Developing Regions", IEEE 3rd International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities (IEEE TridentCom 2007), Orlando, May 2007.

Paper B Amos Nungu, Nsubis Genesis, Björn Pehrson "Serengeti Broadband", The 2nd ACM SIGCOMM Workshop on Networked Systems for Developing Regions (NSDR 2008), Seatle, August 2008.

Paper C Amos Nungu "Analysis of the Serengeti Broadband Network", KTH-Technical Report: TRITA-ICT/ECS R 11:02, ISSN 1653-7238, ISRN KTH/ICT/ECS/R-11-02-SE, ISBN 978-91-7501-088-5, August 2011.

Paper D Amos Nungu and Robert Olsson and Björn Pehrson, "On Powering Communication Networks in Developing Regions", 16th IEEE Symposium on Computers and Communications (IEEE ISCC 2011), Corfu, Greece.

Paper E Amos Nungu and Robert Olsson and Björn Pehrson, "On the Design of Inclusive Ubiquitous Access", The 3rd International Conference on Ubiquitous and Future Networks (IEEE ICUFN 2011), (Received Excellent Paper Award).

Paper F Amos Nungu, Terrence Brown and Björn Pehrson; "Challenges in Sustaining Municipal Broadband Network in the Developing World", Published in "Springer (LNCS), Communications in Computer and Information Science (CCIS) Series" of 2011, Vol 171, pg 26-40.

Paper G Amos Nungu, Terrence Brown and Björn Pehrson; "Business Model for Developing World Municipal Broadband Network - A Case Study". Global Information Infrastructure Symposium (IEEE GIIS 2011)

Paper H Amos Nungu, Björn Knutsson and Björn Pehrson "On Building Sustainable Broadband Networks in Rural Areas", Technical Symposium at ITU Telecom World 2011 (ITU WT11). Geneva, Switzerland, October 2011.

Comments on My Contributions

This thesis has been carried out in the context of ICT for Rural Development (ICT4RD) Program [34], implemented in Tanzania. In all the papers listed, I have been the primary contributor. I have coordinated and integrated all activities and been responsible for the implementation of the results on the ground, producing requirement specifications, collecting and analyzing data. I also supervised all the master students who worked on the program. Rather than list my contributions, I will list the contributions of others:

For the work presented in papers A, Björn Pehrson contributed to the original idea, discussion and editing.

The work in paper B, Nsubis Genesis contributed in the design of the network, implemented the actual network as part of his master thesis work. Björn Pehrson contributed to the discussion.

For the work presented in paper D, Robert Olsson designed the charger controller and provided the wind and solar data logger while Björn Pehrson contributed to the original idea and the discussion.

For the work presented in paper E, Robert Olsson provided the software to run on the router and supervised students who assembled the router, Bjorn Pehrson contributed to the original idea and the discussion.

For papers F and G, Terrence Brown contributed to the original idea and discussion while Björn Pehrson contributed to discussion and editing.

In paper H, both co-authors contributed to the discussion.

Related Publications

1. Amos Nungu and Björn Pehrson, "Towards Sustainable Broadband Communication in Rural Areas", 5th International Conference on Access Networks (LNCS, AccessNets 2010), Hungary, November 2010. (Paper in proceedings, presented as a poster)

2. Amos Nungu, Robert Olsson, Björn Pehrson "On the Design of Affordable and Green High-Performance Routers for Community Networks", the 4th ACM Workshop on Networked Systems for Developing Regions (ACM NSDR 2010), San Fransciso, June 2010. (Short paper, with referees)

3. Amos Nungu, Björn Pehrson "Impact of ICT in Rural Areas: The Case Study of Chalinze ICT Center in Tanzania", 7th Open Access Conference, Accra Ghana, November 2009. (Full paper, with referees)

4. Amos Nungu, Björn Pehrson "Challenges On Deploying Community Networks in Rural Developing Regions", the 1st Workshop on Wireless Broadband Access for Communities and Rural Developing Regions - WIRELESS4D'08, Karlstad, Sweden, December 2008. (Full paper, with referees)

5. Antoine Bagula, Marco Zennaro, Amos Nungu, Mayamiko Nkoloma, "Bridging the Digital Divide in Africa: A Technology Perspective", in Proceedings of the 2011 Wireless Communication and Information (WCI 2011) on Digital Divide and Mobile Applications, ISBN: 978-3-86488-000-1, Berlin Germany, 20-21 October 2011.

Most of the contents of these papers are included in the papers presented in this thesis.

Contents

Chapter 1

Introduction

In this thesis, I will argue that societies and citizens in developed and less developed regions have the same Information and Communication Technologies (ICT) needs. Since over three-quarters of the world's poor live in rural areas of less developed regions [1], they have more need for ICT to contribute to their socioeconomic development than the developed regions.[1] However, while voice networks increasingly penetrate rural and remote areas in the developing world and have made an enormous difference, this does not apply to broadband networks. Since the communication infrastructure in less developed regions, especially Africa, is still significantly behind, the digital divide is increasing rather than closing.

Apart from poverty, the reasons for the broadband penetration difference include the following: Foremost is the late shift in the focus of development cooperation partners from supporting agriculture based to supporting knowledge based economy. Second, a legacy of political unawareness and negligence resulting in non-permissive or under-developed and not enforced policies and regulatory frameworks that create political and commercial risks. Lastly, an overestimation of the market forces, especially the willingness of commercial providers to invest in high-risk projects, causing lack of supporting infrastructures such as optical fibre networks, electrical power and developed supply chains.

The goal of this thesis is to provide answers to the question - "how to establish sustainable broadband markets in under-served areas". These are areas that are often described in terms of low-population density, low purchasing power, poor communication infrastructure, and lack of a developed supply chains and human resources with relevant competencies. Instead of waiting for the commercial providers to build last mile solutions, there is a need to advocate first mile initiatives from the end users to create broadband islands, which are high speed local areas networks. Due to poverty and as a way of capacity building, resource sharing and the use of open source solution to address the communication infrastructure challenges is

[1] Theme of the World Telecommunication and Information Society Day (WTISD) day, 17 May 2011, was "better life in rural communities with ICTs"

encouraged. Sustainability to these initiatives calls for an institutional framework that provides local leadership and ownerships of the process.

Next section will discuss previous efforts to introduce ICT in under-served areas from united nations and its agencies.

1.1 Previous Efforts to Bring ICT in Rural Areas

Development cooperation partners, financial institutions and the United Nations (UN) agencies realized the power of ICT to fight poverty in under-served areas long time ago. Some of the efforts in the last ten years can be traced as follows:

- In September 2000, world leaders came together to adopt the United Nations Millennium Declaration, committing to a new global partnership, the Millennium Development Goals (MDGs) consisting of 8 goals and 18 targets to reduce extreme poverty by 2015 [2]. The eight goals are: eradicating extreme poverty and hunger; achieve universal primary education; promote gender equality and empower women; reduce child mortality; improve maternal health; combat HIV/AIDS, malaria and other diseases; ensure environmental sustainability; and develop a global partnership for development. The 7th target (F) of the 8th goal is relating to ICT, stating that "in co-operation with the private sector, make available the benefits of new technologies, especially information and communications."

- In November 2001, the UN ICT Task Force was created to provide policy advice to governments and international organizations for bridging the digital divide [3]. One result from the Task Force was the establishment of Global e-School and Communities Initiative (GeSCI), a not-for-profit organization to provide demand-driven assistance on a policy level to developing countries seeking to harness the potential of ICT, improving the quality of teaching and learning in primary and secondary education [4].

- In December 2003, UN sponsored the "World Summit on the Information Society (WSIS)" conference, held in Geneva, to bridge the so-called global digital divide separating rich countries from poor countries by spreading access to the Internet in the developing world [5]. A follow-up conference was held in Tunis in November 2005.

- The 2009 world bank report on Information and Communication for Development observed a correlation between broadband connections and the economy of a region [6].

- In 2010, ITU and UNESCO together established the Broadband Commission, with a mission to promote the adoption of broadband-friendly practice and policies so that all the world's people can take advantage of the benefits of broadband [7]. The commission does define broadband by referring to three

characteristics of always on; high capacity; and being able to provide voice, data and video [8]. ITU also has a bold broadband vision, stating that *build on broadband and the rest will follow*, indicating that broadband drive social and economic development, and accelerating progress towards the MDGs [9].

1.2 Challenges when Introducing ICT in Under-served Areas

Apart from policy and advocacy issues, most previous implementation efforts to introduce ICTs in under-served areas have been focusing on creating telecentres. Telecentres are defined as public places where people can access computers, Internet, and other digital technologies that enable them to gather information, create, learn, and communicate with others while they develop essential digital skills [10]. However, as these efforts were made to projects, they had a limited time frame. A wide range of issues that were not dealt with, such as undeveloped supply chains to take care of the recurring technical problems, and lack of business and management skills caused most of the telecentre initiatives to fail as soon as the initial funding finished [10, 11]. Moreover, Internet access costs are extremely high in the developing world due to the dependency of satellite links [12].

We argue that the main reasons for the failures were due to lack of understanding of the local needs and total focus on Internet access. Most of the implementation decisions were made elsewhere (a top-down approach) without involving the local communities, causing a lack of ownership at the local level. As a result of this top-down approach, most technical solutions were imported from the developed world, not optimized to work under the local constraints such as unstable power supply, inexperienced users and lack of local skilled technical support. An evidence supporting this argument is the fact that one of the few successful examples coming out of the telecentre idea that we are aware of is a pioneering center in Sengerema, Tanzania, where the telecentre was complemented with a community radio station actively collecting, disseminating and discussing information from Internet of interest to the local community [13]. Once this initial phase is well understood and implemented, we assume there is no difference in communication needs between developing and developed regions.

These observations led to the idea to start focusing on the need for communication in the local community instead of Internet access. Rather than waiting for last mile connections from commercial providers, the local community could establish their first mile networks, connecting to the outside world when needed.. We will now discuss three areas that we feel form the basis for this thesis. First, the feasibility of starting building local area networks, later extending these networks to the point of presence of a commercial service provider when available. Second, how to make up for the lack of the communication infrastructure necessary to build networks. Third, how to make up for the lack of an institutional framework to provide ownership, leadership, and network operational guidelines.

First Mile Initiatives

Communication infrastructure is as vital to a modern knowledge society as roads but are traditionally handled differently, leaving the former to the market forces to establish while the latter are mostly a public concern. We advocate exploring the reasons for this, at least in the topologically defined market segment that is addressed by universal access fund financing but more generally in the layered model of communication starting bottom-up from passive cables, active links, switched or routed networks, end-to-end transport connections, communication services and applications. In the road analogy, government provides the passive road, and anyone can walk or drive on the roads. This could be translated to government providing the communication medium (for example an optic fibre), which is already the case regarding radio spectrum, and anyone can lease passive fibre to provide active links, networks, services and applications. In an Open Access model, anyone can buy services at any layer at reasonably cost related tariffs and provide services on any higher level in this layered hierarchy [14].

Traditionally, telecom companies own the infrastructure and establish links from their backbone and access networks towards the customer premises, thus establishing last mile connectivity. However, due to the various challenges found in under-served areas to be discussed later in this thesis, last mile connectivity is not provided evenly due to the involved risks and profitability. Hence, if there is a demand strong enough, the users themselves need to take initiatives to build their own networks that will be connected to the service provider networks. This is the first mile network.

Communication Infrastructure

ICT and broadband in particular requires communications infrastructures such as communication links that can be used to provide connectivity and reliable power supply needed for powering network equipment as well as end-user nodes to operate. Under-served areas lack legacy communication infrastructures, hence are faced with a shortage of infrastructure resources that may require substantial capital investments. There is also a need for adequate network equipment having the robustness and performance required, while at the same time being power-lean and affordable.

Unless already provided by the private sector, it is a public sector responsibility to deploy the infrastructure and make it available for anyone to use to provide services to the general public as well as to satisfy dedicated needs, just like roads and other infrastructure of importance for the development of the society.

Institutional Framework

Traditional business models and organizational mechanisms, which are guided by established supply chain, do not work in under-served areas.

On the producer side, there are high estimated risk levels resulting from analyses based on traditional business models. Since many of the infrastructure resources required are missing, the investment level is potentially high. Since the customer base is immature and its size uncertain, so are the revenue estimates. The challenge includes the establishment of a reasonably complete local supply chain, including network and service operators, equipment vendors, trainers, user-support, hosting services, software development, etc.

On the consumer side, there is often low awareness and preparedness to act, lead and own the communication infrastructure to create the first mile initiative. Besides the establishment of the broadband network and services, the user community is required to transform their business processes to take advantage of the new services. On the policy and regulatory side, there might be obstacles in the regulatory framework, such as licensing requirements, etc.

On financing, financial institutions require collaterals before they can provide loans to prospective borrowers. Due to financial risks found in under-served areas, either the financial institutions demand higher collaterals, or the borrowers does not have any acceptable collateral to offer. Few business entities that already have the financial means do not see the business value (profit) in rural areas, hence will never invest there. This leads to lack of adequate financing for positive value investments.

1.3 Approach to Problem Solving

The overarching goal is to reduce the involved risk levels iteratively by demonstrating feasibility. This is best done by deploying pilots, demonstrating their use and collecting the statistics and other data necessary to make detailed risk assessments. Learning from failures in the telecentre initiatives and the success of mobile phones, we propose the creation of self-sustained local area broadband islands defined as local area networks that provide services in a local community with a capacity that is not limiting the spectrum of services.

Our work is in the area of Information and Communication Technologies for Development (ICT4D or ICTD), the general term related to the application of ICT in development programmes in countries facing acute problems like poverty, illiteracy and a general lack of developed infrastructure [15]. Given its combination of research and development, ICT4D brings together many actors in different roles [16, 17]. Hence, an Action Research approach was chosen for carrying out the research. Thus, working with selected communities, we choose to address the problem using participatory Action Research and interpretive research approach. Action Research is defined as a research approach which has dual aims of action and research: action to bring change in the community and research to increase understanding on the part of the researcher, the community, or both [18]. The approach aims not only to discover facts, but also to help alter certain conditions experienced by the community as unsatisfactory with the intention to help the participants to

control their own destines more effectively [19, 20].

The proposed solution aims at establishing networks to serve local communication needs, even if there are currently no, or only narrowband, external connections due to the unavailability or exorbitantly priced uplinks. The lack of reliable power supply is addressed by designing and deploying power supply controllers as well as proposing the use of alternative sources and storage. The lack of availability of network equipments is addressed through the design and assembly of high performance, low-power consumption devices, using readily available hardware components. For the institutional framework, the thesis proposed organizational mechanisms and revenue models based on literature and observations from the deployed networks.

Building Broadband Islands

Participatory Action Research involves participants in both the research and change process, integrating research and action in an ongoing, participatory process [21]. The process also include searching for relevant concepts and recruiting candidates who would enhance the implementation of the solution [22].

The strategy we propose is using a collaborative, participatory approach to launch first mile initiatives while waiting for the access networks and last mile links of commercial providers to arrive. The first mile initiative is key in our research for the fact that users themselves know their needs as well as the challenges surrounding their areas. Hence, a successful solution should come from the users themselves by directly coming up with the solution or being involved in defining the problem, designing the solution and in the implementation process.

The first step is to do a need analysis to determine what kinds of resources are available in order to maximize their use. The analysis should include stakeholders and the supply chain. The approach to raise awareness and stimulate the demand is through identifying local ICT services and applications that matter, that can improve the lives of the local population according to national strategies for rural development and poverty alleviation.

The lack of trained staff is addressed through capacity building programs, training seminars and provisioning of scholarships for higher education. The capacity building programs are divided into three levels: End user level on how to use broadband services, creating ICT literacy; Technician level who deploy and manage the services; and Professional (advanced) level, creating experts who design systems and discuss policy issues affecting under-served areas. Capacity building programs involve students and faculty members at nearby training institutions as well as other stakeholders to reduce cost as well as enhance the multi-stakeholder approach. The students could be learning towards master and doctoral level degrees while the faculty members are supervising the students or doing research for better understanding of local needs and environments as well as academic merits.

Next, we discuss an approach to address the communication infrastructure and institutional challenges presented in section 1.1.

Communication Infrastructure

To address the challenges related to communication infrastructure, we propose the following: Any local infrastructure owner should be approached to negotiate access to excess capacity in order to establish communication links for the network. If they do not exist, the options are to deploy optical fibre, use terrestrial wireless links, organize scheduled physical transport of data between nodes, or use satellite links if broadband is available and affordable. The fiber communication technologies outperform the alternatives and have matured to a point where they are affordable and easy to use. The main cost is in associated civil works which is considerably low in rural and under-served areas.

On the network equipment side, the personal computer technology has matured to a robustness and performance level that makes it possible to design affordable routers up to 10Gpbs with both optical and copper interfaces using carefully selected hardware commercial off-the-shelf components and free, open source routing software.

To arrange reliable power supply may imply the innovative use of alternative power sources, such as the renewable solar or wind, and energy storage, such as ultra-capacitors. The power management should be integrated with the network equipment for graceful shut down in case of power failures.

The Institutional Framework

The ownership of such a first mile initiative starts with individual entrepreneurs mobilizing the community to establish a social business in one form or another resulting in public-private partnerships, successively increasing the private part and decreasing the public. This may be a long process, over a decade or two. The point is that the community value externalities in a way that commercial actors cannot. First mile initiatives also require more adequate business models that regard a broadband network to be a utility for development, a social business [23], rather than a profitable business in its own right. This is an Action Research in nature because it is participatory and outcomes of the research address real-life problems in the respective communities.

The community network proposal begins with looking at basic public sector e.g. education, health and local government, treating them as *anchor customers* of the proposed network, aiming at improving their service delivery. Depending on the technology selected, initial resource mobilization include securing a piece of land for erecting masts or space on existing communication tower in case of terrestrial wireless, right of way or getting a pair of fiber in case of optic fiber, and an office space to host the servers. For the monetary resources, the funding is from different sources as well, such as stakeholders investments (the anchor customers), via e.g. a loan; loan from the central government on behalf of the anchor customers; aid or grant from donor countries; and soft loans from development partners. In-kind contributions could include volunteering time and skills relevant at setting up the

broadband services.

The value added via externalities may result in new revenues or cost savings in other parts of the budgets of the community and other local stakeholders using ICT, motivating them to invest and pay running costs for connectivity and local contents. The development of the supply chain will happen gradually. It will create new business and job opportunities and should involve all local competent human resources, public or private. As the market develops, the transformation from first mile social businesses to the last mile commercial businesses is desirable to create competition that can control cost efficiency and pricing.

Summary of the Proposed Solution

Our proposed solution is represented in the overall broadband market ecosystem summarized in Figure 1.1 where:

- Use commercial-off-the-shelf (COTS) hardware and open source software to create affordable technical solutions to facilitate delivery of broadband services;
- The offered broadband services:
  - Enhance service delivery in the public sector.
  - Create business opportunities, resulting into employment opportunities that will alleviate poverty, resulting into promoting social life.
  - Businesses will also pay tax to the government, boosting the economy.
- However, the implementation process require multi-stakeholder approach from policy makers, infrastructure owners, academia, etc.; public investments to cover the initial costs; the availability of enabling policies; and an organizational framework to harmonize and coordinate all stakeholders.

1.4 Research Methodology

In this thesis, we investigate how to establish sustainable broadband markets in under-served areas by addressing three main issues of: using the broadband islands concept as a way to build first mile networks, how to make up for lack of communication infrastructure, and how to make up for lack of the institutional frameworks.

In Action Research, there are five repetitive, cyclic stages: diagnosing, action planning, action taking, evaluation, and specifying learning as summarized in Figure 1.2 [24]. The phases feed into each other, making an Action Research more an ongoing process than an event.

The research methodology adapted was an experimental, based on iterative system design that fits well with the cyclic phases of Action Research to address the

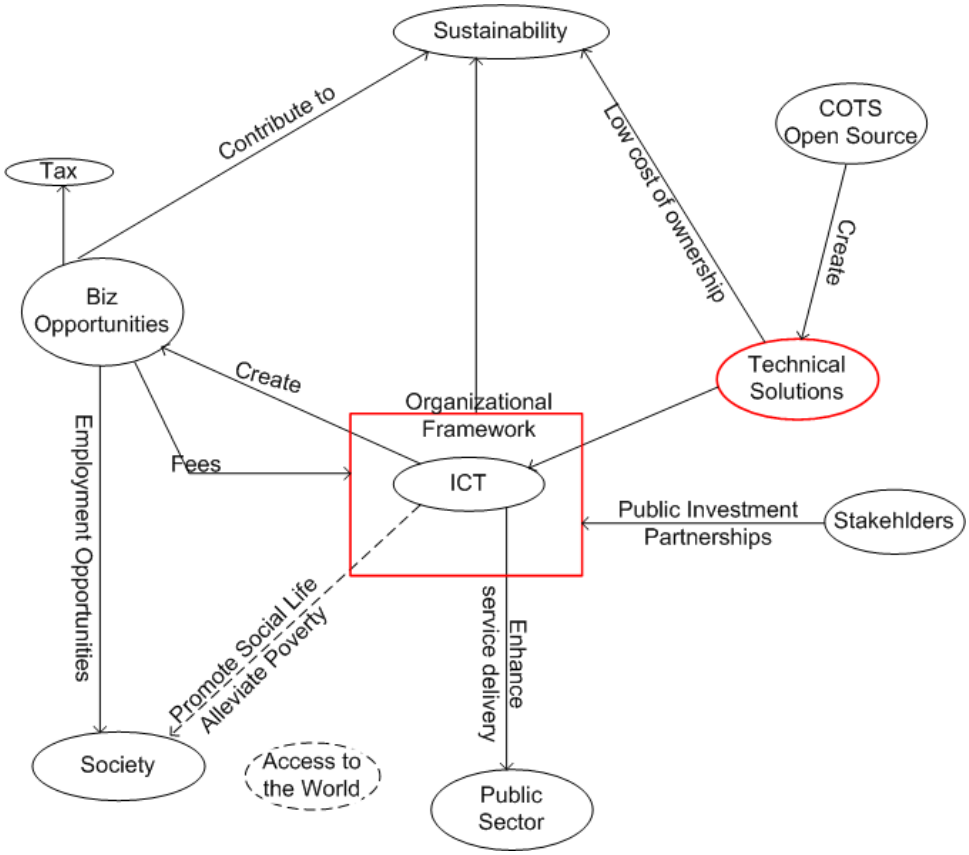

Figure 1.1: Ecosystem in Sustaining Broadband Markets in Under-served Areas.

communication infrastructure part. Interpretive approach [25] was used to complement the experiments in addressing the creation of an institutional framework.

The research started by defining and deploying two broadband islands that was later used to study, evaluate and validate the communication infrastructure needs and the institutional framework requirements. We used the experimental evaluations to address the lack of communication infrastructure by literature review and gathering data from the field; developing requirement specifications; designing; implementing and evaluating results iteratively. We complement the experiments using interpretive approach through observing, evaluating and describing scenarios to propose suitable institutional frameworks. The interpretive approach was used to delineate the socio-technical processes involved in the implementation of broadband islands, from the perspective of various heterogeneous actors. The approach was also useful for explaining the social and organizational context of institutional

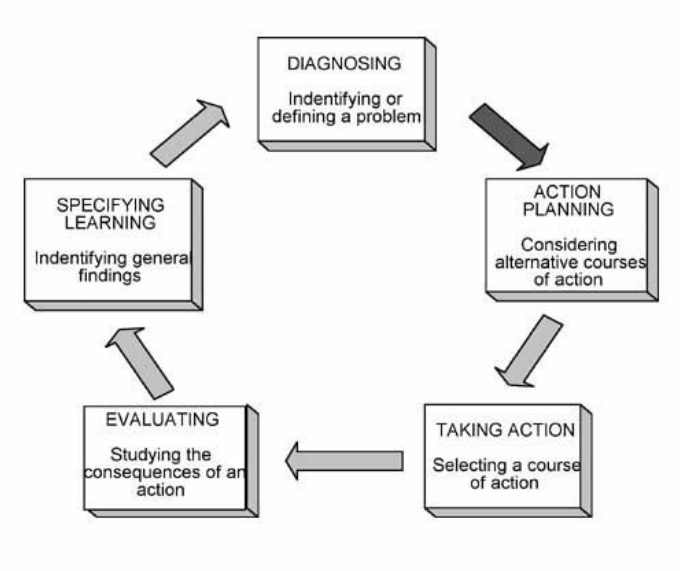

Figure 1.2: The Action Research Process Model. Source [24].

mechanism. Relating to the cyclic stages of Action Research, the diagnosing stage was done earlier during the research proposal writing and problem formulation. The three stages of planning, acting, and evaluation, are undergone by all three challenges: first mile networks, communication infrastructure, and institutional framework. Later we specified the learning by revisiting the whole process, proposing a model describing the situation under study.

Paper A through C are about the establishment of the first mile networks; paper D and E are on the communication infrastructure while paper F and G are on the creation of an institutional framework. Paper H provides the overall solution to build, sustain and scale broadband islands, taking into account the challenges in the communication infrastructure and special institutional framework.

On the first mile initiative challenge, papers A, B and C corresponds to the planning, acting and evaluating stages respectively of the Action Research cyclic model. Motivated by the lack of last mile networks in under-served areas, paper A started by revisiting the broadband island concept, providing guiding principles on its design, deployment, sustainability and scaling up. As a proof of concept as well as constructing a pilot network to investigate characteristics of broadband islands networks, paper B is about the actual design and deployment of the broadband islands. Paper C analyze usage of the network deployed in paper B to determine its usefulness from the user point of view as well as understand kinds of services they look for on the Internet. The study was performed to end users through observations, running surveys and questionnaires. Another set of observations was

done by analyzing captured traffic logs at the gateway to determine surfing behavior, traffic trends, what protocols are most popular, and comparing data from the logs to that collected via face to face interviews and questionnaires.

On the communication infrastructure challenge, both paper D and E undergone the planning, acting and evaluating stages of the Action Research cyclic model. Motivated by lack of communication infrastructure in under-served areas, the experiment in paper D is on the availability and quality of power supply. Its goal was to determine the quality of the national grid, and the feasibility of wind and solar as alternative energy sources. On the quality of national power grid; we studied the frequency and duration of power outages per day, captured via a number of reboots in our monitored routers. On the alternative energy, we measured the intensity of the sun and the speed of the wind for six months; both figures were compared to literature. Through an iterative system design, a power controller was designed that can take various inputs from the main grid, solar or battery, to provide a range of variable outputs. The experiment in paper E is on network elements, motivated by the lack of affordable, and power aware network equipments. Using the network deployed in paper B, we gathered requirement specifications, designed implemented, and deployed an infrastructure router. Two key requirements for the router were defined as being its throughput and power consumption level. The throughput requirement was being able to forward packets at 1GB/s supporting both fibre and copper connections, while the power consumption level requirement was being able to operate using a 12V battery. Iteratively, the router has been refined to improve the forwarding performance to power consumption ratio.

On the institutional framework challenge, both paper F and G undergone the planning, acting and evaluating stages of the Action Research cyclic model. Through observation and evaluation of stakeholders and related processes in the broadband island established in paper B, we proposed an institutional framework for providing an organizational mechanism and a business model necessary to operate and sustain broadband islands. Motivated by the need for ownership and local leadership, paper F studied the organizational mechanism, taking into account the local politics and established rules in a multi-stakeholder approach. Paper G proposed a business model that regards the broadband services as a utility, similar to water etc. Thus, requesting public funds to cover initial costs while striving to raise enough revenue through various means to cover the running costs.

Paper H corresponds to the learning process stage of the Action Research cyclic model. Based on the experiences gained throughout the execution of the research, this paper summarizes the overall approach on how to establish sustainable broadband markets in under-served areas through the broadband island concept. The paper provides a model on how to establish these networks by conducting needs analysis, identifying stakeholders, mobilize resources, designing, deploying and sustaining the implementations. In the process, the paper highlights on how to solve the communication infrastructure and the institutional framework by making reference to the above published papers. The deployment strategy is summarized in Figure 1.3 in a form of a model.

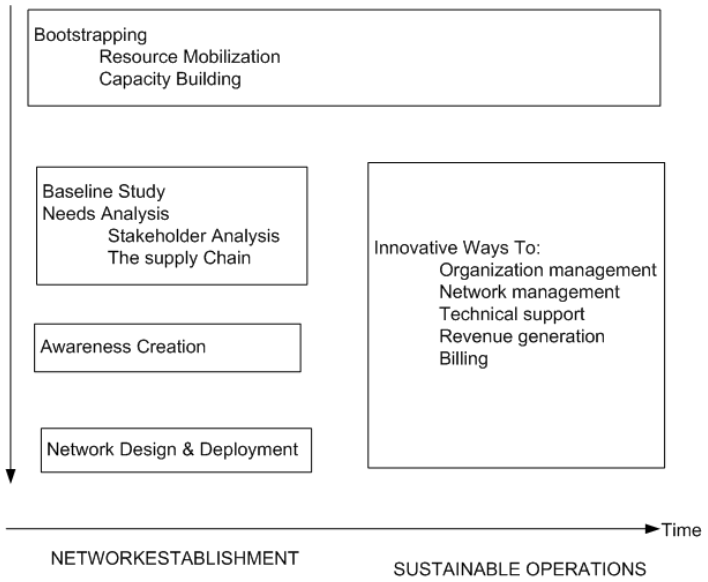

Figure 1.3: A Model for Creating Broadband Markets in Under-served Areas.

1.5 Contributions and Outline

The major contributions of this thesis are:

1. A validated, reproducible and scalable model for the establishment of community networks based on a collaborative, participatory approach. The Model includes resource mobilization, capacity building, needs analysis, awareness creation, network design and deployment, and sustainable operation.

2. The design and validation of affordable, robust, and power-efficient communication infrastructure solutions.

3. A successful institutional framework for local ownership and leadership to operate community networks sustainably.

The broadband island, as an approach to implement and sustain first mile initiatives is introduced in chapter 2. The chapter later describe two broadband islands used in this study which were implemented in Tanzania. Chapter 3 provides background information about ICT development for the Tanzania country. Further, the chapter provides background information, and related work of the three issues addressed in this thesis: the community approach to build broadband networks in under-served areas, the lack of communication infrastructure, and the lack of institutional mechanisms. A summary of the publications included in this thesis,

highlighting contributions for each paper as well as how they contribute towards the overall work is provided in chapter 4. Chapter 5 provides conclusion and recommendations for future work while summary of the publications included in this thesis is provided in chapter 6.

Chapter 2

Broadband Islands

This thesis adapts a definition of broadband as proposed by the 2010 WB report on Building Broadband: Strategies and Policies for the Developing World [26]. The report proposes that broadband be defined beyond the traditional notion of a specific type of network connectivity or minimum transmission speed. Rather, that broadband be viewed as an "ecosystem" that includes its networks, the services that the networks carry, the applications they deliver, and users.

The purpose of this chapter is to elaborate the broadband island concept and its implementations in detail. The discussion will start by defining the broadband island and looking at the reasons to why we propose this approach. Then, followed by a discussion on how to implement broadband islands, including a discussion on how to address the lack of communication infrastructure and institutional framework challenges found in under-served areas. Lastly, the chapter will present an implementation that was used to demonstrate the proof of concept in deploying and sustaining broadband islands.

We use the terms "local" and "community" networks interchangeably to refer to the district or municipal networks. Broadband is referring to the local network, not necessarily the uplink.

2.1 What and Why Broadband Island

We define a broadband island as a self sustained local area network that provides services in a local community with a capacity that is not limiting the spectrum of services. Self sustained refer to the ability to host network services and user applications within the local network. There are many advantages for the first mile initiative, mentioning a few: it is a bottom up approach where the users know their local needs; contents could be produced in local language specific for the local market (no language barrier); imported content could be saved locally to avoid uplink costs; provisioning of local communications channels; sharing the slow and expensive Internet connections; and, first mile initiatives allow collaborations and

cooperation between different entities.

Building and interconnecting broadband islands is not a new idea as such, conferences relating to this topic have been running before [27, 28] and [29]. The contribution of this thesis is rather on three things: the focus, emphasizing local connectivity in under-served areas; the collaborative approach, involving community members; and the proposal for new institutional mechanisms that support the established broadband islands. Our approach is to establish the local area networks where they do not yet exist, as broadband islands, and, as soon as possible, connect them to Internet, e.g. by sharing an existing telecenter uplink or waiting for an opportunity to access the national backbone. At the same time, addressing the communication infrastructure and institutional mechanisms challenges in cooperative efforts.

The purpose is to facilitate the development of basic public sector services required to progress towards the MDGs, primarily healthcare, education, local administration and support to local entrepreneurs. Initial applications include VoIP and email services to facilitate general communications between various connected entities, telemedicine for consultation between rural health centres and district or referral hospitals, tele-teaching and sharing of learning material between schools, public administrative services, portal for market information, marketing of local entrepreneurs, etc. In some cases there already exists an upstream connection via VSAT, mainly through projects or a telecenter. Thus, having a network near or around this connection means that users can share the upstream costs.

2.2 How to Implement Broadband Islands

In our approach to establish broadband islands, implementation start as a single island connecting users in the local community, e.g. schools, hospitals, government offices, etc. The initial size depends on availability of the individual entities willing to participate. The simple motivation is to share an uplink available to a telecentre by extending that link to nearby schools, hospitals and local government offices. A server is located to one member so that they can host simple services such as email and Voice over IP (VoIP).

Scalability is achieved by either expanding existing broadband island, connecting nearby village/town as awareness and resources arise, or join two or more islands existing already to gain overall wider coverage and the network effect so as to increase resource sharing.

Multiple Internet Connections

One major benefit of building the broadband islands is to share expensive resources, including the uplink connectivity. In cases where there is more than one upstream as a result of connecting multiple islands, there are two options. The first option is to keep a single upstream, upgrade its capacity so that each user can get higher capacity for the same amount of money, assuming that not all users will go online

at the same time. The second option is to keep two upstream, use one as a main upstream while the other as a backup, or perform load balancing to provide network resilience.

The second option is less desirable in under-served areas context for two reasons. First, resilience is not as important as high capacity given the price and scarcity of Internet. Also, noting that most of the time both links will come from the same provider, it means that any upstream problem will affect both links. The second reason concern the complexity introduced by having a backup link or load balancing as this will require sophisticated equipments and more technical know-how. Also, if it happens that the backup link is on the leaf of the network connected via a wireless link, it might be that the local link will be the bottleneck.

Technology and Services

We noted in chapter 1 the lack of legacy communication infrastructure in under-served areas. This section discusses the kind of technology and services used to build the broadband islands.

Technology Selection

There are many mature link level technologies for building broadband communication networks; however, the poverty level and lack of trained technical staffs are among things that necessitate technology selection.

Technology selection at a specific location is affected by the demand for services, the regulatory environment, the physical environment, and what is possible to implement and maintain sustainably. Four technologies: Optical Fibre Links, Terrestrial wireless, VSAT and Delay Tolerant Network are presented here.

Optical Fibre Links has high capacity and durability but requires specialized training and tools for installation and maintenance. Any civil works involved in fibre deployment is expensive although there are sometimes innovative cooperative approaches to this in rural areas. There are examples from rural areas of developed regions where local inhabitants sitting on the right of way and appropriate machinery, contribute the civil work part while the telecom or power utility company provides the fibre cables and active network elements [30].

Terrestrial wireless, three candidates are discussed.

- WiFi: The IEEE 802.11 a, b, g and n standards offer maximum throughput of 54, 11, 54 and 65 Mbps respectively in the license-free 2.4 or 5 GHz frequency bands [31]. This is cheap and easy to install technology; it is the obvious starting point in a community network unless there is optical fibre available.

- WiMAX: The IEEE 802.16 standards, with maximum throughput of 144Mbps [32]. Wimax operates in licensed spectrum and is currently used mainly by commercial operators, therefore, less interesting in the initial phase of community network.

- 2.5G/3G: Mobile coverage for voice is almost everywhere, but data, at a broadband capacity is mostly available in urban areas only. This is due to the fact that data volumes are too high for the traditional microwave backbones of the mobile phone operators and require access to a fibre infrastructure.

Very Small Aperture Terminals (VSAT) is satellite based solution, can reach almost every place on earth. However, it is very expensive solution that generally provides low capacity.

Delay Tolerant Network (DTN) protocol may use physical transport for bulk transfer of information. DTN can provide very high bandwidths but has a high latency, eliminating real-time services.

Network Elements and Services

For the lack of local ICT supply chain in under-served areas and due to the advancement of the PC-technology in performance and robustness, and the drop-down in price per storage, the communities should be trained to build their own routers and servers using open source software and commercial-off-the-shelf hardware as a way of reducing implementation and maintenance costs as well as local capacity building and knowledge transfer.

Initial application and services are guided by the awareness level as well as availability of resources. Results from the need analysis are useful to indicate the level of awareness as a basis to plan. However, the MDGs can be used as a guideline, starting with communication (email and voice) as these can be used by everyone and then introduce more advanced services based on readiness indicated in the needs analysis study.

Organization and management

Sustainability and scalability of the last mile initiative require local ownership and leadership. Since the thesis advocate creation of community networks, we propose the creation of a local entity to take ownership of the whole process to provide the necessary management and leadership. The entity could be formed in many ways such as public-private-partnership (PPP), community based organizations (CBO) or membership club. However, the emphasis should always be stressed to the participatory approach to have a community buy-in.

In [33], it is noted that CBO's are usually initiated by educated individuals who have roots in the community but do not live there, while the rest of their team members does not have any management skills. In areas where there are no strong civil society organizations that could take over the operations of the network, PPP is the best option at hand as it combines both the private, the government and the society being represented. Depending on the funding mechanisms, other options could include a members only club, purely publicly owned or purely privately owned.

2.3 The ICT for Rural Development Project

As a proof of concept to the broadband island approach, the thesis participated in two pilot communication networks, in Tanzania. These networks demonstrate the feasibility of the first mile initiatives as well a ground for studying and addressing the lack communication infrastructure and institutional mechanisms problems.

The Information and Communication Technology for Rural Development (ICT4RD) project in Tanzania [34] is a research and development project that was designed with a goal of creating a model for building and sustaining broadband communication networks in under-served areas.

Since 2007, ICT4RD is running two pilot sites, the Serengeti and Wami Broadband Networks. The Serengeti network is connecting two districts of Serengeti and Bunda, with a combined total population of about 5,000 people [35], is found in the Mara region, northern Tanzania. Wami pilot is in Bagamoyo district, about 70km north of Dar Es Salaam, the largest city in Tanzania.

Baseline Study

In the 2005 Poverty and Human Development Report [36], Serengeti and Bunda districts were ranked among the poorest districts in the country, positioned at 116^{th} and 119^{th} respectively out of 119 districts. In 2006, a baseline study was carried out in Serengeti and Bunda districts to benchmark the needs of ICT, focusing on education, health and local government [37]. A similar study was carried out in 2007 for Bagamoyo district [38]. Both studies revealed that: agriculture and livestock are carried out by 90% of the population; both districts rely on the central government for about 95% of their budgets; and a few organizations, public and private, have Internet via VSATs or dial-up, purchased using donor funds, usually via a project. The baseline study further noted that:

- Local government authorities (LGA) require reliable communication both to the central government and to the citizens, thus broadband connectivity would improve their efficiency.

- The education sector has shortage of teachers and textbooks. The use of broadband connectivity would facilitate e-learning to compensate for the deficits and improve the quality of education offered.

- There was lack of trained staffs in the healthcare sector, poor communication channels and insufficient facilities. Broadband connectivity could facilitate tele-medicine where the few available medical doctors would provide consultations to primary health centers via video conferences.

Funding, Partners and Capacity Building

ICT4RD was designed as a research and development project supported by the Swedish International Development Agency (SIDA)[1] and executed through a partnership between the Tanzania Commission of Science and Technology (COSTECH);[2] Dar es Salaam Institute of Technology (DIT),[3] Tanzania; and the Royal Institute of Technology (KTH),[4] Sweden. The project strategy is to build local broadband, community owned, communication networks that will create awareness among partners to stimulate the development of local markets.

In order to attract the necessary initial investments, the focus of the established network was on facilitating basic public services, including education, health and local government. The funds necessary to operate and maintain the network is provided through connecting all sorts of users willing to pay for connectivity. Additional services and applications have been implemented to develop the local market and increase the revenue stream, Internet is also provided through a satellite link. The project advocate sharing of resources and the buy-in of existing communication infrastructure wherever possible in order to reduce implementation costs. Another important part of the strategy to achieve sustainability is to establish and maintain strong ties with training institutions for capacity building and access to pools of technical students looking for apprenticeship opportunities to get experience working life [39].

The project conducted several ICT awareness raising workshops and training seminars. As part of capacity building, eight Tanzanians have been trained at a Master of Science level through the project. During their thesis work, all of them directly contributed to the design and implementations of the technical solutions. Also, most of the applications are developed or customized using students from the academic partners in collaboration with locals.

Serengeti pilot became operational late 2007 [40] while Wami pilot became operational in mid 2008.

Services, Applications and Users

In the ICT4RD networks, applications and services were guided by the outcomes of the baseline study. Both, Serengeti and Wami pilots are self sustained broadband islands with their own network services hosted locally. The idea is to facilitate communications and related broadband services within each sector and between sectors at a district level. In addition to the general services (Internet, email, web and voice), other initial services implemented were those related to the e-health and e-school.

[1] www.sida.se, May 2011
[2] www.costech.or.tz, May 2011
[3] www.dit.ac.tz, May 2011
[4] www.kth.se, May 2011

However, the project later realized that health and education sector operate in a centralized, top-down approach where proper adaption and utilization of e-health and e-school require coordination from the central government. As a result of this top-down approach, there was logistical challenges encountered including transfer of trained staff members to outside the pilot area, bringing in new, computer illiterate ones. Issues specific to education were the lack of digital contents as per the curriculum, hence material has to be digitized first before a teacher can make them available online; for distance learning, it requires time synchronization between participating schools, and no dedicated room to setup video conference sessions. Based on these challenges and the feedback received through observations, interviews and an analysis of network logs, the project focused on personal use to enhance the user experience and cultivate the use and appreciation of broadband services [41], also the focus went to optimization of the Internet through caching and creation of the document repository system as requested by the local government.

Connected users include government offices, health facilities, secondary schools, public resources centers and the private sector (individual homes, through Cafés, or offices).

Communication Infrastructure

The discussion on communication infrastructure is divided between the communication links and power supply.

Communication Links

On the communication link, ICT4RD model is about sharing of the passive infrastructure at cost-related basis. In both pilots, an optic fiber cable is used as backbone and WiFi for the last mile, connecting the end customers. For the Serengeti pilot, a pair of fiber cable is provided by the power utility company (deployed as part of their rural electrification program) while in Wami pilot, a pair of fibre cable is provided by the Ministry of water (implemented in their water supply system). As part of the agreement to the fiber owners, ICT4RD provides them an Internet connection in return to the use of the pair of fiber donated.

For the WiFi part, a mix of both 2.4 and 5GHz free spectrum band is used. Diagrams for Serengeti and Wami pilots are provided in Figure 2.1 and 2.2 respectively.

Power Issues

The Tanzania power generations is mainly hydro and thermal. Information from the power utility company indicates that from October 2009 up to September 2010, about 73% power generation was hydro [42]. Most under-served areas do not have electricity, and power blackouts are very common. The initial customers in ICT4RD were chosen based on having access to electricity, provided by the rural electrifi-

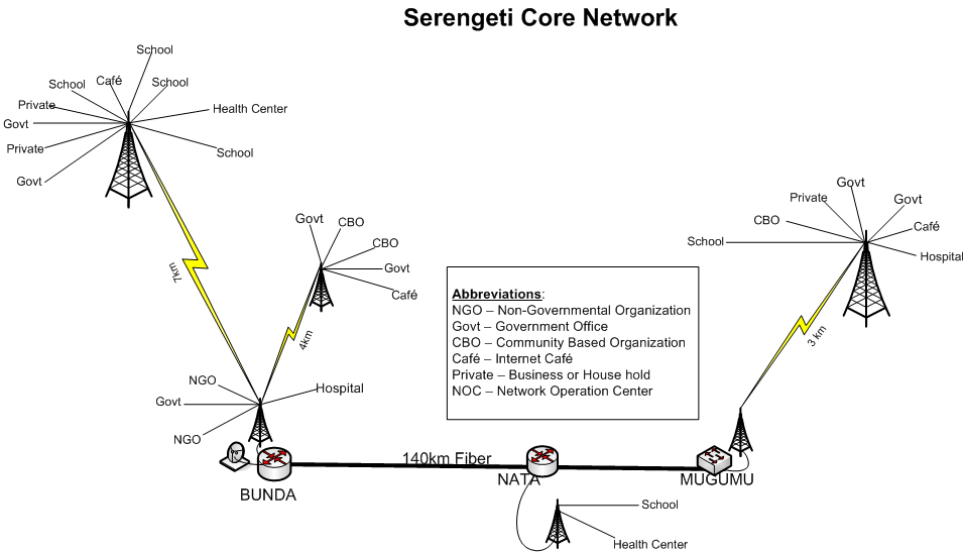

Figure 2.1: Serengeti Pilot Network Infrastructure.

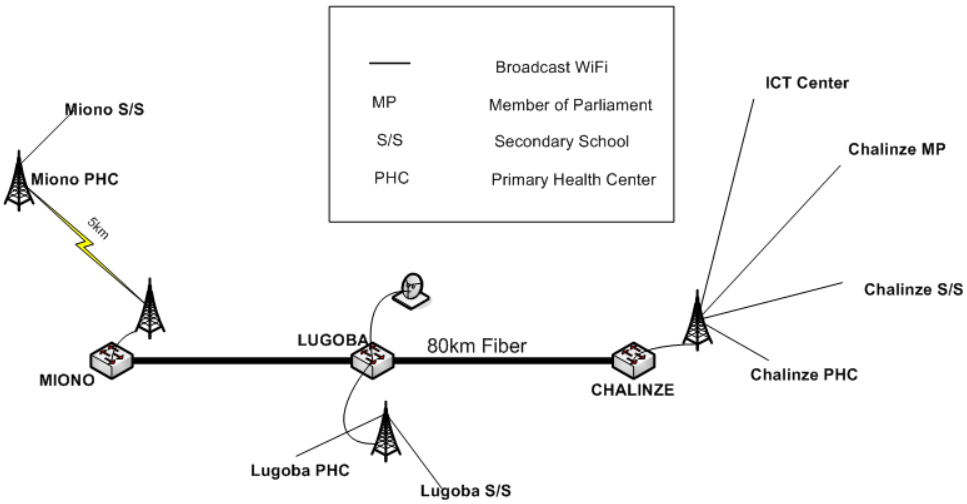

Figure 2.2: Wami Pilot Network Infrastructure.

cation program. Backup power to the network equipments was provided through deep-cycle batteries and uninterruptable power supplies (UPS). However, the batteries and UPSs were damaged very often due to the instability of the power supply, this situation lead to the design and development of power management systems

and the feasibility study of wind and solar as alternative sources of energy [43]

Institutional Framework

In terms of organization and management, Serengeti and Wami pilots are community-owned, in a public-private-partnership. In Serengeti pilot, we created a district ICT board, with a representation from local government, the private sector and the community represented by the civil society organizations [44]. Since the local government is not part of the connected users in Wami pilot, we created a community ICT alliance, with a representation from all connected sectors: education, health and community.

The only difference between the two pilots is the proximity of the municipal headquarters, hence local government authority being part of the network. We have experienced delays in creating the institutional framework in Wami pilot, the sense of ownership is not strong in Wami compared to Serengeti pilot. The weak financial performance in Wami pilot could be attributed to lack of private sector establishments and many established NGOs or entrepreneurs compared to Serengeti pilot, the district headquarter effect. This and the weak sense of ownership implies that the municipal has a major role to play in sustaining these implementations [45].

Chapter 3

Background and Related Work

In this chapter, some background that will help in understanding the work presented in the papers will be presented, along with comments on related work. The chapter will start by providing the background information about Tanzania and later discuss related work to the three research areas: first mile initiatives, communication infrastructure, and the institutional framework.

3.1 Tanzania

Tanzania is a reference country where the thesis created two broadband islands to demonstrate the concept as well as indicates their sustainability. To appreciate the need for broadband islands approach, this section presents the Tanzania country profile, regulatory framework, broadband penetration and national policies.

Country Profile

Tanzania, a country in East Africa is among the least developed countries in the world. According to 2010 the World Development Indicators, Tanzania has a GDP per capita of 523 USD, a size of 948,087 km^2 with a total population of about 42M where: only 57% of children aged 5-14 attend primary school, only 5% of the population have secondary education while only 1% has tertiary education. Access to electricity is available only to 14% of the population. The report also indicates that Tanzania has a mobile-phone penetration rate of 50%, the 4th in Africa, after Nigeria, South Africa and Kenya.

Regulatory Framework

The regulatory body, Tanzanian Communications Regulatory Authority (TCRA), was established in 2003 by merging the Tanzanian Communications Commission and Tanzania Broadcasting Commission to regulate telecommunications, broadcasting, ICT applications and provision of postal services and management of radio

Table 3.1: Access to communication technologies per 1,000 people (United Nations E-Government Survey, 2010).

Telephone lines:	2,9
Mobile subscribers:	306,2
Internet users:	12,2
Personal computers:	9,1

spectrum [46]. The converged licensing framework, service and technology neutral regime adopted by TCRA in 2005 allow a single licensee to provide a variety of services and to lease excess capacity of any communication infrastructure owned by utility companies in the country to provide communication services to customers after acquiring the necessary licenses from the Authority.

Moreover, TCRA provides a framework for communication service providers to build a nationwide back-haul and distribution network infrastructure and to interconnect to each other. The framework provides a technological and service neutral regime where a licensee has the freedom to choose technology which is most efficient and cost effective and to take signals from the market as to which services are most in demand. The regulatory framework allows for the provision of services to different geographic segments of Tanzania or nation wide.

Broadband Penetration

There are contradicting figures from different sources on the Internet penetration in Tanzania. In 2010, ITU conducted a user side survey that reported 1.3% penetration; the regulatory authority (TCRA) conducted a supplier side survey that recorded 11% penetration [47]. Further, the TCRA study noted that: about 82% of Internet connections is via fixed wireless, available total capacity (Internet and data) is 3,459Mbps out of which 43% is satellite and 57% Fibre optic, and used total capacity is 65% of the available capacity for which 49% is fibre optic and 51% is satellite. The study further noted that Internet access is distributed as follows: 5% via Internet Cafes, 55% from organizations and 40% from households.

Access to communication technologies per 1,000 people in Tanzania, according to United Nations E-Government Survey (2010), is summarized in table 3.1.

There is a National ICT Backbone (NICTBB) initiative led by the government, planning to connect all district capitals in the country. As of the writing of this thesis (August 2011), more than 10,000km have been deployed.[1] To reach the end user, operators are expected to build last mile solutions, or communities are expected to build their first mile to complement the NICTBB.

[1] Discussion with Dr. Yonah, director of ICT at the ministry, responsible for NICTBB

National Policies

Several key policy and strategy documents have been developed by the Government of Tanzania recently, including the "National ICT Policy" [48], the "National Strategy for Growth and Reduction of Poverty (NSGRP or MKUKUTA in Swahili)" [49] and the "Tanzania Development Vision 2025" [50]. They all recognize ICT as a key technology in the development of Tanzania into a knowledge society. However, there is no implementation plan for how to introduce ICT in the development processes. The National ICT Policy of Tanzania is generally considered laying out good policies, but lacks an implementation plan. The MKUKUTA strategy identifies ICT as an important tool for its implementation, but status reports do not identify increased use of ICT as a parameter to monitor. The Vision 2025 document states that ICTs are central to competitive, social and economic transformation and a major driving force for the realization of the vision but includes no action plan.

Tanzania passed its Universal Communications Service Access Act in 2006 and the Universal Communications Service Access Regulations in 2009 [51]. The establishment of the Universal Communications Service Access Fund (UCAF) was completed in 2009. The fund became operational late 2011, the government has promised to use this fund to expand connectivity in under-served areas.

In the next sections, we will discuss the thesis related works in the areas of first mile initiatives, communication infrastructure and institutional framework.

3.2 First Mile Initiatives

First mile initiatives, community broadband networks and broadband islands are the topics of Papers A, B and C. This section presents some background information and discussions about these topics, as well as related work. Note that we discuss community at the municipal (district) level for the fact that municipalities are the lowest level in the local government planning and budgeting purposes.

Community networks and first mile initiatives are two terms representing the same idea of deploying communication networks starting at the user side towards the point of presence (PoP) of the service provider. While previous efforts to build municipal communication networks focused on sharing Internet access, broadband island is an approach to implement first mile initiatives without much concern on the PoP the focus is on local communications.

It is noted that the government can contribute in different roles, such as a broadband user creating a demand, as policy-maker defining the rules, financial supporter and infrastructure developer to accelerate broadband penetration [52]. Some authors argue that municipalities could be used as drivers for broadband access in communities while others went further to discuss the economic benefits of a community driven networks, taking an example on Fiber to the Home rollout [53], [54]. In a multi-stakeholder approach, it is argued that the implementation should follow three stages as follows: start with identifying and aligning goals with all stakeholders; followed by deciding on the applications needed, technology to use

and the source of funding; and finish with the actual implementation [55].

Related work is divided into policy and advocacy on community networks and broadband penetration, applications and services that can work well in the local area networks, and three examples of existing broadband island networks.

Policy

A study carried out in 2007 from nineteen members of the Latin America Forum for Telecommunication regulators (REGULATEL) [56] on "New Models for Universal Access to Telecommunications Services" observed that the first generation of the universal access program (UAP) was focusing on voice while the new generation UAP should focus on infrastructure and services leading to IP access. In [57], it is noted that policy distortions and regulations raise costs dramatically in emerging economies, calling up for new approaches in technology selection, business models and the regulatory framework. In another study [58], it was noted that factors supporting broadband growth in a country or a region include the regulatory framework; the structural changes that take place in the information and communications technology markets; the changes of broadband services and their use; the technological developments; the users' need for fast content access; the affordability; the E (electronic)-readiness and in general the technological level of a country or region.

Applications and Services

To overcome the Internet's high costs, the Widernet Project at the University of Iowa created an eGranary Digital Library, a collection of educational web sites compiled and saved into a hard drive for easy access in a LAN. The contents are updated by using Internet connection or by shipping-in CD's with updates [59].
Authors in [60] presented a videoconferencing telemedicine project with the Aravind Eye Hospital in India. Their goal is to diagnose patients that are too far from the hospital to visit in person. They note that ICT solution should optimize the existing systems to be sustainable.
The Digital Study Hall project demonstrated the enormous potential of distance learning applications in developing regions [61].

Examples of Community Owned Broadband Networks

In this sub section, we discuss three deployments related to the first mile initiatives, looking into the context, motivation, funding, technology and management.

Macha works

Macha is an isolated rural community situated in the Southern province of Zambia, 380 km by car from capital Lusaka (a one hour direct flight). Approximately

128,000 people live in traditional rural houses within a radius of 35km of Macha, with more than 20,000 households [62].

A communication network has been implemented in Macha community since 2004 [63]. The main users of the Internet in Macha include the hospital, the research institute, an Internet café, the Community Centres and the primary school. This network was initiated by a Dutch telecommunications engineer who moved to Macha to join his wife working as a doctor at a malaria institute. The institute is a result of a partnership of the Zambian government, Johns Hopkins University of Baltimore and the Macha Mission Hospital [64]. The initial infrastructure was setup with $50,000 in seed money from the malaria institute.

A study in 2010 indicated that the network is a terrestrial mesh wireless network with more than 50 nodes [65]. As of July 2011, Macha has a satellite link of 2MB committed information rate (CIR) both ways, at a price of USD 10.000 per month.[2] Other villages connected with the help of Macha Works includes Chikanta, Chilonga, Chitokoloki, Kalene, Minga, and Mukinge.

To operate this communications network, "Macha Works", a non-profit cooperative company was set up. Macha Works has an ICT unit, LinkNet, which is owned by Macha community [66]. Macha Works itself is an international organization launched and registered in the Netherlands. Operating costs depends on revenues generated through user contributions (service charges) while network expansion or connecting new sites depends on the contribution from other partners like the central government or multilateral organizations. By June 2009, LinkNet had 44 institutional subscribers, including companies, schools, hospitals, religious missions, and social organizations, that pay $30 per month per subscription.

Jokkmokk

Jokkmok is one of the fourteen municipalities in the county of Norrbotten, northern Sweden, with a population of 5,000 inhabitants, and an area of 20,000 km^2 [67]. This translates to 0.3 persons per square kilometre, which is too sparse a population for traditional communications service providers to identify market potential.

In 1998, the municipality itself initiated the roll-out of a broadband network within Jokkmokk, known as City Net, using regional development funds from the government as a grant, with the condition that the municipal was not supposed to operate the network. However, as there were no commercial actors interested in providing ICT services in the area, the municipality decided to initially be responsible, creating an IT unit, Jokknet, that was tasked to operate the network until a commercial operator comes forward [68].

The municipal did extend the national backbone; hence, all users are connected via fibre, through their Fibre-to-the-Home (FTTH) community project. Offered services include Internet connections, telephony and television services to end users. Jokknet also offers back-up servers, secure information storage, and enterprise so-

[2]Email conversation with Gertjan van Stam, founder of Macha Works, July 2011

lutions to business communities. The connectivity has also facilitated other developments such as the use of elearning and ehealth in the municipality and between municipalities. From the range of services offered, it can be seen that connectivity is targeted for each home user or business.

Finally, after twelve years, OpenNet, one of the operators of apartment housing networks in the City of Stockholm took over the operations from 1st November, 2010 [69]. The revenue is the monthly service charges billed all connected customers.

Nepal Wireless

Nangi is a small village in the mid-hills of western Nepal, in Myagdi district, on the Southern flank of the Himalayas, at an elevation of about 2,260 m (7,345 ft). Reaching Nangi usually requires two to three days of traveling from Nepal's capital city.

The Nepal wireless in Nangi is a community-based wireless LAN built around technical volunteerism and donations of funds and equipment [70]. The project's objective is to link the community around the Himalayan mountains in Nepal to the world, with a goal of providing better education, healthcare, communications, means for weather and climate change monitoring, and to stimulate job creation. The project started as a single man's (Mahabir Pun) dream to connect a single high school, which was achieved in 2003. It has grown to connect more than ten villages. With the support of E-Network Research and Development (ENRD), the Nepal wireless project has been replicated in nearby four other districts [71]:

1. Makawanpur wireless networking project has connected seven villages of Makawanpur district in single wireless network is directly connected with the Internet.

2. Ramechhap Wireless Project where more than seven villages have been connected in these villages along with the district headquarters.

3. Baglung Wireless Project where eight schools have been connected along with the health post and other needy users

4. Dolakha District where schools, hospitals and local government offices have been connected.

The network is built based on terrestrial wireless, using the 2.4 Ghz free spectrum, with a shared satellite link to the Internet. Other than Internet access, which is used to facilitate e-commerce services, major services offered are VoIP and email to facilitate communication, as well as local content related to education and health sector. The community accesses the services through public offices (school, hospitals) and the rural information technology centers. Because of lack of national power grids in some areas, and the lack of sun during the monsoon months of June-August, a range of alternative energies such as solar, wind generators, kerosene generators and deep cycle batteries has been employed [72].

Nepal Wireless is operated and owned by the Himanchal Education Foundation, a non-profit corporation based in the US [73].

3.3 Communication Infrastructure

Communication infrastructure is the topic of Papers D and E. This section will give some more background and motivation for the work done and present some related work.

The communication infrastructure consist of network connectivity, specifically link layer technologies and network equipments on one hand, and the availability and accessibility of reliable power supply on the other hand.

On the connectivity part, there is a lot of literature and deployments on the use of WiFi-based, long distance links as a potential low-cost alternative to traditional connectivity solutions for rural regions [74, 75, 76]. There are also examples from rural areas of developed regions where local inhabitants sitting on the right of way and appropriate machinery, contribute the civil work part while the telecom or power utility company provides the fibre cables and active network elements [30, 77].

On the power supply issues, studies on deploying ICTs in rural areas have identified insufficient power supply as a challenge to the operation of communication networks [75, 78]. Another study indicated that less than 20% of Africa's population has access to electricity [79] and for many of them, power rationing and cuts is part of the daily routine. The SIMbaLink project has designed a solar power in Ethiopia, describing their deployment experience and sustainability, especially accountability and trust [80].

3.4 Institutional Framework

This section will discuss some background and related work to the institutional framework presented in Paper F and G.

On the business and management issues, there exist two studies arguing that to reduce business risks, increase the chances of attracting more investments and leverage on the expertise available in the private sector, community networks should be created and managed in a private-public-partnership model [81] and [82]. Another study on the business and management model propose nine possible business models based on two questions "who own vs who run" the community network [83].

3.5 Overall Proposed Solution

Background and related work on how to establish sustainable broadband markets in under-served areas as presented in paper H, will be discussed in this section.

Most published works in ICT4D domain have been focusing on single aspects of either connectivity, power supply or developing applications to solve specific issues such as agriculture, education, etc, but not looking the entire ecosystem.

In our search, we were able to find only one paper that was presented at ITU in October 2011, going with a title "The Rural Broadband Initiative - Toward a New Model for Broadband Access in Haiti and Beyond" [84]. Six success factors are proposed in their rural broadband initiative model highlighted as follows:

- An Ecosystem Approach;
- Ultra Low-cost Wireless Technology;
- Carrier-Neutral and Shared Network Infrastructure;
- Local Entrepreneurship and IT Capacity;
- Low Bar for Participation;
- Focus on Strategic Anchor Tenants.

Coincidentally, with the exception on specific use wireless technology, the remaining factors are inline with our proposal as presented in paper H, and later summarized in Figure 1.1 and 1.3. When it comes to technology, we propose the use of any existing technology the community can get access to, based on cost, durability and capacity offered.

Chapter 4

Summary of the Papers

This section contains a summary of the papers included in this thesis. The papers are arranged in chronological order following the three issues of creating broadband islands, solving communication infrastructures and institution framework as discussed in the approach section.

Paper A proposed the first mile initiatives through building and interconnecting broadband islands while paper B built the actual network. The work by these two papers created a reference concept and network for the rest of the papers.

Paper C analyzes the usage behavior and traffic characteristics of under-served area networks. Paper D and E solve the communication infrastructure challenges, specifically looking into the power supply and network elements respectively. Paper F and G address the institutional framework challenges by looking into the organizational mechanisms and business models respectively.

Paper H summarizes the broadband island concept, creating a model for creating sustainable broadband markets in under-served areas by synthesizing the work performed in all the other papers.

4.1 Paper A: Interconnection of Broadband Islands in Developing Regions

Because of lack of producer lead initiative, broadband services will be a consumer led initiative, building the first mile solutions. However, due to the low income in the area, the first mile initiative should have a strategy to target a few key (anchor) customers that can bear the initial costs.

As an approach to establish the first mile initiative, this paper revisits the concept of building *broadband island*, a local area networks that provide broadband services in a local community with a capacity that is not limiting the spectrum of services.

For the broadband island to succeed, the paper made three assumptions: existence of conducive policies and regulatory framework that allow community lead

initiatives and sharing of communication resources; opening up for innovative business models in building the ICT value chains; and availability of national ICT policies and action programs for public sector areas supporting progress towards the MDGs. Further, the paper argue that by focusing on public sector, providing broadband services related to the MDGs, the public sector will act as initial anchor customers, making it possible to raise initial capital investment through public funding sources.

Key contribution of the paper is on applying broadband island concept to build broadband networks in under-served areas.

The paper was presented at the IEEE 3rd International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities (IEEE TridentCom 2007) held in Orlando, USA. May 2007.

4.2 Paper B: Serengeti Broadband

This paper is a follow-up to paper A, presenting a detailed design and implementation of our reference network (the broadband island).

The Serengeti broadband is built of fibre-optic communication network, extended by WiFi between Bunda and Serengeti, two rural districts in the Mara region in northern Tanzania.

A baseline study is meant to create a benchmark from which to make future references on the impact brought by the introduction of broadband services. The paper highlights the outcome of the baseline study that was carried out for the Serengeti pilot before the actual implementation [37]. The main focus of the paper is on the communication infrastructure in general with a special focus on the network design and deployment, and power backup solutions. Thus, the paper describes in depth the technology used, network layout and setup, antennas, masts and other related hardware used. A number of challenging practical issues are addressed as well.

Key contributions of this paper are the network design for under-served areas and on how to mitigate the many challenges encountered in under-served areas.

During the design and deployment of our pilot networks, the most affordable technical solution available to demonstrate a proof of concept with optical transceivers was a flat Ethernet based on switches with Gigabit interface converter (GBIC). Thus, we deployed a switched network based on Cisco 2950 series Switches. Three years later, when the network had grown to a point that a flat Ethernet did not scale, PC-technology had matured to a point where its performance and robustness

made it possible to build PC-routers with the robustness and performance required while still being power-lean and affordable. The developments made it possible to design and deploy our own PC based router using open source software (bifrost) and commercial-off-the-shelf components (Paper F), thus, replacing the switches with routers.

The paper was presented at the The 2nd ACM SIGCOMM Workshop on Networked Systems for Developing Regions (NSDR 2008) held in Seattle, USA. August 2008.

4.3 Paper C: Analysis of the Serengeti Broadband Network

Bandwidth to the outside world is scarce and expensive, hence a needs to monitor for better optimization and utilization. Also, there is a need for feedback from end users on how they use and benefit from broadband services, reporting on what is working or not working as well as on what are their wishes with regard to new services.

This paper presents an analysis of the Internet traffic captured through the gateway, also feedback gathered via observations and questionnaires from end users. The goal of this paper is to determine the usefulness of broadband services provided as well as nature of the Internet traffic in under-sered areas. The paper has shown that Internet traffic is almost the same to other parts of the developing regions, restricted by the speed and capacity of the Internet.

Key contribution are the Internet surfing behavior under-served areas, kind of Internet traffic inherent in under-served areas, and recommendations on how to improve the adaption rate on the use of the broadband services.

The paper was published as a KTH-Technical Report: TRITA-ICT/ECS R 11:02, ISSN 1653-7238, ISRN KTH/ICT/ECS/R-11-02-SE, ISBN 978-91-7501-088-5, August 2011.
(To be submitted on October 21, 2011, to the 2nd annual Symposium on Computing for Development (ACM DEV 2012))

4.4 Paper D: On Powering Communication Networks in Developing Regions

One of the major challenges in running communication networks described in paper A and B turned out to be reliable power supply. There is a need explore how to decrease the demand for power as well as the feasibility of using alternative power sources, such as solar and wind, and alternative power storage technologies, such as batteries and ultra-capacitors.

In this paper, we present data collected over 2 months from the Serengeti network to discuss the quality of the existing power-grid and the feasibility of using solar and wind energy as alternative energy sources. The measurements on the quality of the power-grid indicated up to 21 power-outages in one single day, with an average of 2 outages per day. We learned that some of the outages are due to planned rationing schemes caused by insufficient power generation while some outages are due to poor wiring or installations. Our measurements and analysis of the feasibility of using alternative power sources indicate wind speeds on the average 2m/s and a persistent high-level insolation, making solar energy the prime candidate as an alternative source of electricity due to the availability of solar equipments/technology in the country.

The paper also proposed power management to be included in the network management system to maximize the availability of the network services and decrease operational costs due to damaged network elements.

Key contributions for this paper are the analysis of the quality and availability of grid power in the pilot area, and the feasibility of wind and solar as alternative sources of energy.

The proposed charge controller takes a range of inputs voltage from various sources, has a built-in mechanism for stepping up/down the input, to provide required output. Our current version, which is a third iteration, supports power from grid, solar, and battery.

The paper was presented at the 16^{th} IEEE Symposium on Computers and Communications (IEEE ISCC 2011) held in Korfu, Greece. June 2011.

4.5 Paper E: On the Design of Inclusive Ubiquitous Access

Apart from power issues in rural areas discussed in paper D, other challenges include lack of skilled personnel and poverty. Thus, a need for robust, cheap and locally available network equipments.

This paper discusses the design of an affordable, high-performance, low-effect router based on open source software and standard off-the-shelf hardware offering both copper and fibre links. Our design is capable of forwarding more than 700kpps at 22.3W. The power consumption is considerably less than all alternatives in our comparison.

Key contributions for this paper are the requirement specifications for the infrastructure router, the actual router design, and the evaluation (performance and

power consumption) of the designed router.

The router design has already undergone three iterations to improve its performance and power consumption ratio, the goal is to achieve high performance at low power consumption.

The paper was presented at the 3rd International Conference on Ubiquitous and Future Networks (IEEE ICUFN 2011) held in Dalian, China. June 2011. (Received Excellent Paper Award).

4.6 Paper F: Challenges in Sustaining Municipal Broadband Network in the Developing World

Municipal or community networks seem to be a constructive first step in the process of establishing sustainable broadband networks in under-served areas. One of the keys to the sustainability and scalability of such networks is a well designed and managed institutional framework based on the local prerequisites.

Identification of strategic partners who can contribute in one way or another to the establishments of the network is a key step. The partners could be local, national or even international organizations or individuals who are actively working in the target area or related developmental issues. The local partners could be the local government itself, the civil society organizations (CSOs) which include non-governmental organizations (NGOs), all faith-based organizations (FBOs), trade unions, etc. The national partners include the central government while the international partners include all multilateral partners and UN agencies.

For a successful organizational mechanism, it is preferable to obtain a buy-in from both members of the society, the public and the private sectors. The public-private-partnership (PPP) will create a sense of inclusiveness and responsibility to the whole community. The entity could be registered as an NGO to avoid government bureaucracy, secure autonomy in its operations, make it possible to apply for development funds from the government and other sources. Further, the entity could be register as a for-profit social enterprise, a company with a mission to save the community where they can sell shares; or a non-profit social business company where profits are re-invested into the company [23]. The formation and mandate of the entity will vary depending on the interplay of the various stakeholders and their readiness to commit themselves in the process. Few examples could be a single entrepreneur, an existing NGO, a newly formed venture specific for this task, or a Public-Private-Partnership (PPP).

In this paper, we report on our experience from the establishment of the Serengeti Broadband Network discussed in paper B. We used a public-private partnership ap-

proach to create a not-for-profit organization to manage and operate the network that was deployed as a research and education effort. We present and discuss our approach, comparing and contrasting to other approaches found in the literature. We conclude that success requires local ownership. Thus, the institutional framework should aim at creating local commitment and leadership.

Key contributions for this papers are the process undergone to create the institutional framework and documentation of the challenges encountered.

The paper was published by Springer, in Communications in Computer and Information Science (CCIS) Series, LNCS, vol. 171, p. 26-40. August 2011.

4.7 Paper G: Business Model for Developing World Municipal Broadband Network - A Case Study

In most developed markets, the supply chain including network and service operators, equipment vendors, trainers, user-support, hosting services, software development, etc. are provided by the private sector.

For the first mile initiative, a viable revenue model is key to financial and operational sustainability [85]. There should be a billing mechanism to collect revenues to cover the running costs such as salaries, electricity bills, communication, etc. Possible sources of revenue include service fees (Internet, repair and maintenance, installation charges, etc) member contributions in case it is a member club service, or external funding in terms of outreach programs paying on behalf of the end users.

Using the public private partnership approach discussed in paper G, stakeholder analysis and the business model canvas tool [87], this paper demonstrate a business model that is relevant in rural developing regions. The goal is to identify all stakeholders, align their needs with the provision of the broadband services. We then use our implementations in paper A and B to validate our proposal.

Key contribution for this paper is the proposal for the business model that is relevant in under-served areas.

The paper was presented at the Global Information Infrastructure Symposium (IEEE GIIS 2011) held in Danang, Vietnam. August 2011.

4.8 Paper H: On Building Sustainable Broadband Networks in Rural Areas

Building on the accumulated knowledge gained through all the past papers A-G, the paper revisiting the research question - “how to establish sustainable broadband markets in under-served areas”.

This paper detail a generalized implementation strategy, gluing together all our work in one blueprint related to first mile initiatives, solving communication infrastructure challenges, and establishing the required institutional framework. The paper finished by making reference to the actual network presented in paper B.

In the Action Research approach, this paper is specifying the learning process by reviewing the outcomes of the previous stages to build knowledge by proposing a framework for building and sustaining broadband networks in under-served areas.

Key contributions for this paper are the provision of a framework on how to develop broadband markets (consumers and producers), the demonstration on how to design technical solutions for such networks, and how to address the sustainability issues.

The paper was presented at the Technical Symposium at ITU Telecom World 2011 (ITU WT11), Geneva, Switzerland, October 2011. (To be published in IEEE Xplore).

Chapter 5

Conclusions and Future Work

5.1 Conclusions

Building upon the increasing awareness of the potential of broadband services to economic growth, and the past experience of ICT projects in rural areas, we set out to find a solution on how to establish sustainable broadband markets in under-served areas. Using an Action Research approach, we have proposed a model on how to establish and sustain broadband markets in under-served areas. Our model was demonstrated and validated through two pilot sites implemented in Tanzania.

The many risks, resulting from under-developed and poorly enforced policies and uncertain revenues, costs and profits, make the business community reluctant to invest. To mitigate the risks, we have cooperated with government and the regulator to propose an institutional framework for public-private, multi-stakeholder partnerships assuming the service provider role until the market is reasonably developed. To secure financial sustainability, the framework includes a clear business plan and revenue models taking into account that it is a social business rather than a profit -making one. In the framework, there are also distinct measures to strengthen the private sector so that commercial actors can take over the producer role once the market has developed. Strengthening the private sector will help to bring in competition, hence innovations and many choices.

Innovations on the infrastructure side are necessary to address the specific challenges found in developing regions, especially regarding infrastructure-sharing, robustness of equipment and power supply. Our design and deployment of a robust and power-lean infrastructure router and a flexible power regulator are examples that must be regarded as major breakthroughs. The high-performance router supporting both fiber and copper technologies is a breakthrough for building broadband networks in challenging environments. The power regulator is extensible to manage different power sources, including the power-grid and the renewable sources solar and wind, different power storage technologies, such as the traditional chemical lead-acid battery and emerging ultra-capacitor batteries. The power regulator also

provides a range of output power levels. It is integrated with the network equipment to manage graceful shutdowns and wake-ups when power is not available, remote control and logging. To overcome the lack of trained staff, we proposed partnerships with research, education, and training institutions. Providing scholarships for higher education as part of capacity building will build a base of local experts. We believe that involving the students building and running these networks will have a bigger impact in the long run as some of them might go to work there after they graduate, slowly reversing the urban-rural migration.

Our experiences from constructive cooperation with policy-makers and the impact reported from local stakeholders, make us conclude that the model proposed and the business and technical solutions demonstrated are reproducible and scalable, given the support by all stakeholders. Advocacy and capacity-building of human resources and the ICT and energy supply chains are the key issues to ensure sustainability.

5.2 Future Work

For future work, a set of recommendations is provided as follows:

1. Quantify the ICT benefits, in terms of cost savings and revenues generated as a result of the introduction of broadband services. This is useful to motivate the decision makers to scale up. A proposal is in being discussed to extend the experiences in the rural areas of African Great Lakes, in all East African Community member states and DRC.

2. Further refine the framework to create a template that can be used as a guideline for replicating and scaling up our experience on a national and regional level. Specifically, look at criteria that can be used to decide on different types of ownership structures, such as municipal, community, private sector or public-private-partnership. The ownership will also indicate what kind of management and organization structure to adopt.

3. Future work on the technical side include

    a) Introduction of resource sharing mechanisms for sharing of links, local and uplinks, network equipment and servers, e.g. via virtualization, cloud technologies, etc.

    b) Refinement of the router design to increase the robustness, not least the network and system management functionality, and to decrease the energy required to forward packets further.

    c) Refinement of the integrated power management system to facilitate a wider use of renewable energy sources and storage technologies.

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Chapter 6

Summary of the Original Work

Paper A

Interconnection of Broadband Islands in Developing Regions

Amos Nungu, Björn Pehrson

IEEE 3rd International Conference on Testbeds and Research Infrastructures for the Development of Networks and Communities (IEEE TridentCom 2007)
May 2007, Orlando, USA

Paper B

Serengeti Broadband

Amos Nungu, Nsubis Genesis, Björn Pehrson

The 2nd ACM SIGCOMM Workshop on Networked Systems for Developing Regions (NSDR 2008)
August 2008, Seatle, USA

Paper C

Analysis of the Serengeti Broadband Network

Amos Nungu

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Paper D

On Powering Communication Networks in Developing Regions

Amos Nungu and Robert Olsson and Björn Pehrson

16th IEEE Symposium on Computers and Communications (IEEE ISCC 2011)
July 2011, Greece

Paper E

On the Design of Inclusive Ubiquitous Access

Amos Nungu and Robert Olsson and Björn Pehrson

The Third International Conference on Ubiquitous and Future Networks (IEEE ICUFN 2011)
June, 2011, Dalian, China
Received Excellent Paper Award

Paper F

Challenges in Sustaining Municipal Broadband Network in the Developing World

Amos Nungu, Terrence Brown and Björn Pehrson

The First International Conference on e-Technologies and Networks for Development (Springer ICeND2011
Aug 3 - 5, 2011, Dar Es Salaam, Tanzania
Published in "Springer (LNCS), Communications in Computer and Information Science (CCIS) Series" of 2011, Vol 171, pg 26-40.

Paper G

Business Model for Developing World Municipal Broadband Network - A Case Study

Amos Nungu, Terrence Brown and Björn Pehrson

Global Information Infrastructure Symposium (IEEE GIIS 2011)
Aug 4 - 6, 2011, Da nang, Vietnam
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Paper H

On Building Sustainable Broadband Networks in Rural Areas

Amos Nungu, Björn Knutsson and Björn Pehrson

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