

ESD.127

Telecom Modeling and Policy Analysis

Project Report

**Reliable Networks in an
Unreliable Network Environment**

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1 Introduction

The development of Information and Communications Technologies (ICTs) in developing countries is a topic attracting large interest among both developing countries and developed countries. Besides the relevant governments, developmental agencies such as the UNDP and ITU-U are working to bring forth the best technologies to give developing countries a boost in their development and narrow the “Digital divide”.

Our team proposes a school computer network for the Kingdom of Bhutan. Students, teachers, and the local community will benefit from greater access to information and faster communication to their neighbors and the world. An integrated systems approach combining models of reliability, performance and cost allow our analysis to specifically address concerns including disruptions from power and communication link failures, before recommending a set of options to implement in Bhutan over a time span of seven years.

An important component of this research is to quantify how and what the system would be used for, such that the benefits would exceed the costs. A number of novel techniques from recent research and development in redundancy, network routing, and caching are also introduced, analyzed, and implemented as part of our solution for the Bhutanese School Network.

The report starts with an introduction to the Kingdom of Bhutan and its related ICT policies. Following, the deployment strategy for the school based network proposal is laid out. A technical introduction to reliability and availability follows with an explanation of how our approach links these models together. The reliability, performance, and cost models for each of the options are described, together with recommended options. Finally, the business case, policy proposition and funding avenues for proceeding with the school network are presented.

2 The Kingdom of Bhutan

2.1 Country Introduction

Situated in the heart of the Himalayas, between Tibet and northeastern India, and just east of Nepal, the Royal Kingdom of Bhutan has a total area of 47,000 square kilometers, which makes it comparable in size to Switzerland (or half of Indiana). Landlocked, Bhutan is almost entirely mountainous: starting on the border with India, the land rises from an altitude of 300 meters to over 7,500 meters. The little flat land that exists is in a few river valleys and in parts of the southern plains. Storms arising in the Himalayas give the country its name, which means “Land of the Thunder Dragon.” The capital, Thimphu, has approximately 30,000 people, while the second main “city,” the Indo-Bhutanese border town of Phuentsholing, has 25,000 inhabitants.¹

Over 90% of Bhutan’s official population of approximately 650,000 people lives in rural areas.² The 1999 GDP was a miniscule \$0.4 billion, or \$1.0 billion according to the purchasing power parity method of calculation. The economy is based on agriculture and forestry, which provide the livelihood for 93% of the population. Problematically, just about 10% of the land is arable, which means that though the overall population density is very low, the ratio to arable land is 100 persons per square kilometer. Agriculture, which is mostly subsistence farming and livestock rearing, accounts for 38% of GDP, followed by industry (37%) and services (25%).

¹ CIA, *The World Factbook, Bhutan*. Available from www.odci.gov/cia/publications/factbook/geos/bt.html; UNDP-Bhutan, *Briefing Report: Bhutan* (Thimphu: UNDP, July 1999). Hereinafter “*Briefing Report*.” Available from <http://www.undp.org.bt/BHUTAN/Brieflc99.pdf>.

² The United Nations’ July 2001 population estimate for Bhutan was 2.05 million. The reason for the large disparity between the UN estimate and Bhutan’s own count seems to lie at least partly in the status of Bhutanese residents of Nepalese ethnic origin. Another explanation for the disparity is that the UN is using projections of outdated estimates of Bhutan’s population. See, for example <http://www.asianinfo.org/asianinfo/bhutan/bhutan.htm> and http://www.undp.org.bt/unfpa/Revised_BhutanCP4-may.pdf.

Bhutan's economy is closely linked to India's, and its currency, the ngultrum, is kept on par with the rupee. Hydropower is seen as a primary area of potential for the economy, and Bhutan currently exports electricity to India. Tourism is another area of potential growth, but Bhutan has to date limited the influx of tourists in its concerns for preserving its culture.³

A theocracy for three hundred years, Bhutan's form of government at the turn of last century became a hereditary monarchy. King Jigme Singye Wangchuck, currently in the 30th year of his reign, is the fourth king in the royal line. A National Assembly was established in 1953, and its powers were expanded in the 1990's: at least in theory it has the power to remove the monarch with a two-thirds vote. The 20 Dzongkhags, or districts, are each headed by a District Officer, while village chiefs are elected by villagers for three-year terms. Finally, it should be noted that English, along with Dzongkha, the Bhutanese language, is an official language of Bhutan.⁴

2.2 Telecommunications and Information Technology

This section provides an overview of the current state of telecommunications in Bhutan. The first subsection introduces the existing telecom network, while the second is focused on the Internet and IT.

2.2.1 Telecommunications Network

Telecommunications services were introduced in Bhutan in the early 1960's—the first network was established to provide communications support for the construction of highways and was very basic, consisting of “step-by-step and Strowger exchanges and open wire cables as

³ CIA *World Factbook*; UNDP, *Human Development Report 2001*. Available from <http://www.undp.org/hdr2001/>; *Briefing Report*.

⁴ *Briefing Report*.

trunks.”⁵ Further development of the telecommunications network began in the late 1980’s and early 1990’s. Construction of the current National Telecommunications Network began in 1991, with grant assistance from the Japan, and digitalization of the network was completed in 1998.⁶

The present network is fully digital and covers all 20 districts.⁷ The network’s backbone is a 34 Mbps digital microwave system with digital switches, which follows the contours of the national east-west highway and covers the most populated districts. There are 8 Mbps links to Remote Line Units (RLU’s) in a few districts with a moderate number of customers, while the more remote districts are connected by 2.4 GHz Digital Radio Multi-Access Subscriber Systems (DRMASS). International services are provided through a satellite earth station in Thimphu, with all international traffic being routed through British Telecom, Singapore Telecom, and KDD in Japan.⁸

As of October 2001, Bhutan had 15,193 main telephone lines, for a teledensity of 2.58.⁹ While this teledensity is actually quite respectable relative to most countries at similar levels of development, it is quite low for a country with such a small population.¹⁰ Furthermore, the majority of telephone lines are in the capital and a few other towns. The teledensity in rural areas is extremely low, and it is estimated that even today over 80 percent of the population has never used a telephone.¹¹

⁵ ITU, *Kingdom of Bhutan: Country Report* (2001). Hereinafter “*Country Report*.” Available from <http://www.itu.int/ITU-D/gender/documents/Asia-PacificIWrkshopKorea/CntryReportBhutan.pdf>.

⁶ *Country Report*.

⁷ See Appendix, Figure 13.1

⁸ *Country Report*.

⁹ *Country Report*. The ITU’s 2000 figures for Bhutan were 13.3 thousand main lines, for a teledensity of 1.97 (

¹⁰ See ITU Basic Indicators (<http://www.itu.int/ITU-D/ict/statistics/>) and UNDP’s *Human Development Index*.

¹¹ *Country Report*; Siok Sian Pek, “Bhutan Joins the Digital Age.” *Choices* (UNDP, June 2001). Available from <http://www.undp.org/dpa/choices/2001/june/j18e.pdf>.

All telecommunications services are provided through Bhutan Telecom, an autonomous state-owned corporation. Formerly the Department of Telecommunications, it was officially separated from the government in July 2000. Cellular services are still not available in Bhutan.¹²

2.2.2 Internet and IT

The Internet was introduced in Bhutan in June 1999 (the same year that cable television officially became available). DrukNet, the country's only ISP, is a state-owned subsidiary of Bhutan Telecom. DrukNet's connection to the Internet was initially through one unreliable 1Mb international satellite link via British Telecom. In August 2001 DrukNet started a second 1Mbps link with KDDI.¹³

As of June 2001, dial-up connectivity, at a maximum speed of 33.6 Kbps, was available throughout Bhutan through the price of a local call, and 64 and 128 KB leased lines were available to businesses. DrukNet had approximately 800 accounts, and estimates for the number of Internet users were as high as 2,500. There were just six Internet cafes (four in Thimphu and two in Phuentsholing), but few individuals could afford to use them. Public access to the Internet was unavailable in the rest of the country. Though few Bhutanese have access to or can afford Internet service, a United Nations Development Program (UNDP) pilot project in 2000 and 2001 offering students free passes to Internet cafes in Thimphu was extremely successful, drawing youths from other regions, including remote districts.¹⁴

In March 2001, the Division of Information Technology (DIT) carried out an "IT Survey" of government organizations, corporations, and private IT companies. While the survey was not

¹² *Country Report*.

¹³ Division of Information Technology, *ICT Development Master Plan for Bhutan* (Thimphu: Ministry of Communications, June 2001). Hereinafter "*ICT Development Master Plan*." Available from <http://www.dit.gov.bt/publications/itmasterplan.pdf>; *Country Report*.

particularly scientific, the 103 responses received did arguably achieve the DIT's goal, which was to "obtain an impression of the present status of Information Technology in Bhutan." The main results of the survey were that while there has been much recent growth in IT, there is "an acute shortage of IT personnel," and there is a need for improved information management. While the DIT's report did not generally extrapolate countrywide totals from the survey results, it did conclude that there could be as many as 4,000 computers in the country. Some specific results include:

- The 103 surveyed organizations had a total of 2,550 computers, 76% of which were Intel Pentium-based systems.
- Half (52) of the organizations reported having a LAN installed (but none of the 10 District administrations did so).
- 87% of the organizations have an Internet connection, though only 47% of the individual computers have Internet connectivity.
- 80% of the organizations requested additional IT personnel; database and application developers and network administrators were particularly needed.¹⁵

2.3 Education Network

Before modernization began in Bhutan, education was provided through monasteries. Planned modern education was only introduced in the late 1950's and, in 1959 there were just 440 students studying in 11 primary schools. It is estimated that even ten years later, in 1970, adult literacy rate in Bhutan was just 10%.¹⁶

Today the literacy is still low, but has risen to near 50%, and the educational system represents one of the most widespread public networks in the country. Free education is provided

¹⁴ *ICT Development Master Plan*; Pek.

¹⁵ Division of Information Technology, *IT Survey for the Royal Government of Bhutan* (March 2001). Available from <http://www.dit.gov.bt/publications/survey.pdf>.

¹⁶ The Planning Commission Secretariat, *Bhutan National Human Development Report 2000: Gross National Happiness and Human Development, Searching for Human Ground*. (Thimphu: Royal Government of Bhutan,

from primary school through college, and in some places includes meals and boarding facilities. Surprisingly, English is an official language of instruction, even at the primary level. There are currently more than 117,000 students in over 350 educational institutions, including 151 primary schools, 110 community schools, 59 junior high schools, and 26 high schools.¹⁷ All high schools have power and telephone connections, while it is estimated that 30% of primary schools have telephone connections, though nearly all have power¹⁸

2000). Hereinafter cited as *BNHDR 2000*. Available from <http://www.pcs.gov.bt/publications/nhdr2000/nhdr2000.pdf>.

¹⁷ *BNHDR 2000*; Bhutan Education Department Website (www.education.gov.bt).

¹⁸ Estimate provided by Sonam Leki Dorji.

3 Bhutan's Development Policy

Bhutan's first five-year development plan was launched in 1961, when Bhutan first sought to end its isolation from the rest of the world and embark on the path of modern development. In 1961, the country had no roads, motor vehicles, electricity, telephones, or postal services. It has been estimated that the life expectancy was about 35 years. The country had just four small hospitals, with two trained doctors in the entire country. As we have seen, there were few schools, and almost no one could read or write. It is estimated that the per capita GDP was \$51.¹⁹

Much progress has been made in the past 40 years. We have already discussed the extent to which the telecom system and the educational network have grown. In 1999, electricity was provided in 39 towns and 375 villages. There were over 100 post offices. The health care system included 28 hospitals, 145 basic health units, and 450 outreach clinics servicing over 90% of the population, and life expectancy had risen to 61.5 years. Despite this progress, however, Bhutan remains a poor country with many challenges. The UNDP's Human Development Index still categorizes Bhutan as a country with "low human development," and ranks it 130th out of 162 countries.²⁰

3.1 Development Priorities

Bhutan's King Wangchuck has officially established as the country's "guiding principle" for development the broad concept of "Gross National Happiness," which goes beyond economic development to include cultural and spiritual values. Bhutan has identified four "essential

¹⁹ Planning Commission, *Bhutan 2020: A Vision for Peace, Prosperity and Happiness* (Thimphu: Royal Government of Bhutan, May 1999). Hereinafter cited as "*Bhutan 2020*." Available from <http://www.pcs.gov.bt/bhutan2020.htm>.

constituents of happiness”: economic development, environmental preservation, cultural preservation and promotion, and good governance. More pragmatically, in its first ever *National Human Development Report* in 2000, Bhutan’s Planning Commission Secretariat listed a number of specific key challenges currently faced by the country in its further development. These include fast population growth, education and employment of women, “rising aspirations” of its more educated youth, the need for private sector growth, rural development, rural to urban migration, environmental conservation, and the preservation of culture.²¹

As we will see below, several of these challenges relate directly to our project, in that we (and the Royal Government of Bhutan) feel that IT can play an important role in addressing them. Particularly relevant are the related challenges of meeting the needs of a new generation of more educated youth and of encouraging private sector growth. Generation of employment for educated youth has been identified as a “major human resources management concern.”²² Improvements in health care (leading to fast population growth) and education have resulted in large numbers of youth who are more educated than ever. Over 40% of the population is under 15 years of age, and the increase in public education means that, during the first five years of this decade, over 50,000 young people will finish school and enter the labor market. And there will soon be over 100,000 children enrolled in primary school. Most of these graduates will not want to continue their parents’ traditional rural lifestyle of subsistence agriculture.²³

Meanwhile, the Government is still the major employer in the country, and the place that most graduates seek work. However, the civil service is near capacity, and few jobs are available

²⁰ *Bhutan 2020*; *UNDP Human Development Indicators*

²¹ *BNHDR 2000*, 4, 18-20.

²² Planning Commission, *Eighth Five Year Plan Mid-Term Review Report*. (Thimphu: Royal Government of Bhutan, Dec 1999), 17. Available from http://www.pcs.gov.bt/publications/8th_mtr/8fypmtr_rep.pdf.

²³ *BNHDR 2000*; *Bhutan 2020*.

in the underdeveloped private sector. A huge priority for the government is therefore to expand the private sector. Ironically, however, expatriate workers account for nearly 40% of all jobs in the private sector. Despite the rise in education of the country's youth, it is still felt that many do not have the skills that the private sector is looking for, and the modern workplace requires. Accordingly, human resources development has been identified as another challenge: the nation's skill base must be widened.²⁴

Another important priority for the Bhutanese government is to better spread the benefits of development to rural areas. There are several different aspects to this issue. First is a general desire for equity in development. The authors of the Government's *Bhutan 2020: Vision* report state that, historically, Bhutan's development has been an "inclusive" process. Clearly then, if 90% of the population is rural, rural development must be a key priority. One of the ways the Government is addressing this need is through an active policy of decentralization, which aims to "empower local communities and give them a voice in the nation's development."²⁵ The government has been restructured to give more power and decision-making authority to District and "Block" (local level) administrations, and plans to continue this process of decentralization.²⁶

The problem of rural to urban migration is another reason that rural development is so important. While the country is still mostly rural, population growth in the major towns far exceeds the national average. The growth of the two main receiving centers, Thimphu and Phuentsholing, is estimated to be as high as 10% in recent years. These towns are poorly equipped to deal with a massive influx of migrants, both in terms of infrastructure and services,

²⁴ BNHDR 2000; *Bhutan 2020*.

²⁵ *Bhutan 2020*, 21.

²⁶ BNHDR 2000; *Bhutan 2020*.

and in some cases because of their physical geography. There are not nearly enough jobs for future migrants, and in addition, there is concern that migration will be destructive to the environment. To stem the tide, the government must improve living standards and create jobs in rural areas, as well as create alternative growth centers.²⁷

3.2 The Role of IT in Bhutan's Development Policy

In January of 2000, just six months after the introduction of the Internet, the Royal Government of Bhutan (RGOB) created the Division of Information Technology (DIT) under the Ministry of Communications.²⁸ The DIT was created to implement the “three broad IT policy objectives” of the RGOB, which are to use IT (1) “to enhance good governance”; (2) “to generate employment and income for the country”; and (3) “to improve the livelihood of all Bhutanese citizens.”²⁹ In June of 2001, the DIT unveiled its *ICT Development Master Plan*, in which it expounds its IT policy and the goals for IT, and spells out national programs and initiatives to meet those goals. The Plan makes clear that the RGOB not only welcomes IT with few reservations, but also has high hopes for its contribution to Bhutan's development. According to this IT master plan, the RGOB has recognized IT as an “unmatched developmental tool” and “an area of new business and employment for all Bhutanese people.”³⁰ Not only is the Government “dedicated to the development and application of IT,” but the country also has the “vision to be a world-class user and provider of IT.”³¹

²⁷ *BNHDR 2000; Bhutan 2020.*

²⁸ The RGOB plans to create a new “Ministry of Communication and IT” by July 2002.

²⁹ *ICT Development Master Plan*, 7.

³⁰ *Ibid.*, 1.

³¹ *Ibid.*, 6.

According to a UNDP report, “the isolated location and the rugged terrain of Bhutan, combined with its low population density, present a special problem to the RGOB in [the] pursuit of [its] development goals, hindering the vast rural population from access to information and communication.”³² These challenges have severely limited the spread of development to rural areas. An example is the fact that half of the country’s population is still over a half-day’s walk from a motor road. IT is seen as a potential solution: “Bhutanese planners believe that... ICT is the long-awaited answer to its most difficult challenge: the highly mountainous terrain and scattered population.”³³

In fact, the *ICT Master Plan* makes clear that IT should play a role in Bhutan’s broad development goals, including those of improved education, rural development, government decentralization, and generation of employment. The main benefits from the implementation of the plan are identified as “developing a modern, efficient, decentralized government,” providing new sources of employment, and enabling Bhutan to become “an active player in the world.”³⁴

In education, an *Education IT Master Plan* has been developed to provide IT training in all schools, with the goals being to “provide computer access to all schools and produce computer literate high school graduates by 2010.”³⁵ In addition, to deal with the immediate shortage of IT personnel, high-school dropouts and unemployed youth will be giving IT training.

The *ICT Plan* calls for the Government to shift to electronic communication “wherever possible.” Programs to enhance communication at different levels of the government include installing LANs at district administrations, setting up a government-wide intranet, and providing

³² UNDP, *BHU/00/004 Information Network for Good Governance, Bhutan*. Available from <http://www.undp.org.bt/undp/Current-projects/overview.pdf>.

³³ Pek, 1.

³⁴ *ICT Development Master Plan*, 40.

³⁵ *ICT Development Master Plan*, 24.

all block administrations that have electricity and telephone connections with a computer and a dial-up Internet connection. In terms of public access, the *Plan* envisions setting up e-mail and Internet access points in post offices throughout the country. The RGOB will also promote IT in Bhutan through IT awareness campaigns, exhibitions, and talks in districts and individual blocks.

Finally, the RGOB believes that IT can help develop the private sector and generate employment. The *ICT Plan* outlines programs designed to provide financial support for the establishment of IT businesses, to improve policies and regulations related to the IT sector, to promote software development for export, and to promote the use of the Internet and IT in existing businesses.

4 Our Proposal

4.1 School Based Networks

Our proposal is to equip schools with computer facilities connected to the Internet. The challenge is to do so effectively and expediently in the Bhutanese environment. Schools were chosen as they form the widest network and the most deployed institution that would tap young children and reach out to the Bhutanese population. Alternatives included post offices and community centers, but neither had the same spread nor mission as that of the school network. Moreover, equipping schools with computer facilities are on the plans of the Bhutan Department for Information Technology and Department for Education.

This proposal is titled, the Bhutanese School Network.

4.2 Bhutanese School Network Proposed Deployment Strategy

Our deployment strategy is to start installing systems in high schools and proceed down the education ladder to community schools. The rationale for starting with high schools is that the next higher level of education, the Bhutan College for Higher Education already has computers with Internet access, though most high schools do not.³⁶ However all high schools have electrical power and at least one telephone line, which would be necessary for our baseline installation.

³⁶ Bhutan Planning Commission. March 2000

	School	Number	Availability of Power	Availability of Telephone Line
I	High Schools	25	All	All
II	Junior High Schools	51	All	All
III	Primary Schools	109	Most (> 75%)	Few (<25%)
IV	Community Schools	133	Few (< 25%)	None (<5%)

Table 4.2.1 Distribution of facilities across school types

The availability of telephone lines and power diminishes down the educational ladder, and as Table 4.2.1 shows, almost all community schools do not have electrical power nor telephone connections. Therefore, our deployment strategy will have two modes:

- Wired (telephone line)
- Wireless (radio link to the nearest wired link or base station with a telephone line)

Where schools that do not have telephone lines will need to use the wireless mode for telecommunications access.

As such, our deployment will be phased into 4 phases with two distinctive modes:

Phase	Mode	Target
I	Wired	High Schools
II	Wired	Junior High Schools
III	Wired/Wireless	Primary Schools
IV	Wireless	Community Schools

Table 4.2.2 Deployment strategy by phases

Phase II can follow a successful implementation of Phase I with little technical modification, as junior high schools have primarily the same infrastructure as high schools.

Phase IV similarly can follow Phase III, though the disparity in availability of power and communications will cause a different set of technical issues than from Phase I and II.

4.3 Areas of Concern

4.3.1 Technical Issues

The main areas of technical concern are in deploying that works well given the physical environment and existing infrastructure in Bhutan. In modeling our proposal, it becomes important to consider how the reliability and availability of the systems we propose fare in relation to their performance and cost. This reliability often depends on the nature of the environment and our analysis methods show how we can address and incorporate such issues into our model.

In the context of Bhutan, the reliability and availability of power sources and communication links are variables that are considered in our evaluation of options for network deployment.

4.3.2 Policy Issues

The main areas of policy concern are user acceptance and governmental support, given the social and cultural environment and the funding capability of the Government. In designing our proposal, the business and social proposition is considered to see how the costs of the systems we propose fare in relation to their benefits. The benefits depend on the evaluation of the local people and the Government towards the introduction of computers and Information Technology for schoolchildren while the availability of funding and payback mechanisms depend on the framework the relevant authorities place for evaluating the contribution of our proposed school network towards society.

In the context of Bhutan, the willingness of the people and the Government to improve the education of their children and in at what level, and the means of funding the Government

seeks to provide for this investment are considered in our evaluations of options for network deployment.

4.4 Modeling Strategy

4.4.1 Purpose of Modeling

To evaluate the options proposed for the Bhutanese School Network in the context of the environment in a developing country, an integrative modeling approach encompassing the following key features was used:

- Cost
- Performance
- Reliability

Our approach is based on the philosophy of:

- Positive Inter-relation
- Final result is intuitive

Positive inter-relation states that the three features of cost, performance and reliability generally interact with each other positively, i.e. the greater the performance, the greater the reliability and similarly with cost and reliability.

For a final result that is intuitive, the fundamental concern is to find a way to quantify a given system by its reliability, performance and cost, and to do so in a manner that is easiest to begin with yet delivers the results that are most easy to understand for the purposes of making a decision.

4.4.2 Integrative Modeling Approach

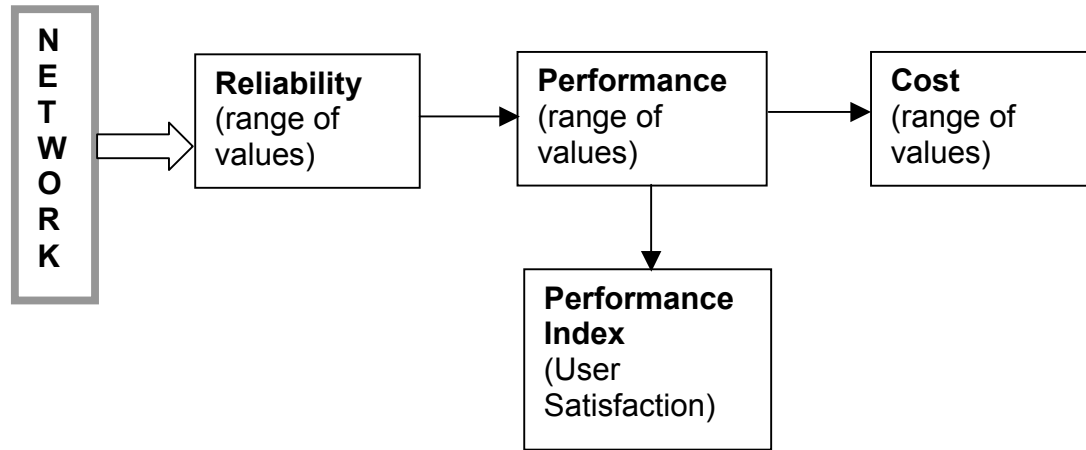


Figure 4.4.2.1. Integrative Modeling Approach

Our integrative modeling approach (Figure 4.4.2.1) takes in a network design, and finds a range of reliability values for it. From this, a range of performance values is generated. Correspondingly, comes a range of costs. For ease of understanding, a Performance Index encapsulating the Performance is derived.

The following sections enter a detailed description of the modeling approach as applied to Bhutan. Section 5 highlights the technical realities of reliability and availability. Section 6 shows their application to the Bhutanese environment. Section 7 introduces our performance model. Section 8, the cost model, extends the input from the performance model. Section 9 considers the sensitivity of the three models, while section 10 summarizes the data with a set of recommendations on deployment. Charts and tables, such as a graph of Cost vs. Performance Index are used to compare different systems.

5 Technical Introduction

To operate successfully, most large distributed systems depend on software, hardware, and human operators and maintainers to function correctly. Failure of any one of these elements can disrupt or bring down an entire system.

5.1 Failures

An example of a large distributed networked system is the public telephone system network (PSTN). Its dependability stems from a design that successfully exploits the loose coupling of system components. Because the PSTN has many similarities with other types of distributed systems such as the school computer networks we are considering, analysis of techniques used in designing PSTNs suggests factors to consider in our design in general.

The literature is full of failure analysis of telecommunications systems, which primarily fall into these categories. Table 5.1.1 shows a list of categories for possible failures of PSTNs. Of note is that almost every failure category is directly applicable to the proposed school network.

Category	Source	Examples
Human-error (PSTN)	Errors made by personnel	Errors in cable maintenance, software maintenance or installation, data entry, or power supply maintenance
Human-error (Others)	Errors made by people other than telephone company personnel	Cable cuttings
Acts of Nature	Major and minor natural events or disasters	Facility damaged from animals, lightning, earthquake, hurricanes or floods
Hardware Failure	Hardware component failures	Failure of cable components, power supplies, synchronization, or others
Software Failures	Internal errors in the software	Software errors under normal operation
Overloads	Service demand exceeds designed system capacity	Busy tone when too many subscribers attempt to connect to server
Vandalism	Sabotage or other intentional damage	Physical acts on equipment or software tampering such as viruses, worms, and Trojan horses

Table 5.1.1. Failure Categories for PSTNs

5.2 Recovery

The ability to recovering from failures is an important process towards ensuring the reliability of the network. Rapid recovery with few extraneous side effects are preferable to those that require expertise to pull off. An example of a side effect is a recovery that requires the entire network to be brought down for an extended period in order to ‘reboot’ the system. However, for some designs, it may be better to bring down the network and restart it, instead of

requiring complex interactions among system components to maintain the level of system consistency in order to survive localized failures.

Again, the literature is rich of examples of recovery methods, particularly for high availability systems such as PSTNs. For example, remote diagnosis allows experts to monitor systems from any location and make up for failures that may be caused by human error.

5.3 Availability and Reliability

For the purposes of our model, variety of failure and recovery methods are abstracted using a standard set of measurements for reliability: availability, and reliability.

These two measures form part of a toolkit for analyzing network systems which will apply towards generic systems that may be implemented in Bhutan.

5.3.1 Availability

Availability is the ratio of time that a service is available to total time. In other words,

$$A = \frac{MTBF}{MTBF+MTTR}$$

where;

MTBF = Mean Time Between Failure (hrs)

MTTR = Mean Time To Repair (hrs)

Total system availability can be determined by progressively decomposing the system into individual components – the hardware and software. The availability of hardware can be further attributed to the availability of the power supply and the communication links and other individual components, and so on for software.

Mathematically, the total availability for a system with components in series is the product of the availability of all the components. In this case, the system availability can be

much lower than the availability of the weakest component. When components are assembled in parallel, however, the total system availability can be higher than that of the most available component.

The methodologies for calculation are elaborated on in Section 6.

In general, increasing availability increases the cost of providing the service. Therefore, a big challenge is striking a balance between availability and cost.

5.3.2 Reliability

Reliability is the probability that something will not fail during a mission time, or a specific period of time. It builds on availability by adding the notion of mission time. The equation for reliability is not fixed, for it depends on the statistical distribution of failures. A commonly accepted simple equation for reliability is

$$R = e^{-\lambda t} = e^{-\frac{t}{\theta}}$$

;where

t = mission time (in hrs)

λ = failure rate (per hr)

θ = mean time to failure (in hrs)

In our analysis, a simplifying assumption is made that the availability of the system does not depend on mission time. Therefore, the calculated system availability is assumed to be the system reliability as well. A more rigorous analysis would make use of a statistical approximation to system reliability, using equations that take into account the number of failure modes in a system.

5.4 Toolkit for Analyzing Network Systems

The techniques introduced above form a basis for a toolkit for analyzing the design of networked computer systems.

For a general system, network design is challenged on two fronts:

- The increase in overall reliability obtained by distributed elements such that failures are localized.
- The resulting complexity from the increased dependability introduced by these distributed systems makes it harder to manage the recovery of the system when it does fail.

In essence, this makes analyzing network systems for reliability complex, as one technique for improving reliability – distributing the network into many small local portions - leads to increased complexity in understanding and improving the dependability of the system.

Keeping the two fronts in mind, the set of techniques above form a toolkit for analyzing possible designs for networked computer systems for the Bhutanese School Network.

5.4.1 Possible Methods of Analysis

There are many possible methods of analysis in our goal of creating a reliable network in an unreliable network environment.

They generally fall into:

- Theoretical
- Simulation

A theoretical approach seeks to obtain the best answer to a given problem or set of problems by defining the problem in terms of an equation and obtained the closed-form solution. However, this is extremely difficult for a real-life system such as the network we are analyzing.

The analytical skill required to solve such a system would be very high and it is unlikely a general solution could be obtained.

The simulation approach seeks to obtain a reasonable answer by systematically creating numerous samples of possible solutions, and then calculating their optimality by evaluating a particular performance index from the solution. By ranking the valuations, a subset of relatively high performing solutions are obtained.

In both cases, it is important that the search space for the solution is large enough to cover the boundaries where the optimal solution may lie, and that the evaluation of the performance index adequately describes our eventual goal: reliable networks for users.

5.4.2 Possible Methods of Improving Reliability

Two key methods involving changes in redundancy and network routing are explored in detail in the analysis in Section 6. A brief description of the philosophy of redundancy and network routing is given below.

5.4.2.1 Redundancy

Redundancy acts to protect against system level failure by inserting additional identical elements that can take over from failed components. The type and amount of component redundancy determines the downtime characteristics of the system using redundancy.

5.4.2.2 Network Routing

Network routing acts to avert the down-effects of system level failure by giving the network the flexibility to seek information in alternative paths quickly. The type and amount of information contained in alternate paths determines the downtime of a system that uses techniques involving changes to network routing.

5.5 Our Approach: Modeling Generic Systems

The method of analysis used in this report is an amalgamation of theoretical and simulation methods. Simple generic designs to improve the reliability of networks are presented in section 6 and their aggregate reliability and availability computed across a range of input parameters, effectively simulating these designs across a large solution space. From these simulations, a range of reliability values (the first component in the set of boxes on Figure 4.2.2.1) is obtained. The reliability values will be part of inputs to the Performance box (the second component on Figure 4.2.2.1).

5.6 Key Variables

The variables in the following method of analysis in Section 6 are:

- **p**: probability of availability
- **u**: utilization
- **Ed**: Expected Data
- **Er**: Expected real-life throughput

5.6.1 Description

5.6.1.1 p

The probability of availability, p is the availability of any component of the system from the lowest level to the highest level, which is the entire system.

5.6.1.2 u

The utilization, u is the amount of time out of the total time per period (one calendar month of 30 days in this case) where attempts are made to access the system.

5.6.1.3 Ed

Expected Data, E_d , is the amount of data out of the total time period (one month in this case) that can be downloaded from remote servers to the local client computer, given the current availability of the system.

5.6.1.4 Er

Expected real-life throughput, E_r , is an estimate of the actual amount of data the local client computer may successfully download in its attempts, given the current availability of the system.

5.6.2 Transforming Ed to Er

An insight in our analysis of unreliable systems was that E_d did not represent the real-life availability of system where utilization is low.

To give an example, consider two examples:

- a) $u=100\%$ and b) $u=30\%$

A detailed description of examples (a) and (b):

- a) A system with $u=100\%$, i.e. in use continuously throughout one month, or for 720 hours a month is analyzed, and that in one month it can transfer 1000 MB of data.

If the probability of availability is $p=50\%$, i.e. half of the month, the system is not available, then the Expected Data is 500 MB.

In this case, our user is trying to access the system 100% of the time, so there is a one-to-one mapping between when the user perceives the system to be down, and when the system is actually down.

- b) A system with $u=30\%$, i.e. in use about a third of a month, or to transfer about 300 MB of data.

If the probability of availability is $p=50\%$, then the Expected Data is still 500 MB, because this is the maximum amount of data that can be expected to be transmitted in one month. Since the user wants to transfer 300 MB, which is less than 500 MB, there does not appear to be a constraint on the user's usage.

However, because the probability of availability p is less than 100%, this means that 50% of the time the user tries to use the system, the system will be unavailable. If the user were to keep trying continuously, then the user would eventually get the system when it is available and succeed in downloading the data.

On the other hand, in real life, users may not be able to retry continuously. There will be a sequence of retries until they give up and may forgo accessing the data. In effect, there is a degradation of service to the user.

Accounting for this degradation of service to the user formed the insight that there needed to be an Expected real-life throughput value, which encapsulates in part that failed attempts to obtain data degrade, or discount, the final throughput.

A rigorous mathematical analysis of Expected real-life throughput would require fitting a statistical distribution to the failures and the a distribution to the user's attempt at accessing the data. Even if a normal distribution was assumed, there would still be a need to perform a t-type

hypothesis test to determine if the user attempts succeed or not, one at a time, to analyze the impact of the unavailability on the user.

Fortunately, the number of samples in our analysis can be very high, as the number of attempts users make can be high. The central limit theorem can be used to approximate the results and allow an estimate of the Expected real-life throughput.

The following block diagram explains the methodology given the assumptions just described:

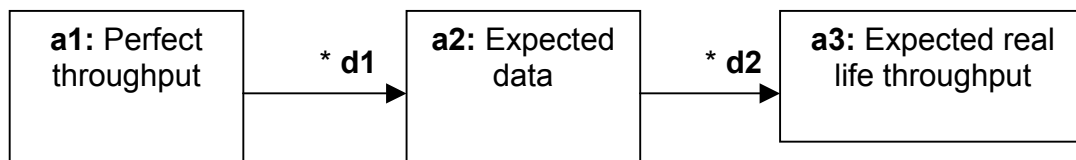


Figure 5.2. Block Diagram showing discounting of Ed to Er.

In steps:

Perfect Throughput (a1) = bandwidth (in kbps) * time per month (in s)

Expected Data (a2) = a1 * d1 [Discount factor for static inherent network unreliability (i.e. the availability)]

Expected real life throughput (a3) = a2 * d2 [Discount factor to account for unsuccessful dynamic network accesses]

The value of d1 is the same as the probability of available p, which can be derived from studying an event tree of failures, as Section X will show.

The value of d2 is approximated to be simply d1 (based on the assumptions described above).

Therefore, total thruptut = a1 * d1²

5.7 Variables Translated to Metrics

The final result from the reliability analysis are the variables, p , u , E_d , and E_r . Section 6 shows the toolkit as described here applied to possible network systems for Bhutan. Essentially, Section 6 aims to compute two core metrics, bandwidth (or throughput per month) and the probability of availability, p (similar to uptime) that will be used in the Performance model described in section 7. Section 8 estimates the cost of the deployed networked described in Sections 6 and 7 and compares it to the metrics introduced here. The final result are charts and tables that can help decision makers to decide where to target their network deployment for now and into the future.

6 Applying the Toolkit on Bhutan

6.1 Assumed Network Environment

Because of mountainous terrain, villages are supplied electricity separately by each area's power plant. Since most of the power supply areas are not linked each other by power transmission lines, once the power facility of an area is under scheduled maintenance, the area suffers from power outage. This sometimes leads to telecommunication line's down.

Shared bandwidth is also one of the causes of the unreliable network environment.

6.2 Techniques for Implementing a Reliable Network

Out of many measures in the literature, three sets of methods are analyzed for improvements to network reliability. As earlier stated, for simplicity, network reliability is evaluated purely on the basis of availability. The three methods are:

- Network redundancy methods
- Network routing method: Peer to peer networking
- Software caching method: TeK

6.2.1 Network Hardware Redundancy

6.2.1.1 Evaluating Extra Lines

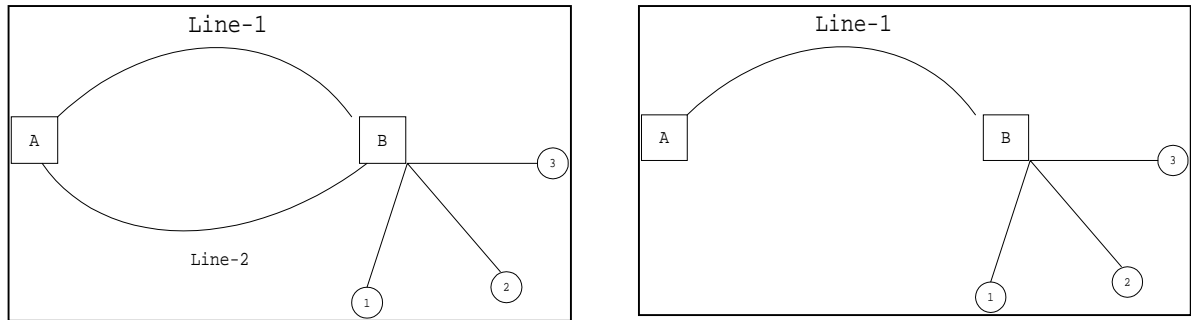


Figure 6.1. The network with redundancy (left) and without redundancy (right)

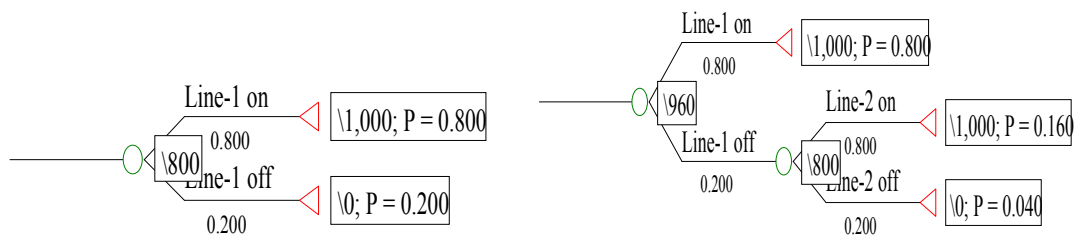


Figure 6.2. The event tree: with redundancy (left), without redundancy (right)

Equipping with a spare telephone line will guarantee the communication when the other telephone line is down. Figure 6.1 shows the networks with and without network redundancy. In this example, we assume as follows: The size of data transmitted between school-A and B is averagely 1,000 kbyte/day; Each line's availability varies from 0 to 100%; Each line's availability is determined by each line's components' availability like the frequency of scheduled power outage.

Figure 6.2 shows the way we calculate the expected data from the network (each line's availability is set as 20%). From the result, the network with a spare line shows higher availability than the one without.

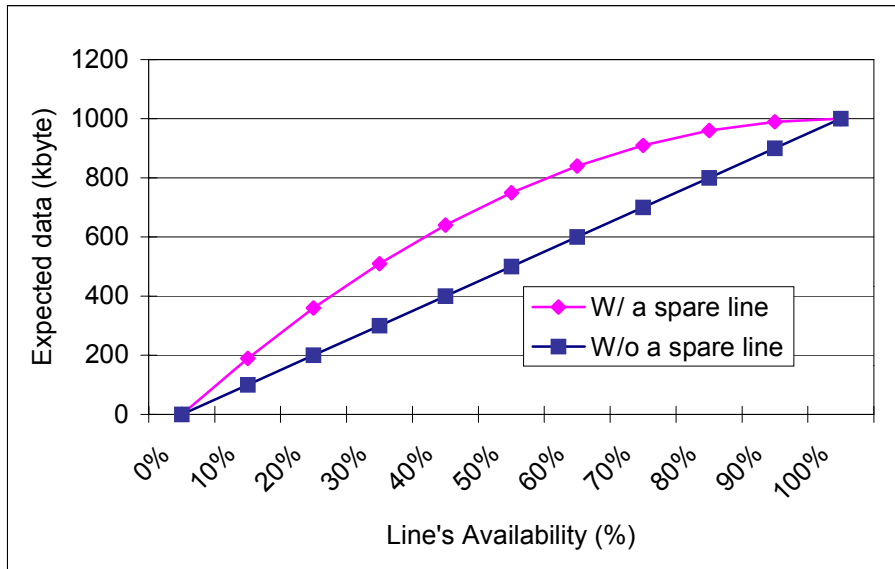


Figure 6.3. The Comparison of Availability

Figure 6.3 compares the expected data of each network, i.e. the availability of the network. From the graph, we can see that the network with network redundancy shows higher availability than the one without.

6.2.1.2 Evaluating Other Topologies

Likewise, we calculated the expected data for other type of network topologies such as ring, mesh, star, and tree (see Figure 6.4.). Although comparing each topology's expected data is neither easy nor simple, we can say generally that the rank of availability is as follows:

1. Mesh
2. Ring
3. Star, tree.

We will build the network redundancy model using the idea of spare line, whose availability is almost as same as that of the mesh topology.

6.2.2 Network Routing: Peer to peer networking

As popularized by the software known as Napster, peer-to-peer networking enables a PC to communicate data to other PCs. Other examples of software include FreeNet, and Gnutella.³⁷ For example in Figure 6.5, we assume that school-A to D are in the same village and use the same texts. Therefore, we can assume that the information which school-A needs to download from the Internet for its educational use can be already obtained by other schools like school-B. Therefore, school-A's PC can attempt to request school-B's PC if it has already downloaded the data from the Internet. The superiority of peer-to-peer networking is that school-A does not have to access the data's source site via the Internet all the way. This fact improves the reliability of the network for school-A because school-A might still be able to obtain its necessary data even if the line on the network-provider-upstream side of school-D is down.

In the evaluation of the measure, we assume like the same as the network redundancy case. Figure 6.6 shows how we calculated the expected data. From the calculation result for each line's availability (Figure 6.7), we can see that the network with peer to peer networking shows higher availability than the one without.

³⁷ *Distributed Systems Topologies*: Nelvin Minar, 2001. An introduction to peer-to-peer technologies.
http://www.openp2p.com/pub/a/p2p/2001/12/14/topologies_one.html

6.2.3 Software Caching: TeK

Offline Internet is a very promising approach, explored, among others, by the TeK group at MIT [TeK]³⁸. The idea is simple. When browsing the Internet, a user will have access only to pages locally stored in a big cache in the local disk. If a page is not locally stored, a request for the page will be queued, and sent the first time the machine goes online. At that time, the page is retrieved, stored to the disk, and made accessible to the user.

But a second way is offered by TeK. When a user is looking for some data on the Net, s/he will fill a form with the necessary keyword describing his/her interest. This information will be sent to a TeK server when the machine goes online. Later on, when the machine goes online again, the TeK system will retrieve the relevant data, and will let the user navigate them, as s/he would do from the result page of any search engine. All the results of previous queries, and queries from other users, are kept stored, and they are available to all the users. Over time, TeK will build a local library with knowledge interesting to the community.

A typical TeK workstation will connect to the TeK server once or more times a day, scheduled in a way to be the cheapest and the least intrusive possible. For instance, the TeK workstation can connect to the server in the night, when connection fees are cheaper and the telephone line is idle. During the connection, users' query are sent via email to a TeK server and processed.

At the same time, results for previous queries are retrieved from the TeK server, in a very compacted form, which strips out redundant HTML, reduces the volume of big pictures and excludes results known to be already in the user's school server. In our estimate, the compression is around 50% of the original size. Also, we estimate that 50% of the pages are already present in

³⁸[TeK] William Thies et al., *Searching the World Wide Web in Low-Connectivity Communities*, 2001

the cache, and not resent. This latter figure clearly averages the initial phase, when the local cache is still empty, and a later phase, when the local cache is rich of relevant information.

This system offers a series of clear advantages.

When connected, the line is used to carry on a sustained transfer of data. There is no idle time in the connection to due user's input when browsing the Internet. This means that the connection is used is a much more efficient way.

- There is no duplicate transfer of data. If some page was already accessed, the system will not download it twice. The system can also be configured to verify if some stored page has become obsolete due to an update in the original document. The system can send the page again only if the original has changed. This also reduces the volume of redundant transfer.
- HTML pages are stripped out of advertising, applets and other types of contents that do not contribute to the information value of the page. This will save precious connection, and the page will be easier to navigate. This kind of technology is today used to simplify HTML for portable low-bandwidth devices.
- As pages are locally stored, users do not experience slow downloading of the information they need. When they will be back a second time to navigate the results of their queries, all their data will be quickly accessed. This can be really important when the connection is slow and pages can take some minutes to be downloaded.
- The total daily movement of data is, as just shown, dramatically reduced. This means that, with the same type of connection (e.g. modem, radio, DSL), a better service can be offered to more users.

The usage of a TeK server to access the Internet can be expedient in enforcing policy choices. For instance, it can be used to filter out some information, such as pornography or gambling sites, which are not deemed suitable to the recipients. If the TeK server is accessed by students, the school director could enforce his/her policies by configuring the TeK server. If it is accessed by the whole country, the server could be set up to implement central Government choices.

At the moment, a TeK server is present at MIT, but it is possible to relocate it in any location with high bandwidth. We suggest Thimphu, or some city at the border with India, be selected to host a TeK server for Bhutan.

The TeK group at MIT showed that this approach can reduce the cost per megabyte of Internet information of up to 3 order of magnitudes. Instead of a costly connection to the Internet, users can take advantage of the cheaper technology of large hard disks.

In the rest of this work, we assume, with the expertise of our contacts in the TeK project, that a page is compressed to 50% of its size, and that 50% are reutilized by the TeK service and not re-transmitted.

As a software system, the functionality of TeK will be fully explored in the performance and cost models. First, the reliability/availability model is described.

6.3 Building Availability Models

In this section, we build availability model for each measure.

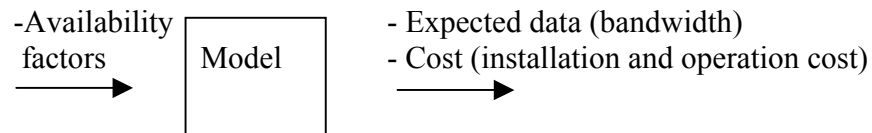


Figure 6.8. The general image of the model's flow

Figure 6.8 shows the image of each model's general flow. The outputs are to be input of our cost and performance models, which will be explained in the later chapters.

6.3.1 Availability Models for Phase I and II

As stated above, our deployment is divided into several phases. Phase I and II focus on schools equipped with both electrical power and telephone, including high schools and junior high schools. It is assumed that Internet is available for every school.

6.3.1.1 Using Network Redundancy

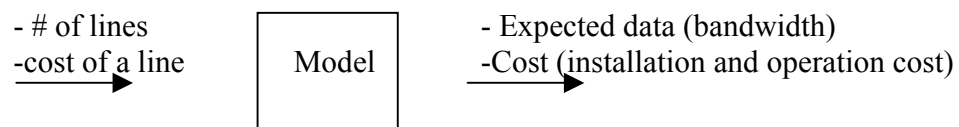


Figure 6.9. The image of the Network Redundancy model's flow

Figure 6.9. shows the image. Table 6.1. shows the availability model (each line's availability (PL) is 80%). The result is shown in Figure 6.10. As we can see from the graph of cost (Figure 6.11), improving availability requires more cost.

6.3.1.2 Using Peer to Peer Networking

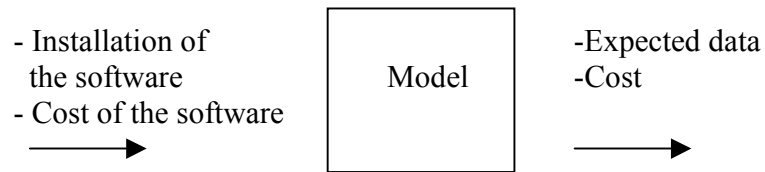


Figure 6.12. The image of the Peer-to-Peer Networking's model's flow

Figure 6.12 shows the image. Table 6.3 shows the availability model (each line's availability (PL) is 80%). The result is in Figure 6.13. As we can see from Figure 6.14, costs increases with improved availability.

6.4 Tables and Figures for Section 6

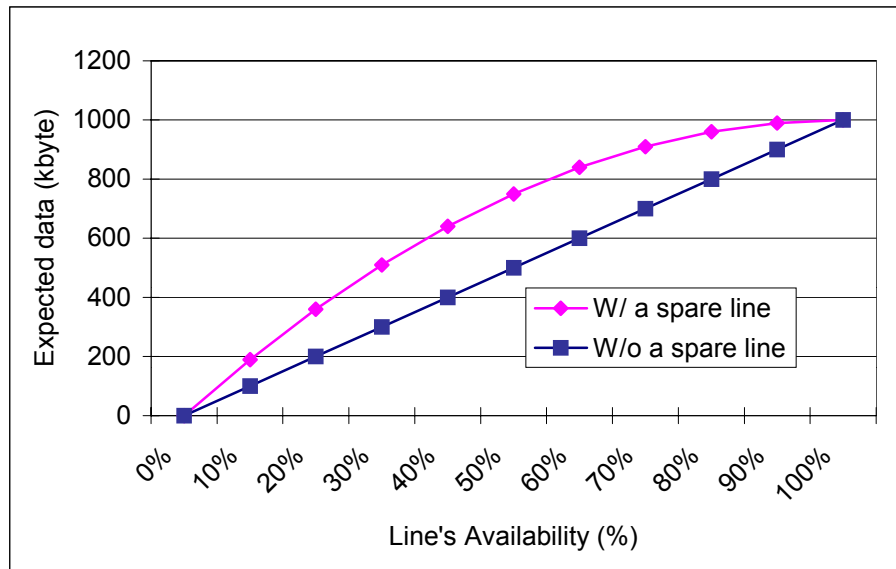


Figure 6.3. The Comparison of Availability

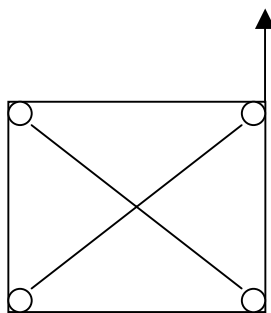


Figure 6.4a. Mesh Topology

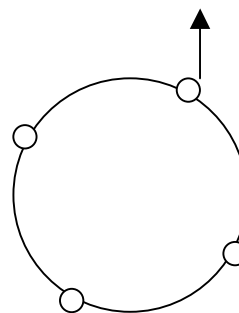


Figure 6.4b. Ring Topology

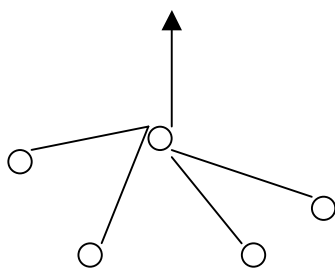


Figure 6.4c. Star Topology

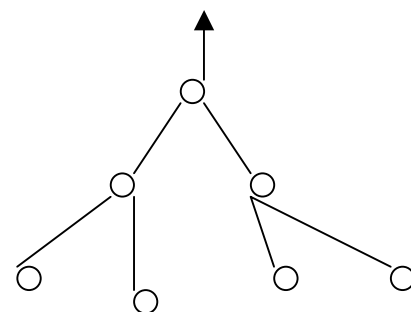


Figure 6.4d. Tree Topology

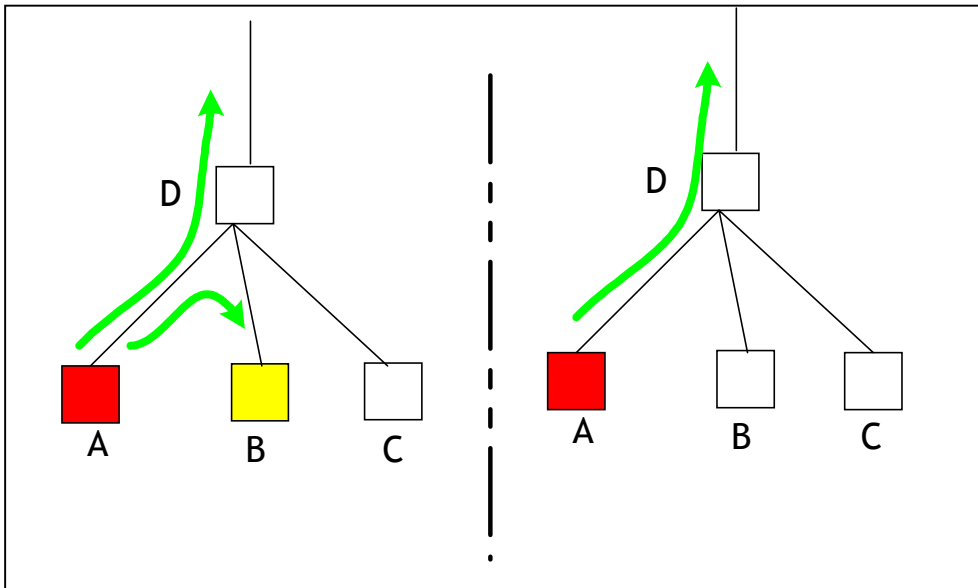


Figure 6.5. The Network with peer-to-peer networking (left) and without (right)

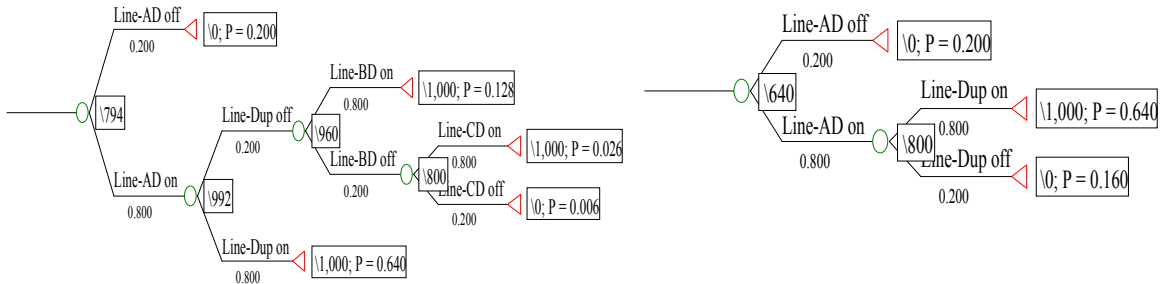


Figure 6.6. The availability event tree computation: with peer to peer (left) and without (right)

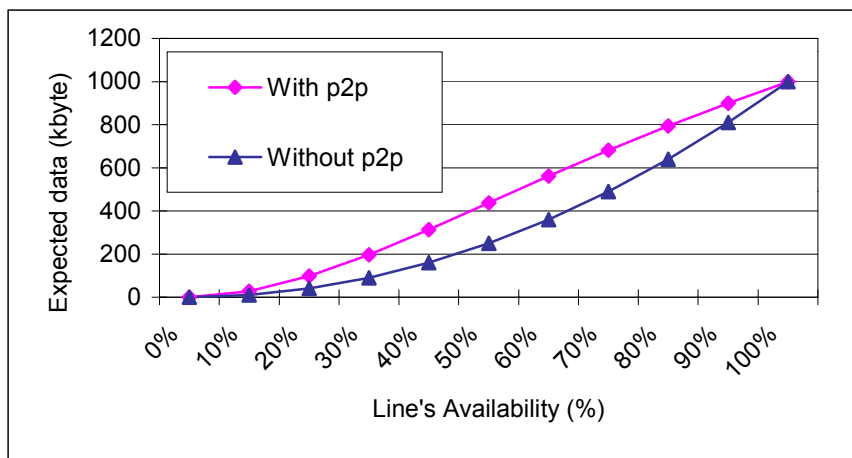


Figure 6.7. The Comparison of Availability

Model: (per school)
ex. PL=80%

Phase I,II (telephone)		
	Performance	Cost
Cost of line(dial-up)		
- Installation Cost		\$14
-Operation Cost/mo		\$157
Cost of line(leased)		
- Installation Cost		\$952
-Operation Cost/mo		\$952
# of data(kB)	1000	
PL(Line-1 on)	0.8	1
PL(Line-2 on)	0.8	1
PL(Line-3 on)	0	0
PL(Line-4 on)	0	0
PL(Line-5 on)	0	0
# of lines		2
Expected data	960	
Cost(dial-up): Inst		\$29
Cost(dial-up): Ope		\$314
Cost(leased): Inst		\$1,905
Cost(leased): Ope		\$1,905

Phase III,IV (radio)		
	Performance	Cost
Cost of line(radio)		
- Installation Cost		\$1,420
-Operation Cost/mo		\$100
# of data(kB)	1000	
PL(Line-1 on)	0.8	1
PL(Line-2 on)	0.8	1
PL(Line-3 on)	0	0
PL(Line-4 on)	0	0
PL(Line-5 on)	0	0
# of lines		2
Expected data	960	
Cost(radio): Inst		\$2,840
Cost(radio): Ope		\$200

Table 6.1. The availability Model of Network Redundancy: Phase I and II (left) and Phase III and IV (right)

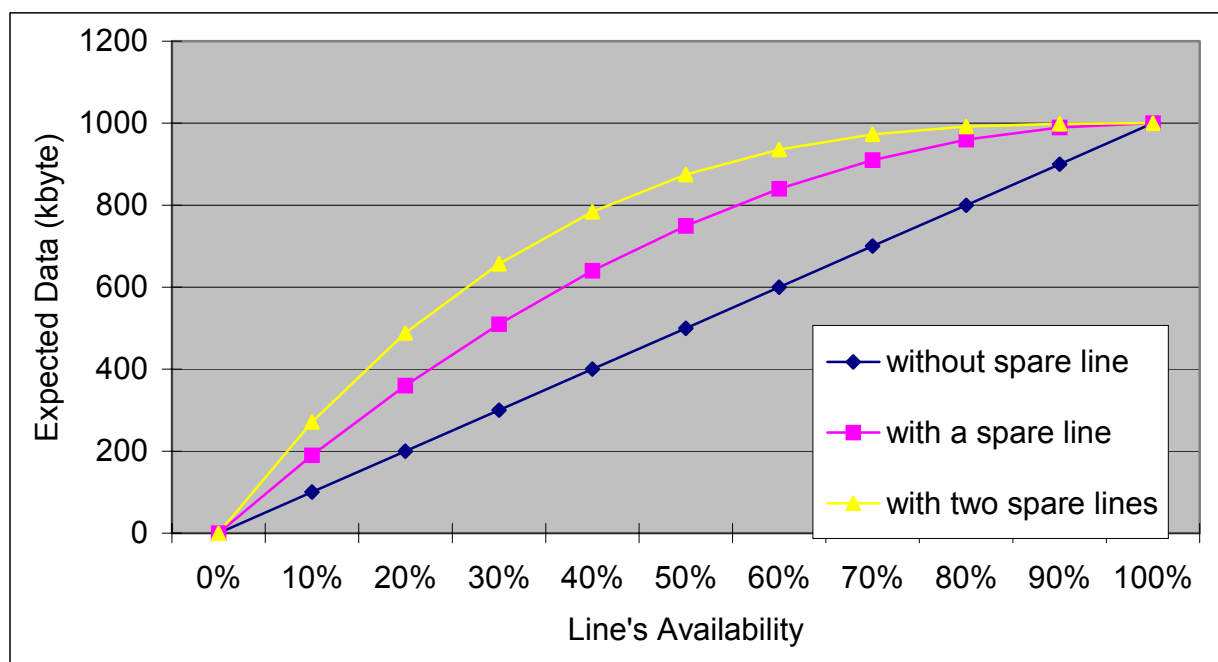


Figure 6.10. The Comparison of Availability (Network Redundancy)

	Inst. Cost	Ope. Cost
Without a spare line	\$1,420	\$100
with a spare line	\$2,840	\$200
with two spare lines	\$4,260	\$300

Table 6.2. The Cost Comparison (Network Redundancy)

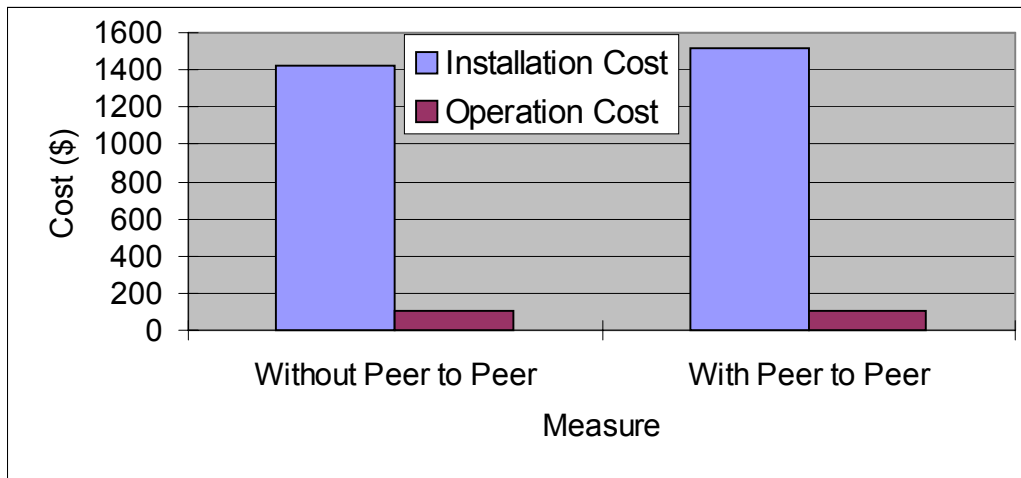


Figure 6.11. The comparison of cost (Network Redundancy)

Model:

ex. P=80%

Plan I (telephone)		
	Performance	Cost
Cost of line(tel.dialup)		
- Installation Cost		\$14
-Operation Cost/mo		\$157
Cost of software		\$100
# of data for A	1000	
P(Line-D-uplink on)	0.8	1
P(Line-A-D on)	0.8	1
P(Line-B-D on)	0.8	1
P(Line-C-D on)	0.8	1
# of line		4
Expected data	793.6	

(per school)

Plan II (radio)		
	Performance	Cost
Cost of line(radio)		
- Installation Cost		\$1,420
-Operation Cost/mo		\$100
Cost of software		\$100
# of data for A	1000	
P(Line-D-uplink on)	0.8	1
P(Line-A-D on)	0.8	1
P(Line-B-D on)	0.8	1
P(Line-C-D on)	0.8	1
# of line		4
Expected data	793.6	

Table 6.3. The Availability Model of Peer-to-Peer Networking

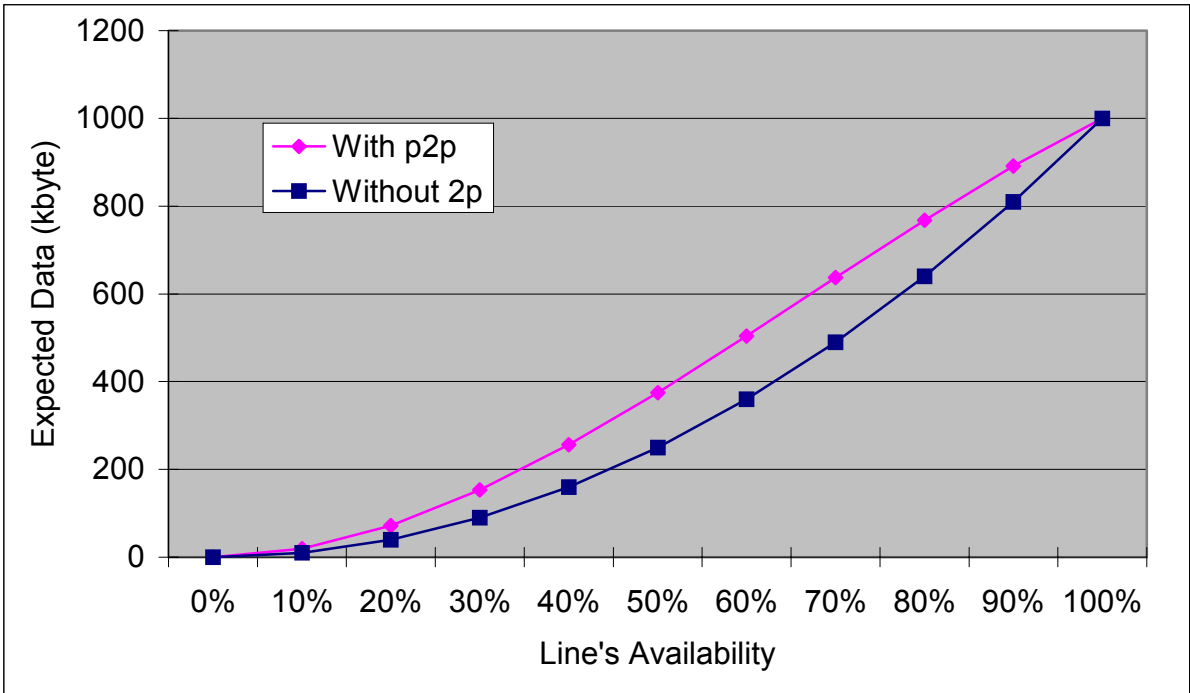


Figure 6.13. The Comparison of Availability (Peer-to-Peer Networking)

	Inst. Cost	Ope. Cost
With Peer to Peer	\$1,520	\$100
Without Peer to Peer	\$1,420	\$100

Table 6.4. The Comparison of Cost (Peer to Peer Networking)

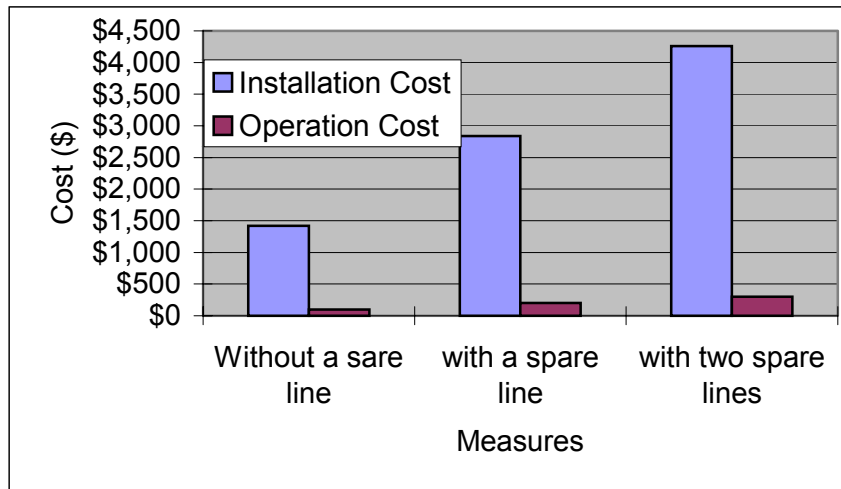


Figure 6.14. The Comparison of Cost (Peer-to-Peer Networking)

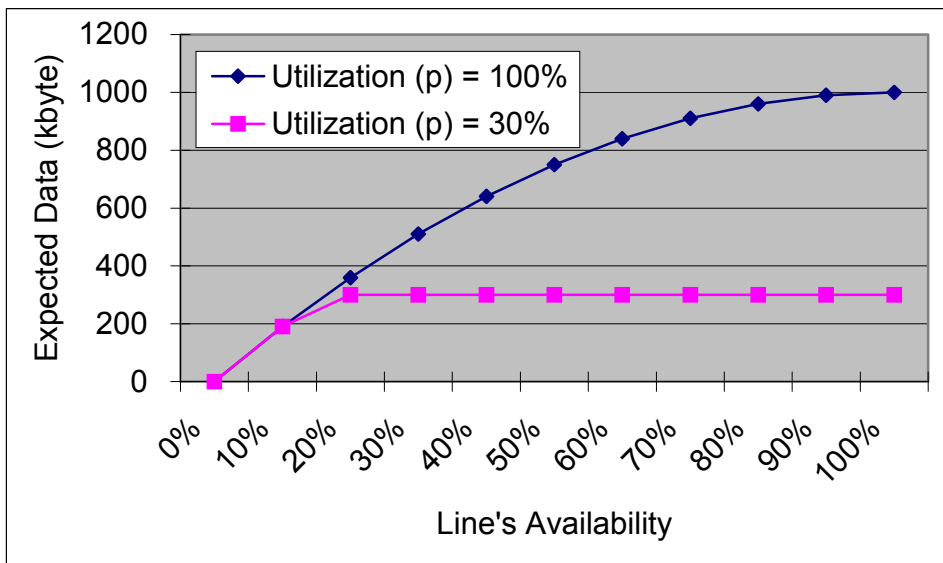


Figure 6.15. The Comparison of Expected Data (Phase I and II)

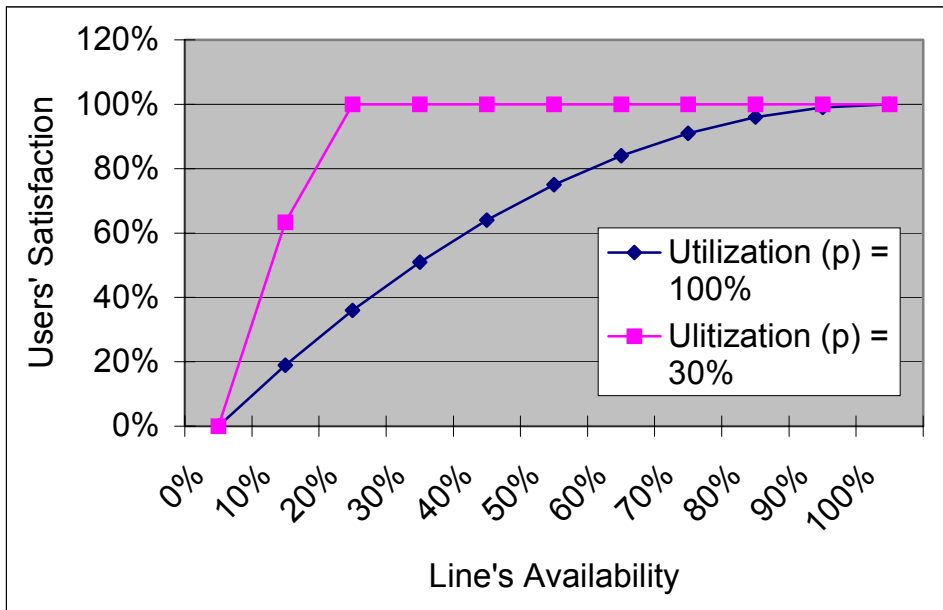


Figure 6.16. The Comparison of Users' Satisfaction (Phase III and IV)

7 Performance Analysis of Deployment Strategies

7.1 The Performance Index

In our analysis, we needed a quick way to compare different systems and the service they could deliver to users. This is why we spent some energy in developing what we called *Performance Index* (PI). PI measures the daily productivity of the Internet connection offered by a specific installation. It is computed as

$$PI = \sqrt{\text{daily 1 - page email} * 10 + \text{web kB} * 0.4 + \text{other service kB} * 0.3 * \sqrt{p}}$$

;where p was defined in Section 5.6.1.1

PI is an absolute value, and it is used only for comparison. In our work, it is used to compare the performance of solutions with similar costs, and the cost of implementations with similar performance.

The rationale for the way it is built is as follows. First, we compute a function of the volume of information that the user desires to transmit through the system. We usually measure the daily performance. Then, we weight this metrics with the probability of success of a connection. If the line is not very reliable, and the probability of actually connecting and retrieving the data is low, the performance will be lower than that of a very reliable connection.

The square root describes the decreasing marginal utility of more connection. The weights are chosen to allow a comparison of apples with oranges, that is emailing, web browsing and other data download and upload. We estimated that a 2-page email is worth as much information as a small web page (50 kb). For other services (PDF, MP3...) we considered a smaller weight of 0.3.

In most of this work, we compare TeK and legacy systems. We are aware of the different service that a legacy system can offer with respect to a system featuring TeK. While a TeK user has to wait to retrieve the results asked for, the latency of online browsing is totally avoided, resulting in a faster work once the results are back.

Consider a user with a modem connection (let's assume 43 kbps), looking for some data in the Net. S/he will query some search engine, and start scanning the first results for the needed data. Let's assume s/he will actually browse 3 from the first set of results, and then refine the query. If the search engine can find the relevant data with 70% probability, the correct results will be found, in average, within $1/0.7 = 1.4$ queries. For every query, the user will browse 3 results. A medium size web page, with pictures, is about 100kb. It will take about 20 seconds to load it from the web. If the page is analyzed for 30 seconds, a query will be probably issued and analyzed in about 4 minutes. The needed result will be found in $4 * 1.4$ minutes, about 6 minutes. In one hour, this user will be able to productively retrieve 11 pages of relevant data.

This table describes the time spent in analyzing and downloading 3 results reported from a query with a search engine. Times are in seconds.

Describing the query	>	Result from engine	>	First result	>	Second result	>	Third result
30		20		30		20		30

Table 7.1. Timing for search engine query; times in seconds.

If a TeK user spend $30 * 40$ seconds = 20 minutes to issues 40 queries, the next day, still assuming 70% of accuracy, s/he will find correct results for 28 queries: in one hour, the second day, s/he will browse, with no latency as information is stored locally, the results for all queries ($40*3 = 120$ results). 28 results will be relevant. The user can choose to browse more than the

first three result, or issue a refined query and see the results next days. With waiting one day, the user has a better chance to find the interesting result.

We are strongly tempted to say that a system featuring TeK, in this scenario, should be awarded a higher performance index: when the bandwidth is limited and poses a constraint, TeK can boost productivity.

In 80 minutes, a user can retrieve 15 pages when online (about 11 queries a hour). Splitting the same time in querying TeK and analyzing the results, the user can access to 28 useful pages. We are unable to compare if 11 pages today are better or worse than 28 tomorrow – they can better for a doctor that needs time-sensitive information to save a patient, probably the second option is better for a student gathering information for a paper, or for a farmer looking for the best crops for the incoming year. This tradeoff is similar to what can be faced with other kinds of communication: for instance, with the postal service, a person can send a big case, or rush a small package spending the same amount of money.

This is why we chose not to incorporate any notion of time in the performance index. Different users have different time-constraints and needs. The choice between these two methods is responsibility of the administrator of the system. For some categories of users, TeK will be a better solution. We believe that students will probably be better served by TeK. Also, TeK will be a cheaper in term of connection costs.

7.2 Performance-Cost Tradeoff

TEK, as said, can be used to reach higher performance with the same infrastructure. This table compare three system, with 2 dedicated phone lines, with 1 dedicated line, and with 1 shared line. Higher performance indices can be reached with TEK. The bandwidth (before

compression) reached by TEK is much higher and allows more performance. If we do not want to use TEK, we have to limit ourselves to lower performance indices.

	EXPLOITING TEK			ONLY LEGACY		
	2 ded. lines	1 ded. line	shared line	2 ded.lines	1 ded. line	shared line
Performance Index	56.9	42.2	26.8	27.8	18.9	9.2
need daily bw	3,238	1,780	718	772	359	84
Feasible legacy?	XXXXX	XXXXX	XXXX	OK	OK	OK
Feasible tek?	OK	OK	OK	OK	OK	OK
Max bandwidth w/legacy	619,200	309,600	77,400	619,200	309,600	77,400
Max bandwidth w/TeK	928,800	464,400	232,200	928,800	464,400	232,200

Table 7.2. Performance Index comparisons between TeK and Legacy connection systems

The following graph shows how costs are kept small even with high performance indices with TEK, while they explode when using legacy.

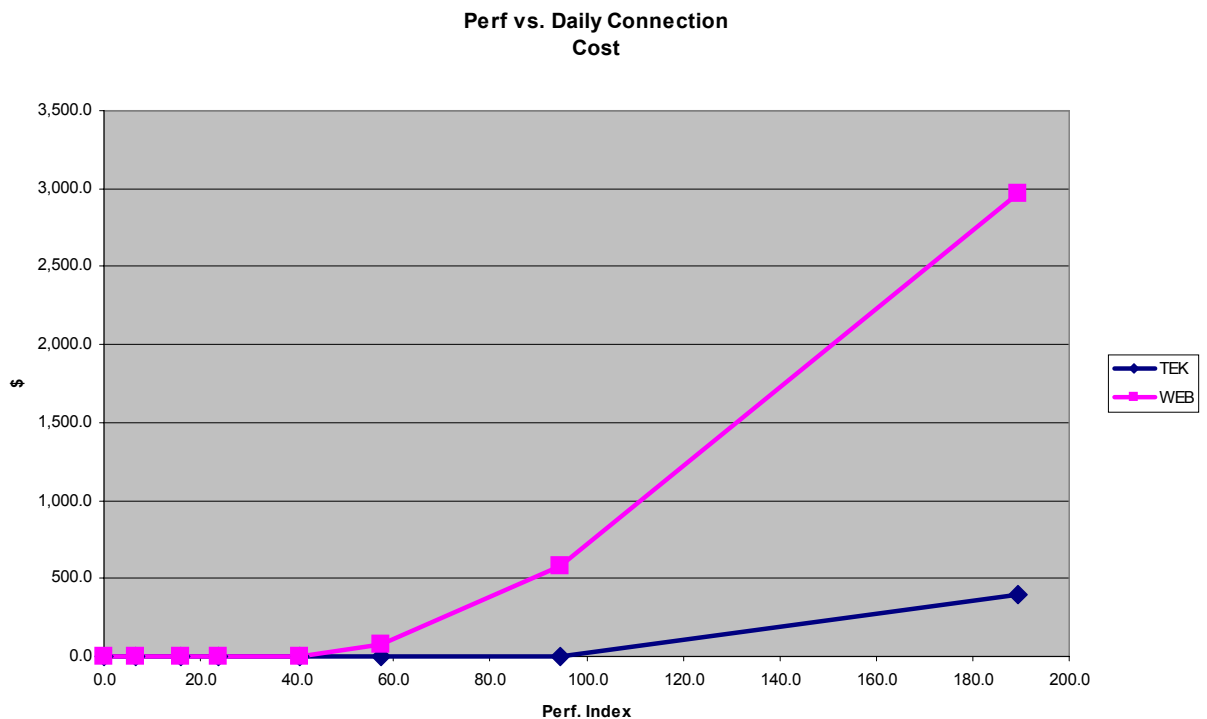


Figure 7.2. Graph of Performance Index vs. Cost with TeK and Legacy (labeled Web).

7.3 Deployment of School Network for Phase I

In the first implementation phase, high schools will be addressed. Our plan aims to give a good Internet connection to all the high schools students in Bhutan. To do this, our model plans to install a large number of computer, and to give the students a package of services that can give them the opportunity to communicate with other students in the world, and to access academic information on the Internet.

The first expenses will be the installation of a computer every 10 students. They will have scheduled access to the Internet as follows.

Activity	Items	Every X days
Email	20 2-page emails	2
Web browsing	2 hours, 20 pages a hour	2
Downloading papers	2 PDF papers	7
Effective users: 70% of the total (800)		

Table 7.3. Demand profile for Phase II users

Every other day, a student will be allowed to send up to 20 emails, and two browse 40 pages on the Internet. Also, every week s/he will be able to download a couple of pages for his/her research. A big part of the student community (students with ongoing projects, involved in student activities) will be allowed to access to the Internet.

Allocated bandwidth: two dedicated phone lines

7.4 Deployment of School Networks for Phase II

In the second implementation phase, junior high schools will be addressed. As all junior high schools have a similar existing power and communication infrastructure, a similar

methodology to high schools (Phase I) is used. The implementation of Phase I can serve as part of the learning curve before proceeding with Phase II.

Table 7.4 shows the assumed demand profile for Phase II users.

Activity	Items	Every X days
Email	20 2-page emails	4
Web browsing	2 hours, 20 pages a hour	7
Downloading papers	2 PDF papers	15
Effective users: 50% of the total (400)		

Table 7.4. Demand profile for Phase II users

Allocated bandwidth: One shared telephone line

7.5 Deployment of School Networks for Phase III

Phase III and IV focus on schools without electrical power and telephone, including primary schools and community schools. We will have to borrow telephone line via some measures to the nearest facility with a telephone line. In order to make this possible, we propose to build a network with short wave radio system as the measure because the measure is cheap and reliable. In fact, the short wave radio communication had been used for international telecommunication until satellite telecommunication became available. The measure is also appropriate for Bhutan like mountainous country. Using short wave radio transmission gives 8 kbps data communication. Although this bandwidth might sound a little narrow for data communication, we assume that the bandwidth would be appropriate because people of phase III and IV would not use the Internet so often. We propose to use solar power system as a power supply measure because the measure costs little and easy to setup.

Activity	Items	Every X days
Email	15 2-page emails	4
Web browsing	1 hours, 15 pages a hour	7
Downloading papers	0 PDF papers	
Effective users: 40% of the total (100)		

Table 7.5 Demand profile of phase III users

Allocated bandwidth: two radio lines

The assumed demand is shown in Table 7.5. A computer will be prepared for every five students. We are going to build two radio lines, connecting a school with different two schools equipped with telephone facility. In our analysis, the operation cost includes the telephone fee.

The necessary components for the wireless communication are a short wave transceiver, a Terminal Node Controller (TNC), and an antenna (see Fig 1). The costs are about \$500, \$400, and \$20 respectively³⁹. This communication method is called packet radio, whose protocol, AX25, was established in 1982 by the Amateur Radio Relay League of America. TNC corresponds to a modem of telephone-based data communication.

7.5.1 Cost Structure for Phase III

7.5.1.1 Solar Power

The system mainly consists of a photovoltaic module, a battery, offering around ten hour power supply. The availability of the components is good. The output power requirement

³⁹ Martin Diggins, *Enhancing Distance Education through Radio-Computer Communication*, 1990, <<http://cleo.murdoch.edu.au/aset/confs/olnt90/diggins.html>>

is to supply a PC, a printer, and a set of communication system. Its approximate total installation cost is around \$500 in 1994⁴⁰. Its operation cost is low because the solar energy is free.

7.5.1.2 Wireless Communication

The necessary components are a short wave transceiver, a Terminal Node Controller (TNC), and an antenna (see Figure 7.5). The costs are about \$500, \$400, and \$20 respectively⁴¹. This communication method is called packet radio, whose protocol, AX25, was established in 1982 by the Amateur Radio Relay League of America. TNC corresponds to a modem of telephone –base data communication.

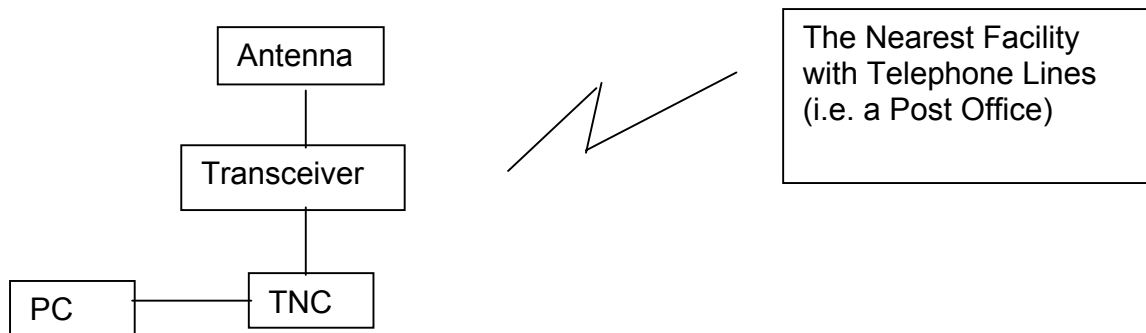


Figure 7.5. The system using wireless communication

Peer-to-peer networking software is assumed to be available from the Internet freely. The setup, installation and support costs are not included in this computation.

⁴⁰ : Richard Perez, "Photovoltaic Power for the Permanently Portable," Home Power #38, pp32, December 1993/ January 1994, <http://www.humboldt1.com/~michael.welch/extras/laptopv.pdf>

⁴¹ : Martin Diggins, *Enhancing Distance Education through Radio-Computer Communication*, 1990, <http://cleo.murdoch.edu.au/aset/confs/olnt90/diggins.html>

7.6 Deployment of School Networks for Phase IV

The strategy for this phase is similar to that of Primary Schools in Phase III. We will use the same model and just different numbers. In phase IV, there are more schools without electrical power than phase III. Therefore, total cost required for solar power systems will be much more than that of phase III.

Activity	Items	Every X days
Email	15 2-page emails	4
Web browsing	1 hour, 15 pages a hour	7
Downloading papers	0 PDF papers	
Effective users: 40% of the total (50)		

Table 7.6. Demand profile of Phase IV users

The assumed demand is shown in Table 7.6. A computer will be prepared for every 25 students. We are going to build one radio line, connecting a school with another school, equipped with telephone facility. In our analysis, the operation cost includes the telephone fee.

Allocated Bandwidth: one radio line.

8 Cost Analysis of Deployment Strategies

We developed a complex model cost to determine the feasibility of our project. The model starts with a short description of a proposed architecture, with 7 parameters:

- Installation cost in dollars, including computers, solar panels, telephone lines and radio links,
- Daily average day hours uptime,
- Daily average night hours uptime, exploited by tek,
- Offered bandwidth (kbps),
- Hourly connection cost,
- Yearly cost of maintenance,
- Number of users.

These parameters are computed starting from our estimation of the single costs (computers, telephone lines...). With these data, we can easily compute the average available bandwidth, and we can allocate it to the users. We then design a performance profile that fits the available bandwidth. Using TEK, we can reach higher performance indices. We then compute the connection costs for the desired performance. This allows us to quickly computed the deployment costs. The following table and graph show the costs for the first eight years. In the first four years, the equipment is all bought and installed. After that, the maintenance costs fades out and stabilize around 2 million dollars a year.

Year	Phase I	Phase II	Phase III	Phase IV	Total
0	1,730,750				1,730,750
1	1,646,926	2,967,000			4,613,926
2	1,482,233	1,172,534	854,000		3,508,767
3	1,334,010	1,055,281	871,075	494,760	3,755,126
4	1,200,609	949,753	783,968	896,718	3,831,047
5	1,080,548	854,777	705,571	807,046	3,447,942
6	972,493	769,300	635,014	726,341	3,103,148
7	875,244	692,370	571,512	653,707	2,792,833

Table 8.1. Deployment cost of all phases over 7 years.

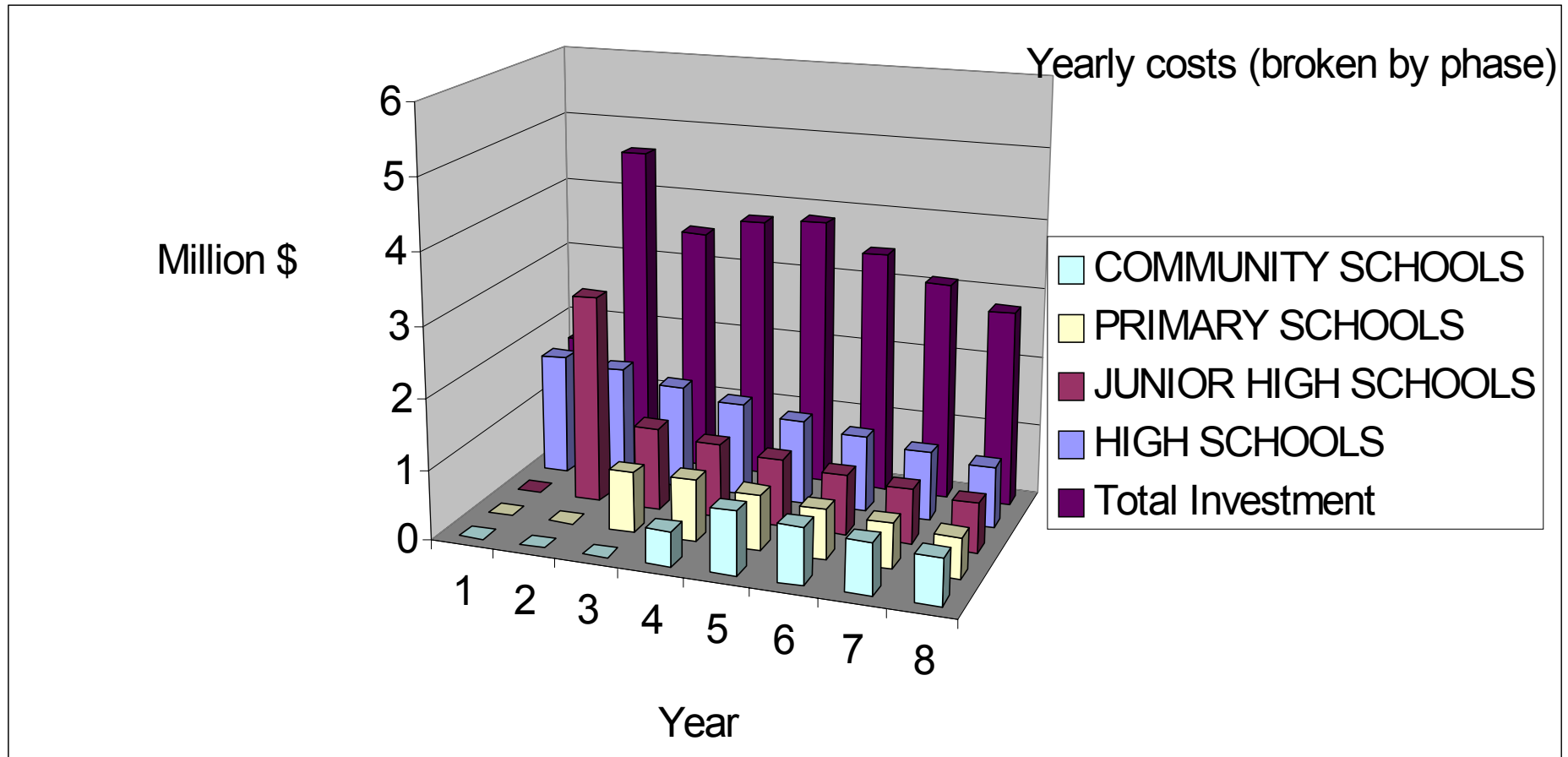


Figure 8.1. Comparison of deployment costs across phases

9 Overall Analysis of Results

9.1 Accuracy

The analysis methods and the integrated approach presented are versatile and with addition expansion can be adapted for different developing countries and network environments. For our case study on Bhutan, and for the Bhutan School Networks, the realism of the results depends heavily on the accuracy of data and the assumptions made.

While data on the number of schools and the population is rather accurate, the performance and cost of the hardware devices and the overall Bhutanese School Network system will vary widely depending on what can be procured from the market at the time of implementation. For example, the ISP, Druknet may reduce its connection costs or the price of installing computers, communication links and power can change dramatically. Historically, the prices of computer hardware have been falling over time, giving the benefit of doubt in favor of having over-estimated the costs.

The data for reliability and performance indexing is much more malleable. As assessed earlier, a true systems reliability analysis would require engineering knowledge of an entire network design, beyond a business case proposition. Our analysis has, however, extended beyond introducing reliability as a simple variance in bandwidth, and availability but shown a toolkit of methods for quantifying it. Given a more detailed network system scenario, the overall accuracy of this analysis should improve significantly and become a viable decision-making factor next to the cost model.

9.2 Sensitivity

To verify the validity of our assumption, we run a sensitivity analysis for the model. Four parameters affect particularly the final costs: the yearly cost of replacement and maintenance of hardware (expressed as a percentage of the original costs), the reduced cost of hardware in the future due to technology improvement, the cost of connection, and the cost of initial equipment.

We saw how different values affect the final cost. For our comparison, we verified the yearly cost at the 5th year, that is when all the phases are started and running.

Parameter Name			Change In Final Cost
Connection cost (\$/min)	MIN	0.03	89%
	MAX	0.05	126%
Initial equipment cost PC cost (\$)	MIN	400	91%
	MAX	800	109%
Replacement (%)	MIN	0	73%
	MAX	25%	118%
Discount rate/Moore's law (%)	MIN	85%	80%
	MAX	95%	124%

Table 9.2.1 Variation in baseline parameters for sensitivity analysis

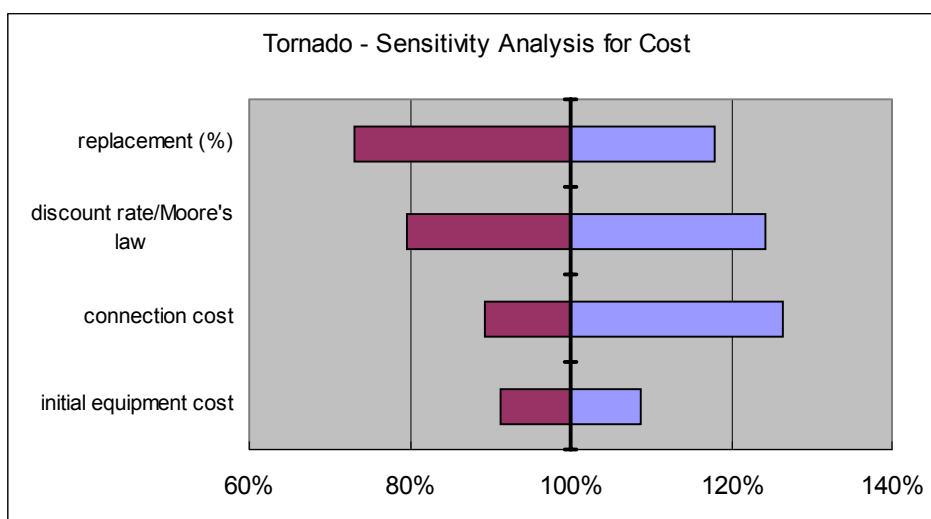


Figure 9.2.1. Tornado sensitivity chart.

The connection cost can contribute to drive the costs quickly up. Also, the replacement costs have a big impact. According to the cost of maintenance, the final costs can move from 80% to 120% of the costs we computed. The maintenance costs are affected by the cost of transportation, the cost of technicians and other factors we cannot easily determine. Similarly, the way technology becomes cheaper over time can change strongly the final costs. On the other side, the initial cost of equipment does not have a strong effect.

This analysis shows that the budget we propose is consistent within a range $\pm 20\%$. If the costs are in the maximum range, the budget can still be met by reducing proportionally the number of computers or the hours of connection with small effort.

10 Recommendation

10.1 Deployment Strategy

According to the Bhutan Education Master Plan, we propose to phase the deployment in four phases. The first will cover the high schools in the country, the second junior high schools, the third primary schools, and the last phase will cover community schools. The first phases will be more standard installations: in towns, we can rely on a good connection. Phases I and II will mostly consist in installing computers and modems in the schools. Phases III and IV will include setting up a radio connection from the school to another hub, equipped with modem. The hub will redirect the communication from the radio link to the telephone line. The expertise developed during phases I and II will be important in addressing the two latter phases.

For phase I, we propose the installation of a computer every 10 students, and to schedule the available bandwidth to students as shown in section 7.3. Students will have abundant email connection, reasonable web browsing and the opportunity to download, when needed, bigger documents such as PDF papers. We propose to install the TeK software to reduce the connection costs and improve users' satisfaction. We verified that the most effective solution is to dedicate two phone lines to Internet connection. This offers enough bandwidth to reach the proposed performance goal, and limits costs.

Phase II will be similar, the main difference being that the Internet connection will be carried on by the existing phone line. The line will be used 3 hours a day just for Internet connection, and will be used 8 hours in the night. These night hours can be usefully exploited by TEK, to download data that the students can use during the day. The reduced connection will affect the performance offered by the system that as shown in section 7.4.

Primary and community schools, in many cases, do not feature phone lines and electric power. The installation and maintenance costs will include the setup of solar panels and radio links to the nearest telephone line. Actually, the cost model imagine to setup a dedicated line at the connection point, even if in many cases the low traffic of the schools can be interleaved with other traffic.

In phase III, we install a computer for every 20 students. There will be two radio links to two different locations to improve reliability. The dependence to solar power and radio connection limits strongly the available bandwidth. Nonetheless, using TeK, the students will be able to experience a reasonable connection, as shown by the schedule in section 7.5.

Phase IV will be similar. We propose to install a computer every 25 students in the primary school. Also, only one radio link will be available. The reached performance is described in section 7.6.

We propose to start the four phases with one year of distance from one another. This will allow to collect expertise and experience, and to schedule the funding.

10.2 Funding Strategy

Our funding strategy is two-pronged. First, we will seek support from the UNDP, which has been very active in supporting IT development in Bhutan in recent years, through both small and large projects. Second, we will propose directly to the RGOB's Ministry of Education to incorporate our models into their existing *Education IT Master Plan*. The integrated approach described by our models fit logically into this existing plan, and will bring with them the benefits of increased reliability and lower costs.

10.2.1 UNDP and other Donor Agencies

Much of Bhutan's development, both in general and specifically in telecommunications, has been funded by bilateral and multilateral donors. In 1961, Bhutan's roads were built with India's assistance, and the entirety of the first two five-year plans was financed by the Government of India through grants. Other important donors have included various UN agencies, the Asian Development Bank, and bilateral donors such as Japan, Switzerland, Denmark, Germany, and the Netherlands. In 1984, 71% of the country's revenues consisted of grants, with India providing about half. Bhutan has been able to decrease its reliance on donors somewhat during the 1990's, but its development still depends largely on foreign aid. In terms of recent telecommunications development, organizations that have been active include the UNDP, the Japan Human Resources Development Fund (HRDF), UNESCO, and the Asian Development Bank. As has been noted, the National Telecommunications Network was established with grant aid from Japan.⁴²

We propose to apply for funding from the UNDP, which has been particularly active recently in the development of IT in Bhutan, and has been involved in both large-scale projects and smaller pilot initiatives. According to the UNDP Resident Representative in Bhutan, the UNDP has promised that it "will take the lead in bringing new information technologies to remote parts of the world." In Bhutan, the UNDP has done just that. In 1999, the agency helped to establish DrukNet, at a cost of \$115,000. In addition, the UNDP funded the training of telecommunication staff and, in 2000, helped establish the DIT.⁴³

⁴² *BNHDR 2000; Bhutan 2020.*

⁴³ Pek, 1.

In a smaller project in 2000, the UNDP ran an initiative in which it purchased blocks of Internet access time directly from Internet cafes in Thimphu and distributed them to unemployed youth. The cafes provided full-time assistants to the participants, and their progress was tracked, so that their skills could be evaluated. The project was also designed to gauge interest in IT by Bhutanese youth. Interest was high enough that the project was repeated in 2001.

In a larger project, the UNDP, with funding assistance from the Japan HRDF, has launched a \$450,000 “Information Network for Good Governance” program at Bhutan’s Planning Commission. Designed to help in the government’s goals of decentralization and rural development, the program is expanding Internet access outside of Thimphu, both in the form of a vertical communication network between the central government and district administrations, and through online information networks and databases for select communities.⁴⁴

We believe our project is in line with what the UNDP has been doing in Bhutan, and are confident we can receive funding.

10.2.2 Education IT Master Plan

Our second funding strategy will be to go directly to the Ministry of Education, and seek to have our project integrated into its existing *Education IT Master Plan*. This plan, budgeted at \$24.1 million, includes future programs to develop IT facilities in public schools.⁴⁵ As mentioned above, the Ministry of Education intends to provide IT training in all schools, with the goals being to “provide computer access to all schools and produce computer literate high school graduates by 2010.”⁴⁶

⁴⁴ BHU/00/004 *Information Network for Good Governance*; Pek.

⁴⁵ *Education IT Master Plan: A Summary*. (PowerPoint presentation.) Available from <http://www.dit.gov.bt/training/workshops/march30-2001/education-masterplan.pps>.

⁴⁶ *ICT Development Master Plan*, 24.

We believe our project can be integrated into the current plan, and will provide both increased levels of reliability and cost savings.

11 Future Path

11.1 Opportunities for Bhutan

The Bhutanese School Network is only a first step towards enhancing the schoolchildren's ability to seek information from the world and for the communities to communicate together.

Bhutan has highlighted several opportunities that they can engage in to provide employment for its people. They include providing IT services such as transcription and design to customers, including those that are geographically distant but communicable over the Internet. The Government can aid the spread of entrepreneurship and small businesses by managing and disseminating information about the provision of grants and microloans over the Internet. In summary, the ability of its population to engage in a changing economy where manipulation of knowledge and information is valued, will ease development for the physically-separated country.

11.2 Improvements to Modeling Techniques

The logical improvement would be an expansion on all three major portions of the integrated approach to be able to conduct simulations on different scenarios. For the reliability model, improvements would be integrating reliability in addition to availability, and applying the analysis across a better baseline set of input parameters. For the performance model, improvements would be profiling users better to form a greater correlation between the raw throughput and user satisfaction. The inclusion of latency, or time, into the performance model could be attempted, but as explained earlier, it is heavily fraught with uncertainty towards how different users, from different psychological, social, and cultural backgrounds would affect their

perception of latency in performance. Finally, for the cost model, including support, training, and installation costs could augment the fixed and variable costs of implementing the network. So would considering the financial options including the cost of capital (i.e. discount and interest rates).

12 Summary and Conclusion

To summarize, the Bhutanese government, as far as evidenced from the various master plans, is eager to embrace IT on its own terms.

Schools are good places to being, because of their extensive network, especially among children. They are also relatively well equipped with infrastructure such as power and communication links.

When implementing a system, we need our models to account for reliability because the availability of power and communication are uncertain. The integrated approach with a sequential link from reliability, to performance, and then finally to cost provides a good method for specifying the desired performance, based on user satisfaction, with respect to cost, in an environment with significant variances.

Improved reliability is achieved with innovative software techniques such as TeK and Peer-to-peer networking, without big increases in hardware costs.

Our deployment strategy is in line with plans from the Bhutanese Government and the methodology and suggestions offered should be of interest to planners considering such a Bhutanese School Network deployment.

14 Thanks

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