A linear response surface analysis approach to evaluate QoS factors in wireless networks

J.A. Brand

21085714

Dissertation submitted in partial fulfilment of the requirements for the degree

Master of Science at the Potchefstroom campus of the North-West University

Supervisor: Prof. H.A. Krüger

Co-supervisor: Mr. H. Foulds

November 2012

ABSTRACT

With the growth of wireless networks and the increase in personal internet use for a wide diversity of applications, the importance of the quality of service (QoS) delivered to clients has become of great importance. In order to evaluate QoS, this study explores the application of the linear response surface analysis (LRSA) technique as an evaluation tool for QoS factors such as Throughput and Delay. An 802.11n prototype wireless network is constructed in order to capture QoS data that is then used to construct LRSA models in order to evaluate the QoS factors. The LRSA models are maximised and minimised while constraining specific measured QoS factors and the subsequent results are analysed. Based on this analysis, recommendations for the improvement of wireless networks are made as well as the use of the LRSA technique to evaluate QoS within a wireless network.

Keywords: Quality of service (QoS), Linear response surface analysis (LRSA), Wireless Networks, Optimisation, Throughput, Delay

OPSOMMING

Met die groei van draadlose netwerke en die toename in persoonlike internet gebruik vir diverse toepassings, het die belangrikheid van dienskwaliteit ("*Quality of Service*") wat aan kliënte gelewer word verhoog. Ten einde dienskwaliteit te evalueer word die toepassing van die lineêre responsoppervlak ontleding (LRO) tegniek as 'n evalueringshulpmiddel vir faktore van dienskwaliteit soos Deurvloei en Vertraging deur die studie ondersoek. 'n 802.11n prototipe draadlose netwerk is opgestel vir die vasvang van dienskwaliteit data wat gebruik word om LRO modelle te konstrueer ten einde die faktore van dienskwaliteit te evalueer. Die LRO modelle word gemaksimeer en geminimeer terwyl spesifieke faktore van dienskwaliteit beperk word, gevolg deur die ontleding van die resultate. Gebaseer op hierdie ontleding word aanbevelings gemaak oor die verbetering van draadlose netwerke so wel as die gebruik van die LRO tegniek vir die evaluering van dienskwaliteit binne 'n draadlose netwerk.

Sleutelwoorde: Dienskwaliteit, Lineêre responsoppervlak ontleding (LRO), Draadlose Netwerke, Optimeering, Deurset, Vertraging

Acknowledgements

Firstly, I will thank God for being with me this past year and for providing me with the ability to study and the power and perseverance to complete this work.

I wish to express my sincere appreciation to my supervisors, Prof. Hennie Kruger and Mr. Henry Foulds for their patience and their help in finalising this dissertation.

I would also like to thank the people closest to me, my mother Sonnette, and my father Kobus, for all their support, not only in the past year, but the preceding years also and for providing me with the opportunity to complete a fifth year of studies.

To my companion of the past four years, Stephanie, thank you for all your support and love this past year.

To Chris and Roswitha Maritz, thank you for your support and advice whenever I sought it.

To my brother, Sarel, thank you for your support and advice.

To Robert, my thanks for your support and interest in this study.

To the following personnel of the Faculty of Natural Sciences, Lusilda Boshoff, Prof Machiel Kruger and Prof Hattingh, I thank you for your time and your advice on the problems I experienced during the study.

To Mr. Malcolm Ellis for the language editing.

CONFERENCE PROCEEDINGS

Excerpts from the current study have been presented as follows:

A linear response surface analysis approach to evaluate QoS factors in wireless networks

BRAND, J.A.; Kruger, H.A.; Foulds, H.2012.
(Presented as a poster presentation at the Southern African Telecommunication Networks and Applications Conference (SATNAC) in George, South Africa,2 to 5 September 2012)

A linear response surface analysis approach to evaluate QoS factors in wireless networks

BRAND, J.A.; Kruger, H.A.; Foulds, H.2012.
(Presented as podium presentation at the 41st Annual Conference of Operations Research Society of SA (ORSSA) in Johannesburg, South Africa, 17-19 September 2012)

Table of Contents

List of Figures

Chapter 1 - Introduction

Chapter 2 - Quality of Service in Wireless Networks

Chapter 3 - Linear Response Surface Analysis

Chapter 4 - Prototype Wireless Network

Chapter 5 - Empirical experiments and results

List of Tables

Chapter 3 - Linear Response Surface Analysis

Chapter 4 - Prototype Wireless Network

Chapter 5 - Empirical experiments and results

Chapter 1

Introduction

1.1 Introduction

In the last few years, wireless technologies have become more popular with businesses who have sought to discard wired networks due to their innate limitations. One of the most deployed wireless technologies over the world is the IEEE 802.11 wireless LAN (Hamidian & Körner, 2006). It is flexible and cost effective, providing users with a ubiquitous communication medium and will possibly play an important role in the future of wireless communication.

The quality of service provided by a wireless network is key to the popularity and usefulness of a network (Hamidian & Körner, 2006). This makes it important to measure quality of service as it is important to both the user and network provider as the provider wishes to provide the best quality of service to its customers and the customer expects the best quality of service (Sharma & Singh, 2011). There are a number of mathematical methods available that can be used by network administrators to evaluate the quality of service of their networks.

Stepwise models, such as linear regression and linear programming, could be used to evaluate the quality of service. These techniques analyse the relationship between certain variables and can be used to predict possible values of appropriate QoS factors based on the values of other variables (Bruwer & Hattingh, 1985). These techniques, however, have some limitations in regards to explaining interdependencies between variables and determining the exact variables to include in a model. The techniques may, therefore, result in unrealistic solutions in some instances. In order to overcome such limitations, a LRSA approach is proposed for the evaluation of the QoS of a wireless network.

The purpose of this chapter is to guide the reader through the research study by presenting the problem statement, the goals of the study and the methodology employed. A layout of the study, explaining the purpose of each chapter is also presented.

1.2 Problem Statement

Quality of service can be defined as a collection of techniques applied in a network in order to ensure predictable results for the network (Ivanovich *et al.*, 2003). Well-known QoS metrics include throughput, jitter, delay and packet loss. These metrics are influenced by a number of factors such as hop count, signal strength etc. Figure 1.1 shows the relationship between the QoS metrics and the factors influencing it.

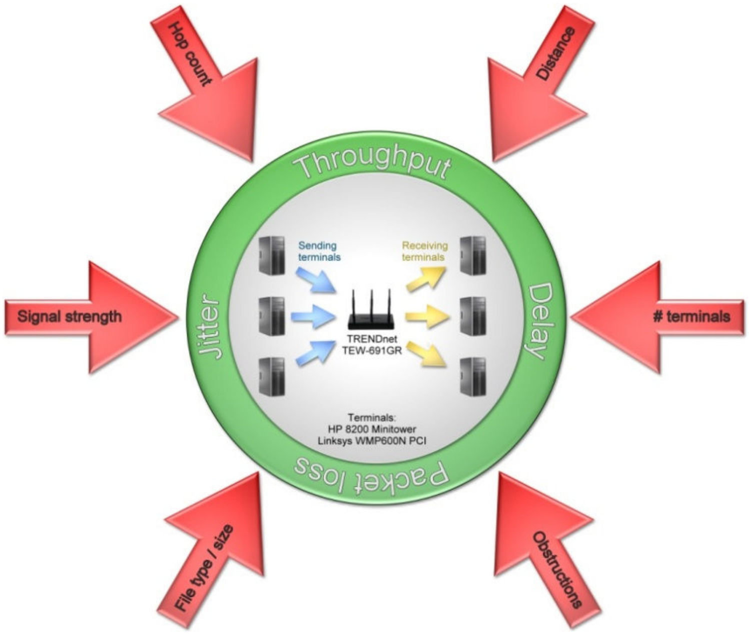


Figure 1.1 Relationships between QoS and Influencing Factors

The importance of QoS, linked with the increased importance of wireless networks, implies that QoS in wireless networks should be evaluated regularly with a reliable instrument in order to improve or maintain QoS levels.

As noted in the introduction, there are several techniques available to evaluate QoS. However, due to certain limitations, a different approach based on linear response surface analysis (LRSA) is implemented in this study as a technique to evaluate QoS factors in a wireless network. The LRSA technique uses a mathematical programming approach to investigate the behaviour of specific factors on QoS metrics such as throughput and delay.

1.3 Research Goals

The research has the primary goal of determining the feasibility of the linear response surface analysis technique as an evaluation method for quality of service factors in a wireless network. This will be accomplished by addressing the following secondary research goals.

- Providing an overview of the quality of service factors in wireless networks;
- Providing an overview of the linear response surface analysis technique;
- Constructing a prototype wireless network (802.11n) to generate appropriate quality of service data;
- Performing an analysis on the generated quality of service data using the LRSA technique; and
- Interpreting the results and making appropriate recommendations concerning the improvement of wireless network performance.

1.4 Research Methodology

The research study can be divided into three phases, a literature study, construction of a prototype wireless network and thereafter, an empirical study to apply the LRSA technique. The first phase consists of a general literature survey into two topics, quality of service and the linear response surface analysis technique. The survey of quality of service literature includes a presentation on computer networks including wireless networks, as well as quality of service and the factors thereof. The prototype wireless network construction phase provides an overview of the prototype wireless network used for this study and the software used for data generation. This will be followed by a discussion of the empirical experiments using the linear response surface analysis technique to evaluate the quality of service factors and to demonstrate the effectiveness of the technique as a quality of service evaluation method.

1.5 Dissertation Overview

This section describes the structure of the rest of the dissertation and briefly explains the purpose of each chapter.

Chapter 2 provides an overview of, and introduction to, wireless networks, as well as the factors that influence the quality of service delivered by these networks. The chapter also highlights previous studies on these factors.

Chapter 3 briefly presents linear regression and linear programming; the techniques on which the linear response surface analysis technique is built. The chapter also describes the linear response surface analysis technique.

Chapter 4 describes the construction of the physical prototype wireless network that was constructed in order to generate data on quality of service factors. The software that was used to capture quality of service data, as well as the methods used to transform the data, are presented in this chapter.

Chapter 5 applies the developed linear response surface analysis models to a variety of subsets of the generated data set. The results of the empirical experiments are evaluated and discussed.

The last chapter will demonstrate how the goals set forth for the study were achieved. The chapter also includes appropriate recommendations based on the results of the study.

1.6 Chapter Summary

Chapter 1 served as an introduction to the research study, explaining the research problem and providing the objectives of the study as well as the methodology to be followed for the remainder of the study. The structure of the study, together with a brief explanation of each chapter, was also presented.

Chapter 2

Quality of Service in Wireless Networks

2.1 Introduction

The study has, as an objective, to determine the suitability for use of linear response surface analysis (LRSA) to evaluate quality of service (QoS) factors for wireless networks. Therefore, there are two main areas of study that will be involved in this research project, firstly, QoS in wireless networks and thereafter, linear response surface analysis. To provide sufficient background and to gain an understanding of these two areas, this chapter presents an introductory overview of the first area, QoS in wireless networks.

The chapter starts with a brief overview of computer networks in general. This is followed by a discussion on wireless networks that will include the ISO OSI network model, wireless network topologies and the 802.11n-protocol used in wireless networks. Then, a review of QoS will be presented. The review will discuss the limitations and importance of QoS in wireless networks, as well as the metrics used to measure QoS. The chapter concludes with a brief review of related work and studies on QoS estimation and measurement techniques.

2.2 Computer Networks

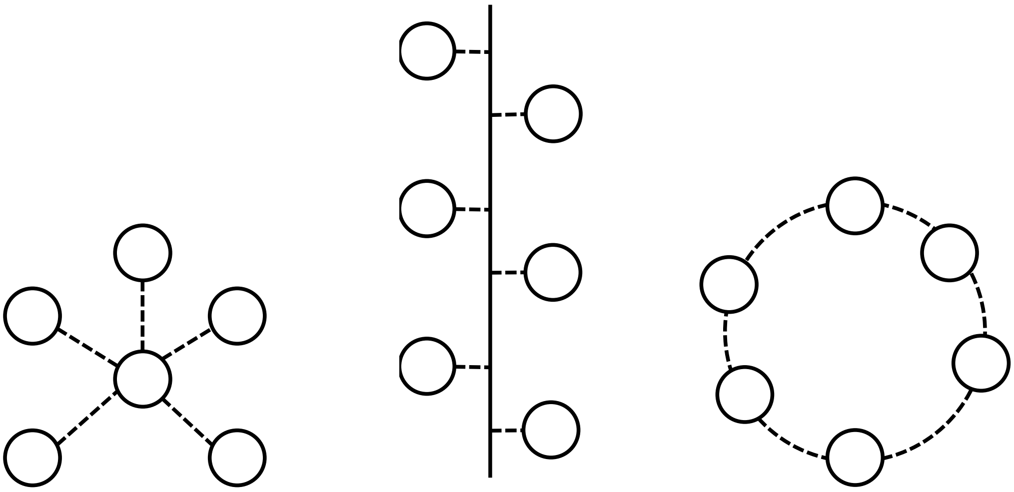
In modern society, computer networks have become vital to the way we communicate, trade and operate. These networks provide the channels for information within organisations to flow continuously between systems and people located in different departments or perhaps in different organisations. Therefore, computer networks enable the effective operation of a business as they allow for collaboration in an effective and efficient way.

A computer network can be defined as a communication system that links two or more computers or peripheral devices (often called nodes) and enables the transfer of data between the components (Bocij *et al*., 2008). Networks are constructed on different scales of which one of the most well known is a local-area network (LAN), a computer network within a workgroup or single office. A computer network that spans across borders to form national or international networks is known as a wide-area network (WAN). A wide-area network consists of multiple local area networks that are connected to one another in order to allow the network to spread across a greater geographic area and to connect more users. See Figure 2.1 for a classification of the different scales of networks.

Interprocessor distance	Processors located in same	Example
1 m	Square meter	Personal area network (PAN)
10 m	Room	Local area network (LAN)
100 m	Building	
1 km	Campus	
10 km	City	Metropolitan network (MAN)
100 km	Country	Wide area network (WAN)
1000 km	Continent	
10 000 km	Planet	The Internet

Figure 2.1 Classification of interconnected processors by geographic area (Tanenbaum, 2003)

There are a number of different arrangements for connecting computers and devices in a network. The physical layout of a computer network is known as the network topology. Some of the possible network topologies, as summarised by Tanenbaum (2003), are given in figure 2.2.



Star Topology Bus Topology Ring Topology

Figure 2.2 Network Topologies (Tanenbaum, 2003)

A network's topology might also be classified on a logical scale. The same network topologies apply with logical classification. This alternative classification method allows for a network that cannot be constructed according to a specific topology, due to physical limitations such as the environment, to function as if it was constructed according to the network model. For example, a network physically set up as a star network may function as a token ring network, with the use of a token allowing each node in the network a chance to transmit.

Regardless of the physical or logical setup of a network, networks share a set of advantages and disadvantages. Bocij *et al*. (2008) summarise the key advantages and disadvantages of network technology as follows.

Advantages

- Lower transaction cost due to less human input
- Improved sharing of information and hardware resources
- Reduced costs through sharing of hardware and software
- Reduced time for communication when compared with traditional methods
- Increased security of data through backups and restricted access

Disadvantages

- Over-reliance on networks for mission-critical applications
- Cost of initial setup and administration
- Disruption during initial setup and maintenance
- Reduced security due to more external access points

To conclude this brief introduction on computer networks, the next subsection will look at the Open System Interconnection (OSI) reference model of the International Standards Organization (ISO), which governs how data should be sent between nodes in a network (Balchunas, 2012).

2.2.1 ISO OSI Reference Model

The Open System Interconnection (OSI) reference model was designed in 1979 in an effort to standardise data communication and is used as a framework to describe the architecture of a computer network (Tanenbaum, 2003). The model consists of seven layers with each layer providing a service to the layer directly above it. The layers are numbered from the bottom layer upwards and Figure 2.3 illustrates the different layers in the OSI model.

Layer 7	Application	
Layer 6	Presentation	
Layer 5	Session	
Layer 4	Transport	
Layer 3	Network	
Layer 2	Data Link	LLC
		MAC
Layer 1	Physical	

Figure 2.3 OSI Reference Model (Tanenbaum, 2003)

The function of each layer can be summarised as follows (Tanenbaum, 2003).

The *Physical Layer* is the first level of the OSI model and controls the physical connection between the two nodes involved in the communication. This layer is concerned with transmitting raw bits over the communication channel that may be, for example, a guided medium such as a copper cable, or an unguided medium, such as an infrared signal.

The *Data Link Layer* provides the means for establishing and maintaining a connection between two machines, ensuring reliable transmission of data over the physical layer as well as detection and possible correction of physical layer errors. The data link layer is divided into two sub-layers called the Logical Link Control (LLC) and the Medium Access Control (MAC) sub-layers. The LLC sub-layer is the upper sub-layer and offers data-link layer services to the network layer that is independent of the physical medium in use. This allows different protocols to communicate over 802.11 networks as if it is the same (Ni *et al*., 2004). The MAC sub-layer provides control over the physical layer by determining channel allocation procedures, addressing, error checking and fragmentation and reassembly (Ni *et al*., 2004; Crow *et al., 1997*).

The Network Layer offers services for sending data units, such as packets, from source to destination across a network. The network layer is also responsible for handling addressing and protocol problems in order to allow heterogeneous networks to be interconnected.

The Transport Layer accepts data from the session layer, and then, if necessary, splits this data into smaller units, passes these to the network layer and ensures that the destination receives the units correctly. The service provided to the session layer and ultimately to the users of the network is determined by the transport layer.

The Session Layer allows for the establishment of a session across the network between pairs of users on different machines. It is responsible for the creation, management and termination of such a session.

The Presentation Layer is concerned with the syntax and semantics of the transmitted data. It allows for the exchange of data structures that are defined in an abstract way, enabling machines with different data representations to communicate.

The Application Layer has a number of application protocols that are commonly used by users. This includes application protocols for file transfer, e-mail, web browsing etc.

Traditionally, the connections between nodes in a local area network (LAN) are constructed with the use of cables such as twisted-pair cabling and fibre-optic cables. However, the use of wireless media has become increasingly important. The next section will give a short overview of wireless networks.

2.3 Wireless Networks

The use of mobile computing devices such as notebooks and tablet computers, personal digital assistants, smartphones and their ilk has become the fastest growing segment of the computer industry (Schiller, 2003). The use of wireless network technology has therefore become an important and critical issue for modern day business.

According to Whitman & Mattord (2012), a wireless network (WLAN) is a computer network with no physical wired connection between senders and receivers of the network, but rather a connection via radio waves and/or microwaves in order to maintain communications.

Wireless networks (WLANs) have many uses and they are used by both enterprises and private users as an alternative to the high setup and maintenance costs of wired networks. A common use is the portable office where people often need to perform tasks from anywhere and at any time. Tanenbaum (2003) mentions a number of other areas where wireless networks are proving to be of great value. These include fleets of trucks, taxis, busses, etc. who need to communicate with a central office. It may also be of great use to rescue workers at disaster sites (for example, floods or earthquakes) where normal communication systems have been destroyed. Wireless networks are also important in hostile military situations where it is hard to deploy traditional networks due to the geographic terrain. Crow *et al*. (1997) pointed out that wireless networks are also used in structures that are hard to wire such as warehouses, concrete buildings and historical buildings.

According to Schiller (2003), wireless networks have advantages and disadvantages that can be summarised as follows.

Advantages

- Flexibility of nodes to communicate with one another if they are within radio coverage range
- No need for planning of the wiring
- Wireless networks are more robust than wired networks.
- Alternative to the high maintenance of wired networks

Disadvantages

- Quality of service is lower than on wired networks
- Greater security concerns
- Expensive to establish

The wireless network that will be used to generate quality of service data in this study is based on the IEEE 802.11 standard. To gain an understanding of the underlying technology, the next section will cover some of the aspects of the IEEE 802.11 standard.

2.3.1 The IEEE 802.11 Standard

The International Standards Organization (ISO) is a voluntary, non-treaty organisation with more than 80 member countries and almost 200 technical committees who develop standards for a vast number of subjects, not least, computers and information processing (Tanenbaum, 2003). One of the major role players in these standards is the IEEE (Institute of Electrical and Electronic Engineers). The IEEE is the largest professional organisation in the world and in addition to its numerous activities, it has a standardisation group that develops standards to be maintained in the area of electrical engineering and computing.

The IEEE 802.11 standard for wireless local area networks (WLANs) is a key standard and is one of the most used wireless technologies (Ni *et al.*, 2004).

Since the project for an international standard was initiated in 1990 (Black*, 1992*) there have been many modifications and additions such as 802.11b/g/n due to the rapid evolvement of WLAN technologies (Vassis *et al.*, 2005; IEEE, 2007). The original standard specified a protocol known as 802.11a. The 802.11a protocol provided for communication over the 5GHz unlicensed band providing data rates of between 6Mb/s and 54Mb/s. A newer variant known as 802.11b suggested using the 2.4GHz band with a data rate of up to 11Mb/s. This variant was followed by 802.11g, which conjugated the 802.11a and 802.11b standards and provides for a physical layer using the 2.4GHz band with a data rate of 54Mb/s (Bocij*, 2008*). One of the recent specifications, the 802.11n, will be discussed in Section 2.3.3.

An important aspect of the 802.11 standard is that it defines the specification of the first layer (physical layer) of the OSI model (see Section 2.2.1) as well as the specification for the MAC sub-layer in the data link layer of the OSI model (Crow *et al., 1997*). These two specifications will be briefly presented in the next two sub-sections before the discussion on wireless networks is concluded with a short discussion on wireless topologies and the 802.11n protocol.

2.3.1.1 The IEEE 802.11 Physical Layer

The physical layer specifies the data rate and frequency to be used in the WLAN. The most descriptive feature for a group of wireless devices is whether they transmit within the licensed or unlicensed radio frequencies (Peha, 2008). A system that wishes to transmit over a licensed frequency must receive permission from the regulator to operate within the frequency band. Systems or devices using unlicensed frequencies have no such restriction; this increases the number of devices using the unlicensed band.

The original 802.11 specification called for three different implementations on the physical layer in order to prevent prolonged collision periods. The three implementations are (Vassis *et al.*, 2005):

- Radio transmission in the 2.4GHz band with Direct Sequence Spread Spectrum (DSSS).

- Radio transmission in the 2.4GHz band with Frequency Hopping Spread Spectrum (FHSS).
- Infra-red (IR)

The three implementations of the physical layer provide the network with a bandwidth of 1 or 2Mb/s. This bandwidth was subsequently increased to 54Mb/s with the release of new protocols, as discussed in previous paragraphs.

2.3.1.2 The IEEE 802.11 MAC Sub-layer

The 802.11 MAC sub-layer defines two functions for coordinating the medium used to send data. The two functions are called the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF). The DCF implementation is mandatory for all nodes within a network while PCF is optional. In DCF, data transmission is asynchronous whilst PCF only deals with synchronous transmissions. The operation of the two functions will be briefly discussed in the next few paragraphs.

The *Distributed Coordination Function* (DCF) supports asynchronous data transfer and is mandatory in both the *ad-hoc* and infrastructure modes (see Section 2.3.2 for a discussion and definition of the two different modes). It is a medium access scheme that is based on Carrier Sense Multiple Access With Collision Avoidance (CSMA/CA). With CSMA/CA, a node must first sense the medium before sending data in order to ensure that the medium is not in use by another node (Hamidian & Körner, 2006; Ni *et al*., 2004; Crow *et al., 1997*).

Two mechanisms for sensing the medium can be used, physical carrier sense sensing at air interface (physical carrier sensing) and carrier sensing at the physical MAC layer (virtual carrier sensing) (Ni *et al*., 2004; Crow *et al., 1997*). If physical carrier sensing is used, a node senses the physical medium for other nodes and their activity by analysing packets in the network as well as channel activity through signal strength from other nodes. In the case of virtual carrier sensing, the sending node notifies the other nodes in its network that it is going to occupy the medium, together with the duration of the transmission. The other nodes then defer any communication for this interval (Ni *et al.*, 2004; Crow *et al., 1997*).

The collision avoidance of the CSMA/CA function is handled through a random backoff procedure. This procedure is summarised by Ferreira (2009) as follows.

A node wishing to send data across the network must first sense the medium; if it is found to be busy the node must wait until the channel becomes idle before computing a random backoff interval time which is defined as follows.

$$t_{backoff} = random[0, CW] \times t_{slot}, \tag{2.1}$$

$$CW_{min} < CW < CW_{max} \tag{2.2}$$

where $t_{backoff}$ is the backoff time measured in μs, $random$ is a random value in the interval $[0, CW]$ and t_{slot} is a pre-specified slot time measured in μs. CW is the current value of the contention window and is bounded by pre-specified minimum ($CW_{\min}$) and maximum (CW_{max}) values.

The backoff timer is stored by the node and decrements only when the channel is idle using the following formula.

$$t_{backoff} = t_{backoff} - t_{slot} \tag{2.3}$$

Once the timer expires, the node is authorised to access the medium.

In the event of two nodes being granted access to the medium at the same time, a collision will occur. In wireless networks, a collision cannot be detected, due to the absence of a wired medium, therefore a positive acknowledgement is used to determine if a transmitted frame was received. If the receiver does not respond with an acknowledgement in a specified period, the sender infers that a collision has occurred. The sender then doubles its contention window and starts a new backoff procedure.

The *Point Coordination Function* (PCF) provides added functionality such as medium access delay and minimum transmission bandwidth (Hamidian & Körner, 2006). It divides the channel access time intervals, known as beacon intervals, which are indicated by a beacon frame transmitted from the access point AP (Crow *et al., 1997*). This beacon time is composed of a contention free period (CFP) and a contention period (CP). During the CP, the DCF scheme is used and at least one frame must be allowed to transmit within a beacon (Ni *et al.*, 2004).

PCF uses a polling scheme to determine which node may transmit in a given beacon. The polling scheme is controlled by the (AP) in the basic service set (BSS) and thus only networks in infrastructure mode can use PCF (see Section 2.3.2).

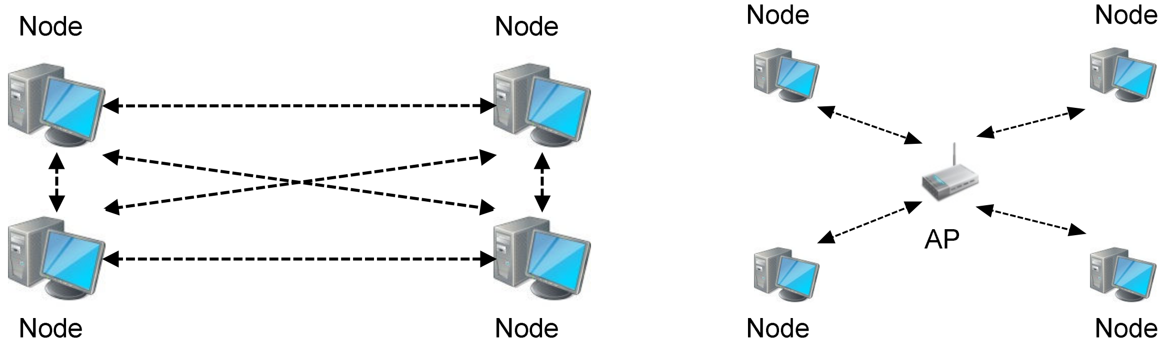
The AP maintains a list of all the nodes within the BSS and each node is then polled during a contention free period in the order in which the nodes occur in the AP's list. If a node has a frame to transmit, it is allowed to transmit when it is polled.

2.3.2 The IEEE 802.11 Architecture

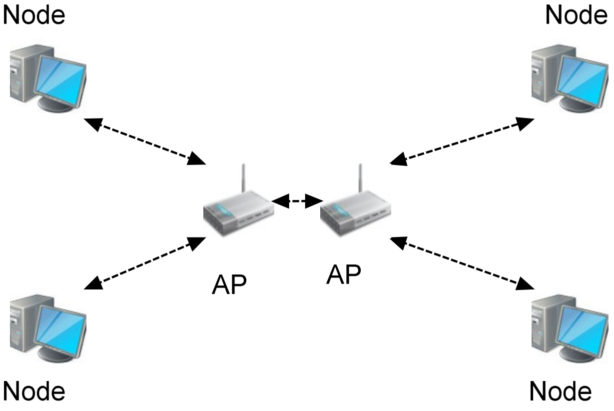
An 802.11 WLAN can be constructed by means of a basic service set (BSS) which presents the basic building block on which the network is based. A BSS is defined by Crow *et al*. (1997) as a group of nodes that are under the direct control of a single coordination function.

A WLAN can be configured in one of two ways in the IEEE 802.11. These two architectures are known as *ad hoc* mode and infrastructure mode. In an *ad hoc* network, all the nodes are grouped within wireless reception range into a single BSS. In this architecture, the nodes communicate directly with one another, as no access point (AP) is present. Nodes are not allowed to relay messages from other nodes which mean that only single-hop communication is possible. The implication of this rule is that there is no single node controlling the flow of communication over the network (Ni *et al.*, 2004).

In infrastructure mode, the nodes in a BSS are connected through a single access point (AP) which provides nodes with specific services and range extensions. Nodes wishing to communicate within the BSS do so by relaying their messages through the AP. The infrastructure mode also includes the connection of multiple AP's to extend the network over multiple BSSs. An interconnection of multiple BSSs is known as an extended service set (ESS) (Ni *et al.*, 2004; Crow *et al., 1997*). This allows for a network which can cover a larger geographic area and wireless devices can maintain their connection to the network even if the wireless AP through which it is communicating changes. Figure 2.4 (a-c) shows the different architectures.



a) *Ad Hoc* Mode b) Infrastructure Mode: BSS



c) Infrastructure Mode: ESS

Figure 2.4 802.11 Network Modes

2.3.3 The 802.11n Protocol

The different variants of the IEEE 802.11 standard were discussed in Section 2.3.1. One of the most recent protocols for wireless technology is the 802.11n protocol (Shrivastava *et al.*, 2008). This section will briefly present the new advantages and benefits of this protocol.

The 802.11n protocol significantly increases the data transmission rate of the physical layer and utilises the available spectrum in a more efficient way. These enhancements are achieved with the introduction of a number of new techniques to the IEEE 802.11 standard. Shrivastava *et al.* (2008) lists four techniques that have been introduced in order to enhance the standard. A brief summary of these four techniques are presented below.

A new technique called *Multiple Input Multiple Output* (MIMO) was introduced. The technique allows APs using the 802.11n protocol to transmit two or more streams of data in the same frequency channel. The technique also uses spatial multiplexing to achieve better data throughput and to increase the range of the wireless network (Roberts, 2010).

A new feature called *channel bonding* makes the 802.11n protocol backward compatible with the earlier variants of the 802.11 standard such as 802.11b and 802.11g. Channel bonding is possible because the 802.11n protocol has two different channel bandwidths in which data can be transmitted, a 20MHz and an additional 40MHz channel.

The protocol also makes use of a technique known as *frame aggregation* to increase the amount of data that can be sent at a time. The technique allows a node to combine multiple frames into a single frame before sending it across the network.

Finally, the 802.11n uses *antenna diversity* to minimise the effects of multipath interference. This leads to less signal degradation and higher data rates for indoor scenarios where data rates tend to be lower due to signal degradation.

This section concludes the discussion on computer networks in general and wireless networks. The remainder of the chapter will focus on quality of service (QoS) and related concepts.

2.4 Quality of Service

Quality of service (QoS) refers to a set of attributes that relates to the performance of a network connection (Ferreira, 2009). Olifer and Olifer (2005) define QoS as a technology that uses various mechanisms to decrease the negative effects of congestion in packet-switched networks. QoS can be characterised as parameterised QoS or prioritised QoS (Ni *et al.*, 2004).

Prioritised QoS is a measurement of the relative delivery priority. This measurement is to be used in the medium access control to enhance the transfer of data frames between nodes. An example of prioritised QoS is the effect of the routing protocol used in a computer network.

Parameterised QoS is a strict measurement that is expressed in terms of quantitative values, for example, the throughput of a computer network.

The objective of this study is to evaluate QoS of a wireless network by employing a linear response surface analysis technique. In order to evaluate and compare QoS factors, quantifiable values are needed to build a model. These quantifiable performance metrics will be introduced in Subsection 2.4.2. Due the very nature of parameterised QoS factors, the study will focus on parameterised QoS rather than on prioritised QoS and so prioritised QoS will not be discussed further.

2.4.1 The Importance of Quality of Service

The goal of QoS is to provide guarantees of the ability of a network to deliver predictable results. One of the fastest growing sectors in networks and telecommunications is wireless communication and to ensure customer satisfaction, which is normally driven by cost and service quality (Ivanovich *et al.*, 1998), it becomes important to continuously monitor and evaluate QoS.

The 802.11 architecture is one of the widely deployed wireless communication methods (Ni *et al.*, 2004) and the use of this technology can be increased by supporting applications that require a certain level of QoS (Hamidian & Körner, 2006). It is therefore important to measure QoS in order to ensure that these required levels are achieved and maintained.

QoS can increase network resource utilisation significantly (Roberts, 2010). Roberts (2010) explains this as follows: In a network with multiple users, queues develop as data is routed across the network. These queues may lead to unpredictable and variable network delays that are unwanted, particularly in time sensitive applications such as video- or data-streaming. The effects of such queues in a packet switched network can be avoided or mediated by deploying QoS over the network or by making use of unprovisional network services. The latter, however, leads to underutilisation, meaning that QoS is the preferred solution.

The importance of the QoS extends to the importance of the network itself as well as to the areas in which networks can contribute. Example areas include economy, education, healthcare and democracy.

According to Kushwaha (2011), the use of information communication technologies, such as computer networks, by small and medium enterprises (SMEs) raises the productivity of this particular business sector and in the economy in general. SMEs play a vital role in encouraging growth, creating job opportunities and reducing poverty. Kushwaha (2011) further states that governments in developing countries should promote the growth of the SMEs. Fast, reliable and high quality computer networks can aid in the promotion of the SME sector.

Computer networks and new learning technologies contribute towards education in a constructive way. According to Hashemi (2011), computer networks can empower students to think more independently as they have the opportunity to select and extract information freely. Learners who think independently have a more successful and stable learning process. Virtual classrooms require fast, high quality computer networks (Hashemi, 2011). These will enhance the education system of a country as these networks offer the possibility of reaching learners in rural areas, as well as allowing a small population of teachers to reach a much greater group of students.

Healthcare systems, known as PACS (Picture Archiving and Communication System), use computer networks to send medical images that are displayed at various resolutions to users with different requirements. The information can then be analysed and processed as a reference for medical treatment (Aldosari, 2012). The benefits of this system include improvement of operational efficiency and productivity, availability of images any time and any place and improvements to hospital workflow that, in turn, benefits patient care. This is just one example of how computer networks improve health care systems.

According to Weiss (1998), computers and computer networks can be seen as models for democracy, as well as creation tools of a revitalised genuine democratic community. This link has already been realised by the earliest computer enthusiasts. Computer networks are creation tools as they allow unmoderated exchanges of information and knowledge and form a key part of the modern human social interaction, which is key in a strong democratic community. These claims by Weiss are substantiated by Zhou *et al.* (2011) who states that information and communication technologies (ICTs) have been incorporated into studies of collective action. Research by Howard (2010) also showed that the internet was used to maintain strong and weak network ties for political mobilisation and that the internet is more resistant to state control than are other media.

2.4.2 Quantitative Metrics of Quality of Service

QoS can be measured in various ways as the user's ways of using the wireless network may greatly influence the way in which the user perceives the QoS provided. However, providing QoS in an 802.11 network is difficult for the functions of the MAC layer are not designed primarily for QoS and the physical layer has a "noisy" and variable nature (Ni *et al.*, 2004).

Performance metrics are typically measured for different sender and receiver flows across a network and include such metrics as delay, jitter, packet loss and throughput. These metrics are used in the study and will be discussed below.

Delay

The delay of a packet in a network is the time elapsed from the packet leaving the source to the time the packet arrives at the destination (Garnal *et al.*, 2004). This is usually expressed as a one-way delay or round-trip delay (Ferreira, 2009) and is determined by the following formula.

$$Delay = TX(i) - RX(i) \tag{2.4}$$

where TX is the timestamp when the packet was transmitted at the sender and RX is the timestamp when the packet was received at the receiver and i is the packet order.

It should be noted that the study focuses on the sending of an entire file and not individual packets. The delay is therefore measured as the time taken to send the file across the network. This means that the delay (in this study) portraits the sum of the individual packet delays, including the queuing delay at the source.

Jitter

Jitter, also known as packet delay variation, is the variation of the delays between consecutive packets. These delays occur within a packet switched network because some packets may follow a shorter or better route than other. Jitter can be calculated with the following formula:

$$Jitter = Variance\ (|\{TX(i) - RX(i)\} - \{TX(i-1) - RX\ (i-1)\}|) \tag{2.5}$$

where TX is the timestamp when the packet was transmitted at the sender and RX is the timestamp when the packet was received at the receiver and i the packet order.

Packet Loss

The occurrence of one or more packets of data transmitted over a computer network failing to reach their destination or being received correctly is known as packet loss. It is known to be one of the main error types of digital communication (Chandure & Gaikwad, 2012). Packet loss is the result of various reasons such as jitter and signal loss for example.

Packet loss can be calculated with the following formula.

$$P_{loss} = P_{sent} - P_{received} \tag{2.6}$$

where P_{loss} is the number of packets lost or received incorrectly, P_{sent} is the number of packets sent from the sender and $P_{received}$ is the number of packets received correctly at the receiver. The study used this formula to calculate packet loss.

It should be noted however that packet loss can also be determined by calculating a packet delivery ratio (PDR) which is the proportion of transmitted packets that is received at the intended destination (Ferreira, 2009). The PDR can be calculated as

$$PDR = \frac{RX_{total}}{TX_{total}} \times 100 \tag{2.7}$$

where PDR is the proportion of successfully received packets, TX_{total} is the number of packets transmitted at the sender and RX_{total} is the number of packets received at the receiver. PDR is expressed as a percentage.

Instead of using a packet delivery ratio, a packet loss ratio can also be calculated using the following formula.

$$Packet\ Loss\ Ratio = 1 - PDR \tag{2.8}$$

Throughput

Throughput is generally defined as the average rate at which data is successfully delivered over a communications channel (Vidua & Uthariaraj, 2011). This rate is normally measured in Kb/s or Mb/s. Throughput is calculated with the following formula:

$$Throughput = DS/ST \tag{2.9}$$

where DS is the size of the correct data received across the network and ST is the time it took to send the data.

2.4.3 QoS Limitations on the MAC and Physical Layers

In Sections 2.3.1.1 and 2.3.1.2, the physical and MAC layers of the IEEE 802.11 standard were presented. These two layers are involved in the sending of data and will have an influence on the QoS. This section briefly presents some of the limitations of the two layers that will influence the QoS.

The limitations on the physical layer are primarily due to the medium difference between wired and wireless networks. These differences are found in the characteristics such as delay, bit error rate and low bandwidth (Ni *et al.*, 2004). A high bit error rate, for example, leads to infrequent transmissions causing variable delay and jitter. This may degrade the QoS of the network.

The QoS limitations in the MAC layer depend on the coordination function used in the layer. There are two coordination functions, namely, a distributed coordination function (DCF) and a point coordination function (PCF). Section 2.3.1.2 discussed these two functions in detail. The DCF can only provide best-effort services with no guarantee of the level of QoS in the network. All traffic flows have the same priority causing the nodes in a BSS to compete for the available resources (Hamidian & Körner, 2006). The PCF on the other hand, is designed to use time-bounded data transfer that may cause certain problems limiting the level of QoS it can provide. Examples of these problems include nodes that cannot communicate their QoS requirements to an access point, unpredictable beacon delays and difficulties in controlling transmission time (Hamidian & Körner, 2006).

2.5 Related Work on QoS Estimation and Measurement

This section will reference examples of related work in the literature that deal with QoS estimation and measurement.

Ferreira & Helberg (2009) described a testbed implementation of QoS routing enhancements for wireless *ad hoc* networks. They presented a four-node wireless prototype testbed that was constructed to analyse *ad hoc* routing protocol behaviour. In their analysis, they made use of statistical techniques such as regression analysis where the response variables were taken as the QoS factors, that is, throughput, jitter, delay and packet loss ratio. The predictors were signal strength measured at the sender and receiver as well as node distance. Their evaluation showed that the delay metric exhibits beneficial QoS properties.

Salvador *et al*. (2007) proposed a novel modelling approach towards predicting network QoS. The purpose of their study was to create a model that had all the important wireless network aspects integrated into the model. The idea was that the model should be applicable to any network without any *a priori* knowledge of the network, for example, the topology of the network or knowledge on how the users use the network. The construction of the model, which consisted of three distinct parts, was based on a set of measured data (inbound and outbound data) of a particular network. These measurements were taken at different access points for several QoS metrics such as average delay, jitter and delay bounds. The proposed model used an inference procedure to infer the network's QoS parameters. The implementation of the model delivered results indicating excellent performance for any QoS metric at multiple access points.

A wireless link model based on network calculus (NC) was suggested by Agharebparast & Leung (*2005*). The suggested model is a sequence of NC components that is used to model a network node. By using these mathematical methods, the deterministic and stochastic QoS metrics (for example, throughput, delay, etc.) can be calculated. Agharebparast and Leung found the model to be effective in solving specific QoS problems and they argued that their method is both systematic and simple to use.

In their study, Futernick *et al*. (2003) used the transmission blocking problem as a metric for QoS. Their analytical model was based on a linear regression model and was used to evaluate and measure the QoS in *ad hoc* wireless networks.

Belzarena & Aspirot (2003) also considered a regression model to evaluate QoS. Their approach, which is called a statistical learning approach, is based on two phases. In the first phase, the learning phase, a specific function is built. The second phase, called the monitoring phase, is then used to estimate values for a response variable by using the function that was constructed during the first phase. Their study produced accurate results in various simulations and operational networks.

A fast algorithm based on Markovian and long-range dependent models for finding QoS violations and spare capacity estimation was suggested by Li (2000). The algorithm employs ordinary least squares regression and proved itself to be robust and able to produce rapid estimations.

The use of histograms to estimate the QoS of a wireless network was suggested by Siler & Walrand (1998). They proposed an algorithm to infer the loss rate and delay distribution from a histogram of the occupancy of a single first-come, first-served queue at arrival times.

To conclude this section, a brief summary from the work of Ferreira (2009) concerning studies on specific metrics will be presented. Only the metrics will be given and for a more comprehensive discussion and references to researchers who have conducted studies on these metrics, Ferreira (2009) should be consulted.

A summary of the metrics related to QoS is given below (Ferreira, 2009).

- Hop Count

The hop count metric is also known as the shortest path metric. It is commonly used in reactive routing protocols and is simple to implement.

- Round Trip Time (RTT)

The RTT, also referred to as delay, is based on timestamps of broadcasts together with acknowledgments received. A node in a network can compute the RTT of each of its neighbours by utilising the timestamps and acknowledgements.

- Per Hop Packet Pair Delay (PktPair)

The PktPair metrics works on the same principle as the RTT metric, but in this case, two messages are broadcast in a back-to-back fashion by the node in question.

- Expected Transmission Count (ETX)

The ETX metric is designed to identify high throughput paths and account for asymmetric links. It predicts the number of transmissions required to send successfully a packet over a link, by considering the forward and reverse packet delivery ratios.

- Estimated Transmission Time (ETT)

The ETT metric is an extension of the ETX metric and includes the effect of multiple bit rate communication.

- End-to-end Delay

End-to-end delays are computed for each link in the network and allow for the opportunistic use of routes with lower delays.

The metrics studied by Ferreira (2009) relate to prioritised QoS metrics as the study focused on network routing algorithms. However these metrics have close similarity to the quantitative parameterised metrics measured in this study, for example, RTT and delay as RTT is influenced by the delay of the network.

2.6 Chapter Summary

The aim of this chapter was to provide an introductory overview of wireless networks and quality of service (QoS) concepts as they relate to a network. The chapter started with an outline of computer networks in general. This was followed by a discussion on wireless networks. Aspects covered included the IEEE 802.11 standard and architecture and the 802.11n protocol. Next, a discussion concerning QoS was presented including appropriate definitions, metrics and limitations. The chapter was concluded with a brief overview of related studies on QoS.

Chapter 3 will offer an overview of the linear response surface analysis (LRSA) technique that will be used to evaluate the QoS of a wireless network.

Chapter 3

Linear Response Surface Analysis

3.1 Introduction

In the previous chapter, an introductory overview of wireless networks was given. As it is the objective of this research project to investigate the use of linear response surface analysis (LRSA) in the evaluation of QoS factors in wireless networks, this chapter will offer a background study to LRSA and associated concepts. The chapter starts with a discussion on linear regression and briefly examines simple and multiple linear regression models. This is followed by a discussion on linear programming where aspects such as solution methods and sensitivity analysis are highlighted. Finally, an overview of the LRSA technique is presented and elucidated using an illustrative example.

3.2 Linear regression

Effective managers determine which factors affect, or are related to, important business variables that they wish to understand, predict or control (Brightman, 1999). These business variables are called dependent variables. Managers then identify predictor variables, which they believe affect a dependent variable. One of the most popular and valuable techniques to further analyse the variables and their relationships is regression analysis. Regression analysis is used primarily for the purpose of prediction. The goal in regression analysis can be seen as the development of a statistical model that can be used to predict the values of a dependent, or response variable, based upon the values of at least one independent, or predictor, variable.

A linear regression function is referred to as a simple linear regression model when only one predictor variable, x, is used to estimate values of the dependent variable y. Multiple linear regression is used when two or more predictor variables $(x_1 \dots x_n)$ are used to predict values of y.

The following two sections will give an introductory overview of simple and multiple linear regression.

3.2.1 Simple Linear Regression

A simple linear regression model is a statistical tool that provides the ability to estimate the mathematical relationship between a dependent variable, y, and a single independent variable, x, (Wilson and Keating, 2007). Bowerman *et al*. (2005) defines a simple linear regression model as follows.

$$y = \beta_0 + \beta_1 x + \varepsilon \tag{3.1}$$

where

> β_0 is the y-intercept. β_0 is the mean value of y when $x = 0$, β_1 is the slope. β_1 is the change (amount of increase or decrease) in the mean value of y associated with a one-unit increase (or decrease) in x. If β_1 is positive the mean value of y increases as x increases. If β_1 is negative, the mean value of y decreases as x increases.
>
> ε is an error term that describes the effects on y of all factors other than the value of the predictor variable x.

It is assumed that the error terms are independently distributed continuous random variables with $E(\varepsilon) = 0$ and $Var(\varepsilon) = \sigma^2 > 0$. This assumption implies four other related principles that are explained by Bowerman *et al*. (2005) as follows.

- *Independence assumption*. Any one value of the error term ε is statistically independent of any other value of ε. That is, the value of the error term ε corresponding to an observed value of y is statistically independent of the value of the error term corresponding to any other observed value of y;
- *Normality assumption*. At any given value of x, the population of potential error term values has a normal distribution;
- At any given value of x, the population of potential error term values has a mean equal to zero; and
- *Constant variance assumption*. At any given value of x, the population of potential error term values has a variance that does not depend on the value of x. That is, the different populations of potential error term values corresponding to different values of x have equal variances. The constant variance is denoted by σ^2.

Point estimates for the parameters β_0 and β_1 are usually indicated by b_0 and b_1. The estimated regression model is then expressed as

$$\hat{y} = b_0 + b_1 x \tag{3.2}$$

Deviations of the predicted values ($\hat{y}$) from the actual values of y are called residuals or errors and are denoted by e where

$$e = y - \hat{y},$$

or,

$$e = y - b_0 - b_1 x. \tag{3.3}$$

To calculate the point estimates b_0 and b_1, the ordinary least squares method can be used. Wilson & Keating, (2007) explain this as follows.

The ordinary least squares method seeks to find estimates of the slope and intercept parameters that minimise the sum of squared residuals:

$$Minimize \sum e^2 = \sum (y - b_0 - b_1 x)^2 \tag{3.4}$$

By taking partial derivatives of the sum of squared residuals with respect to b_0 and b_1, setting the partial derivatives equal to zero, and solving the two equations simultaneously, the following formulas are obtained.

$$b_1 = \frac{(\sum xy - n\bar{x}\bar{y})}{(\sum x - n\bar{x}^2)} \tag{3.5}$$

$$b_0 = \bar{y} - b_1 \bar{x} \tag{3.6}$$

where

n = number of observations;

$\bar{x} = \frac{1}{n}\sum x$; and

$\bar{y} = \frac{1}{n}\sum y$

Bowerman *et al.* (2005) provide a technical discussion and examples on how to test the significance of predictor variables and how to construct a prediction interval for the mean value of the dependent variable.

This section is concluded with a short reference to a measure of usefulness of a simple linear regression model, called the simple coefficient of determination, as well as a measure of the relationship between the two variables y and x, called the simple correlation coefficient.

The simple coefficient of determination for a simple linear regression model is defined as (Bowerman *et al.*, 2005).

$$r^2 = \frac{Explained\ Variation}{Total\ Variation} \tag{3.7}$$

where

Total variation = $\sum(y_i - \bar{y})^2$;
Explained variation = $\sum(\hat{y} - \bar{y})^2$;
Unexplained variation = $\sum(y_i - \hat{y})^2$; and
Total variation = Explained variation + Unexplained variation.

r^2 is the proportion of the total variation in the n observed values of the dependent variable that is explained by the simple linear regression model.

The simple correlation coefficient, which measures the strength of the linear relationship between the variables y and x, is defined as

$$r = +\sqrt{r^2} \text{ if } b_1 \text{ is positive, and} \tag{3.8}$$

$$r = -\sqrt{r^2} \text{ is negative,} \tag{3.9}$$

where

b_1 is the slope of the least squares line relating y to x.

The correlation coefficient r can take on values between -1 and 1, because the value of r^2 is always between 0 and 1. A value of r close to 0 indicates little or no linear relationship between y and x, while a value of r close to 1 or -1 indicates a strong linear relationship between y and x. A value of r close to 1 means that y and x are highly related and are positively correlated whereas a value of r close to -1 means that y and x are highly related and negatively correlated. When $r =$ 1, y and x have a perfect linear relationship with a positive slope and when $r =$ -1, y and x have a perfect linear relationship with a negative slope.

3.2.2 Multiple Linear Regression

Simple linear regression, as examined in Section 3.2.1, is a special case of multiple regression. In most cases, some part of the change in the dependent variable, y, cannot be attributed to changes in the independent variable, x. If the unexplained portion of the change could be reduced, the conclusions and predictions would be more accurate. Usually, more than one independent variable, $x_1 \dots x_k$, is necessary to predict the behaviour of the dependent variable more accurately. A linear regression model that employs more than one predictor variable is termed a multiple linear regression model. The general form of such a model is defined as follows (Bowerman *et al,* 2005).

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \dots + \beta_k x_k + \varepsilon \tag{3.10}$$

where

$\beta_0 + \beta_1 x_1 + \beta_2 x_2 + 3x_3 + \dots + \beta_k x_k$ is the mean value of the dependent variable y when the values for the predictor variables are $x_1, x_2, x_3, \dots, x_k$;
$\beta_0, \beta_1, \beta_2, \dots, \beta_k$ are unknown regression parameters relating the mean value of y to $x_1, x_2, x_3, \dots, x_k$; and
ε is an error term that describes the effects on y of all factors other than the values of the predictor variables $x_1, x_2, x_3, \dots, x_k$.

Furthermore, it is assumed that n observations exist, with each observation consisting of an observed value of y and corresponding observed values of $x_1, x_2, x_3, \dots, x_k$. It is also assumed, as with the case of the simple linear regression model, that the error terms are independently distributed random variables with $E(\varepsilon) = 0$ and $Var(\varepsilon) = \sigma^2 > 0$. The four implied assumptions related to the independence, normality, a zero mean for the error terms and constant variance are the same as presented in Section 3.2.1 for the simple linear regression model.

The multiple linear regression model is often expressed in matrix terms in order to make use of matrix algebra to solve for the coefficients in the multiple linear regression model (Kutner *et al.*, 2005). For the general regression equation in (3.10), the matrix expression is

$$\boldsymbol{Y} = \boldsymbol{X}\boldsymbol{b} + \boldsymbol{e} \tag{3.11}$$

where

$$\boldsymbol{Y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \tag{3.12}$$

$$\boldsymbol{X} = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1k} \\ 1 & x_{21} & x_{22} & \dots & x_{2k} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_{n1} & x_{n2} & \dots & x_{nk} \end{bmatrix} \tag{3.13}$$

$$\boldsymbol{b} = \begin{bmatrix} b_0 \\ b_1 \\ \vdots \\ b_k \end{bmatrix} \tag{3.14}$$

$$\boldsymbol{e} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix} \tag{3.15}$$

where

$\boldsymbol{Y}$ is an $n \times 1$ vector of responses;
$\boldsymbol{X}$ is an $n \times (k+1)$ matrix of constants;
$\boldsymbol{b}$ is a $(k+1) \times 1$ vector of parameters; and
$\boldsymbol{e}$ is an $n \times 1$ vector of independent normal random variables.

It should be noted that the $\boldsymbol{X}$ matrix contains a column of 1's to allow for the intercept, β_0, as well as a column of n observations for each of the k variables.

To obtain the values of $\boldsymbol{b}$, the method of least squares can be used. According to this method, the sum of the squared deviations must be minimised as follows.

$$\sum \boldsymbol{e}_i{}^2 = \boldsymbol{e}'\boldsymbol{e} = (\boldsymbol{Y} - \boldsymbol{X}\boldsymbol{b})'(\boldsymbol{Y} - \boldsymbol{X}\boldsymbol{b}) \tag{3.16}$$

where

$\boldsymbol{e}' = (\boldsymbol{Y} - \boldsymbol{X}\boldsymbol{b})'$, the transpose of $\boldsymbol{e}$.

Thus

$$\begin{aligned}\boldsymbol{e}'\boldsymbol{e} &= (\boldsymbol{Y}' - \boldsymbol{b}'\boldsymbol{X}')\,(\boldsymbol{Y} - \boldsymbol{X}\boldsymbol{b})\\ &= \boldsymbol{Y}'\boldsymbol{Y} - \boldsymbol{Y}'\boldsymbol{X}\boldsymbol{b} - \boldsymbol{b}'\boldsymbol{X}'\boldsymbol{Y} + \boldsymbol{b}'\boldsymbol{X}'\boldsymbol{X}\boldsymbol{b}\\ &= \boldsymbol{Y}'\boldsymbol{Y} - 2\boldsymbol{b}'\boldsymbol{X}'\boldsymbol{Y} + \boldsymbol{b}'\boldsymbol{X}'\boldsymbol{X}\boldsymbol{b}\end{aligned}$$

since $\boldsymbol{b}'\boldsymbol{X}'\boldsymbol{Y}$ is a scalar and is therefore equal to its transpose $\boldsymbol{Y}'\boldsymbol{X}\boldsymbol{b}$

$\boldsymbol{e}'\boldsymbol{e}$ is now minimised by setting $\frac{\partial \boldsymbol{e}'\boldsymbol{e}}{\partial \boldsymbol{b}} = 0$

$$\frac{\partial \boldsymbol{e}'\boldsymbol{e}}{\partial \boldsymbol{b}} = -2\boldsymbol{X}'\boldsymbol{Y} + 2\boldsymbol{X}'\boldsymbol{X}\boldsymbol{b} = 0, \tag{3.17}$$

$$\boldsymbol{X}'\boldsymbol{Y} = \boldsymbol{X}'\boldsymbol{X}\boldsymbol{b}, \tag{3.18}$$

and

$$\boldsymbol{b} = (\boldsymbol{X}'\boldsymbol{X})^{-1}\boldsymbol{X}'\boldsymbol{Y}, \tag{3.19}$$

where

$(\boldsymbol{X}'\boldsymbol{X})^{-1}$ is the inverse of $(\boldsymbol{X}'\boldsymbol{X})$.

The linear response surface analysis technique used in this study is based on a multiple linear regression model. The multiple linear regression model therefore plays a significant role in this research project, and for this reason, a brief overview of the most important techniques used to judge overall model quality is presented. This overview is based on the work of Bowerman *et al.* (2005) and refers to the summary presented by van der Westhuizen (2011). The definitions and descriptions are therefore quoted from these two sources without referencing it further.

In order to compute intervals and test hypotheses when using a multiple linear regression model, it is necessary to calculate point estimates of σ^2 and σ (the constant variance and standard deviation of the different error term populations).

Suppose that the multiple linear regression model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon$$

utilises k predictor variables and thus has (k+1) parameters $\beta_0, \beta_1, \beta_2, \ldots, \beta_k$. Then, if the regression assumptions are satisfied and if SSE denotes the sum of squared residuals for the model, and n is equal to the number of observations

- a point estimate of σ^2 can be denoted by s^2 as follows

$$s^2 = \frac{SSE}{n-(k+1)}; \tag{3.20}$$

- and a point estimate of σ can be denoted by s as follows

$$s = \sqrt{\frac{SSE}{n-(k+1)}}. \tag{3.21}$$

To assess the utility of a multiple linear regression model, a quantity called the multiple coefficient of determination, denoted by R^2, is often calculated. This coefficient is computed using the following formulas:

Total variation = $\sum(y_i - \bar{y})^2$;
Explained variation = $\sum(\hat{y} - \bar{y})^2$;
Unexplained variation = $\sum(y_i - \hat{y})^2$;
Total variation = Explained variation + Unexplained variation; and
The multiple coefficient of determination is then given by

$$R^2 = \frac{Explained\ variation}{Total\ variation}. \tag{3.22}$$

R^2 is the proportion of the total variation in the n-observed values of the dependent variable that is explained by the overall regression model.
The multiple correlation coefficient is denoted by $R = \sqrt{R^2}$.

Many analysts recommend the use of an adjusted multiple coefficient of determination to avoid overestimating the importance of the predictor variables. The adjusted multiple coefficient of determination, R^2_{adj}, is given as

$$R_{adj}^2 = \left(R^2 - \frac{k}{n-1}\right)\left(\frac{n-1}{n-(k+1)}\right), \tag{3.23}$$

where R^2 is the multiple coefficient of determination, n is the number of observations, and k is the number of predictor variables in the model under consideration.

Another way to assess the utility of a regression model is to test the significance of the regression relationship between y and $x_1, x_2, \dots, x_k$. This is called an F-test and is performed as follows:

Suppose that the regression assumptions hold and that the multiple linear regression model contains $(k+1)$ parameters; the test is

$$H_0\colon \beta_1 = \beta_2 = \cdots = \beta_k = 0 \tag{3.24}$$

versus

$$H_1\colon \beta_1 = \beta_2 = \cdots = \beta_k = 0 \tag{3.25}$$

The overall F-statistic is defined to be

$$F(model) = \frac{Explained\ variation/k}{Unexplained\ variation/[n-(k+1)]}. \tag{3.26}$$

Also the p-value related to $F(model)$ is defined to be the area under the curve of the F-distribution (having k and $[n-(k+1)]$ degrees of freedom) to the right of $F(model)$. Then, H_0 is rejected in favour of H_1 at level of significance α if either of the following equivalent conditions holds:

1. $F(model) > F_{[\alpha]}$; or
2. p-value < α.

The point $F_{[\alpha]}$ is based on k numerator and $n-(k+1)$ denominator degrees of freedom.

In addition to the above techniques, it is also possible to construct confidence intervals for means and prediction intervals for individual values. A comprehensive discussion and technical details of these aspects can be found in Bowerman *et al.* (2005).

This concludes the introductory overview of linear regression that forms the basis for the linear response surface analysis technique used in this study. The next section will present a background overview of linear programming that also forms part of the linear response surface analysis technique.

3.3 Linear Programming

Linear programming describes graphical and mathematical procedures that seek the optimum allocation of scarce and limited resources to competing products or activities. The process of selecting values of decision variables that minimise or maximise some quality of interest is then called linear optimisation (Evans, 2010). It is one of the most powerful techniques available to decision makers and has found a range of applications in business, government and industry.

There are different types and extensions of general linear programming but, according to Bazaraa *et al.* (2005), all variations can be manipulated into the following form of a linear programming model.

$$Minimize(Maximize)\ c_1x_1 + c_2x_2 + \cdots + c_nx_n, \tag{3.27}$$

subject to

$$a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \geq\ b_1, \tag{3.28}$$

$$a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \geq\ b_2, \tag{3.29}$$

$$\vdots, \tag{3.30}$$

$$a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n \geq\ b_m, \tag{3.31}$$

$$x_1, \dots, x_n \geq\ 0, \tag{3.32}$$

where $c_1x_1 + c_2x_2 + \cdots + c_nx_n$ is the objective function to be minimised (or maximised). The $c_1, c_2, \dots c_n$ coefficients are known coefficients (for example, cost coefficients) while $x_1x_2 \dots x_n$ are the decision variables. The inequality $\sum_{j=1}^{n} a_{ij}x_j \geq b_i$ denotes the i-th constraint and the right hand side vector is represented by $b_1, b_2, \dots b_m$. Note that the inequalities can be either greater or equal than (≥) or less or equal than (≤).

A feasible solution for this type of model is obtained when a set of values for the decision variables $x_1x_2, \dots, x_n$ satisfies all the constraints. A linear programming problem therefore seeks to find, among all feasible solutions, the one that minimises (or maximises) the objective function.

A linear program model can also be formulated in matrix notation. The formulation is as follows.

Let $\boldsymbol{c} = [c_1, c_2, \dots, c_n]\ (1 \times n)$,

$$\boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} (n \times 1),$$

$$\boldsymbol{b} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix} (m \times 1),$$

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & & \\ a_{m1} & a_{m1} & \dots & a_{mn} \end{bmatrix} (m \times n).$$

The model is then stated as

$$Minimize\ (maximize)\ \boldsymbol{cx} \tag{3.33}$$

subject to

$$\boldsymbol{Ax} \geq \boldsymbol{b}, \tag{3.34}$$

$$\boldsymbol{x} \geq \boldsymbol{0}. \tag{3.35}$$

There are five important requirements or assumptions for a linear program problem. Render *et al.* (2011) summarise these assumptions as follows:

It is assumed that conditions of *certainty* exist, that is, numbers in the objective function and constraints are known with certainty and do not change during the period being studied. *Proportionality* exists in the objective function and constraints. This means that if, for example, production of one unit of a product uses three hours of a particular scarce resource, then making 10 units of that product will use 30 hours of the resource.

The third assumption deals with *additivity*. Additivity simply means that the total of all activities equal the sum of the individual activities.

The *divisibility* assumption states that solutions need not be integers. Instead, they are divisible and may take any fractional value.

Finally, all answers or variables are assumed to be *non-negative*.

To solve a linear programming problem, different methods may be employed. A problem with two decision variables can be solved by using graphical methods. For larger problems, the simplex method is normally used. Once an optimal solution is obtained, further analyses can be performed to determine how sensitive the solution is to changes in resources and other parameters. The next three subsections will give a high-level overview of the methods to solve a linear program and the sensitive analysis.

3.3.1 Graphical Methods

When there are only two decision variables in a linear programming model, a graphical representation is the easiest way to solve the problem. Two different approaches, the isoprofit method and the corner point method, can be used.

Isoprofit method

Moore & Weatherford (2011) define an isoprofit line as a contour of a profit function. A contour of the function $f(x_1, x_2)$ is the set of all combinations of values for the variables (x_1, x_2) such that the function $f(x_1, x_2)$ takes on a specified constant value. Render *et al.* (2011) summarise the steps of the isoprofit method as follows:

- Graph all constraints and find the feasible region.
- Select a specific profit (cost) line and graph it to find the slope.
- Move the objective function line in the direction of increasing profit (or decreasing cost) while maintaining the slope. The last point it touches in the feasible region is the optimal solution.
- Find the values of the decision variables at this last point and compute the profit (or cost).

Corner Point Method

If an optimal solution for a linear program problem exists, then an optimal extreme point (or corner) also exists (Bazaraa *et al.,* 2005). Hence, it is only necessary to evaluate all the corner points of a feasible region.

Render *et al.* (2011) summarise the steps of the corner point method as follows:

- Graph all constraints and find the feasible region.
- Find the corner points of the feasible region.
- Compute the profit (or cost) at each of the feasible corner points.
- Select the corner point with the best value of the objective function found in step 3. This is the optimal solution

To illustrate the two graphical methods, a two-variable example is presented.
Consider the following linear programming problem.

$$Maximize\ 40x_1 + 50x_2$$

subject to

$$x_1 + 2x_2 \leq 40,$$
$$4x_1 + 3x_2 \leq 120,$$
$$x_1, x_2 \geq 0.$$

To obtain a solution for this linear program, values for the decision variables, x_1 and x_2, need to be chosen which will maximise the objective function. The optimal solution is the best feasible solution and, therefore, the values for the two decision variables should be located in the feasible region. Graphically, the objective function (isoprofit line) can be moved from the origin, parallel to itself, until it reaches an extreme point within the feasible region. The graphical solution is shown in figure 3.1.

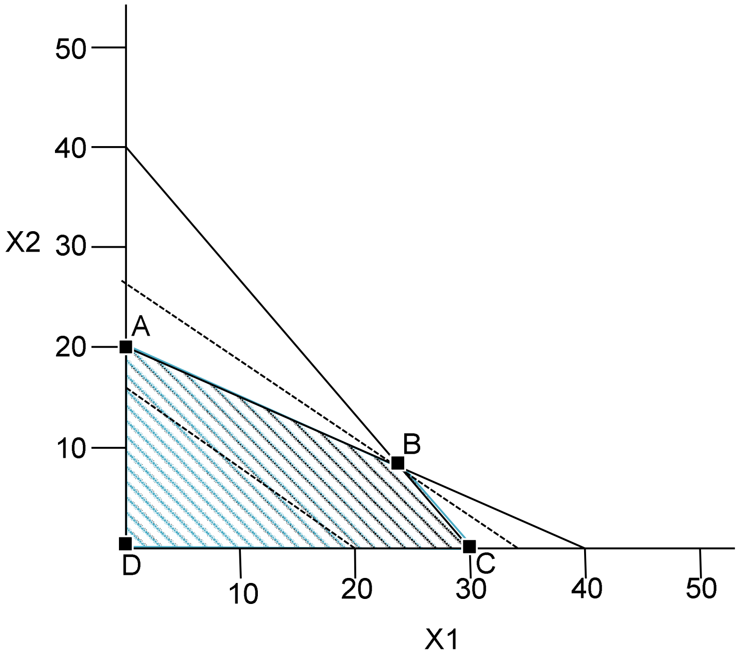


Figure 3.1 Graphical Solution

In Figure 3.1, the feasible region is indicated as the area within the corner points ABCD. The dotted line is the objective function (isoprofit line) while the solid lines depict the constraints. The optimum point is B where $x_1 = 24$ and $x_2 = 8$. The optimum solution is obtained by substituting these values into the objective function that results in a maximum value of 1360.

To apply the corner point method, the four different corner points are considered. These points are A with coordinates (0, 20), B (24, 8), C (30, 0) and D (0, 0). The objective function value for the corner points are 1000, 1360, 1200 and 0 respectively. This implies that B is the optimal solution.

The solution for the linear program in the above example was unique. However, for some linear programming models, the general rules do not always apply and special cases may occur. These special cases include alternate optimal solutions (when an objective function parallels a constraint line segment), infeasible problems (no feasible solution area exists) and unbounded problems (the solution space is not completely closed in).

The graphical method works only when there are two decision variables, but it provides a valuable insight into how larger problems are structured. To deal with larger and the real life problems with a larger number of variables and constraints, a solution procedure called the simplex method is usually used. A short discussion on the simplex method will be given in the next sub section.

3.3.2 The Simplex Method

The simplex method was developed by George B Dantzig in 1947 and is a popular and effective tool for solving optimisation problems (Bazaraa *et al.*, 2005). As noted previously, the theory of a linear program states that the optimal solution will lie at a corner point of the feasible region. The simplex method systematically examines all corner points in a many-sided, many-dimensional feasible region, by using algebraic steps, until an optimal solution is found.

The simplex method will be illustrated using the same linear programming model presented in the graphical method example. The linear program model was given as

$$Maximize\ 40x_1 + 50x_2$$

subject to

$$x_1 + 2x_2 \leq 40,$$
$$4x_1 + 3x_2 \leq 120,$$
$$x_1, x_2 \geq 0.$$

The first step involves converting the inequality constraints into equations. This is achieved by adding slack variables S_1 and S_2 to the constraints.

$$x_1 + 2x_2 + S_1 = 40$$
$$4x_1 + 3x_2 + S_2 = 120$$

An initial simplex tableau can now be constructed with a first basic feasible solution where $x_1 = x_2 = 0$ so that $S_1 = 40$ and $S_2 = 120$. The first simplex tableau is presented in table 3.1. In table 3.1, x_1 and x_2 are the decision variable columns and S_1 and S_2 the slack variable columns. The 'Solution Mix' column shows the variables in the current solution while the C_j column depicts the gain per unit. The 'Quantity' column shows the constant values. The second row represents the gain per unit and in the following two rows, the two constraint equations are given. The gross gain (profit) row is indicated by Z_j while $C_j - Z_j$ represents the net gain.

	Solution Mix	x_1	x_2	S_1	S_2	**Quantity**
C_j		40	50	0	0	
0	S_1	1	2	1	0	40
0	S_2	4	3	0	1	120
	Z_j	0	0	0	0	0
	$C_j - Z_j$	40	50	0	0	

Table 3.1 The Initial Simplex Tableau

Following the first simplex tableau, five steps are completed to compute the values needed for the next tableau (Render *et al.*, 2011)

1. Determine which variable to enter into the solution mix next. One way of doing this is by identifying the column (pivot column), and hence the variable, with the largest positive number in the $C_j - Z_j$ row of the preceding tableau. Producing this variable will contribute the greatest additional profit per unit;

2. Determine which variable to replace. A basic variable must be chosen to make room for the new variable chosen in step 1. Divide each amount in the quantity column by the corresponding number in the column selected in step 1. The row (pivot row) with the smallest nonnegative number calculated in this way will be replaced in the next

tableau. The pivot number is the number at the intersection of the pivot row and pivot column;

3. Compute new values for the pivot row. To do this, divide every number in the row by the pivot number;

4. Compute the new values for each remaining row. All remaining row(s) are calculated as follows

$$(\text{new row numbers}) = (\text{numbers in old row})$$

5. Compute the Z_j and $C_j - Z_j$ rows, as demonstrated in the initial tableau. If all numbers in the $C_j - Z_j$ row are 0 or negative, an optimal solution has been reached. If this is not the case, return to step 1.

To apply these steps, the pivot column, -row and –number, must be identified in table 3.1. In this case, x_2 is the pivot column, with the largest positive $C_j - Z_j$ value. S_1 provides the smallest nonnegative number and is therefore the pivot row. The pivot number, 2, is located at the intersection of the pivot-column and -row. After establishing this information, the second tableau can be completed. Table 3.2 provides the second simplex tableau.

	Solution Mix	$\boldsymbol{x_1}$	$\boldsymbol{x_2}$	$\boldsymbol{S_1}$	$\boldsymbol{S_2}$	**Quantity**
C_j		40	50	0	0	
50	x_2	0.5	1	0.5	0	20
0	S_2	2.5	0	-1.5	-0.5	60
	Z_j	25	50	25	0	1000
	$C_j - Z_j$	15	0	-25	0	

Table 3.2 The Second Simplex Tableau

The same procedure is followed to obtain the last tableau. In this case x_1 is the pivot column, S_2 the pivot row and 2.5 the pivot number. Table 3.3 presents the third and last tableau which contains the optimal solution for this problem, with $x_1 = 24$ and $x_2 = 8$ to obtain a profit of 1360.

	Solution Mix	x_1	x_2	S_1	S_2	Quantity
C_j		40	50	0	0	
50	x_2	0	1	1.2	-0.3	8
40	x_1	1	0	-0.6	0.6	24
	Z_j	40	50	36	9	1360
	$C_j - Z_j$	0	0	-36	-9	

Table 3.3 The Third Simplex Tableau

The procedure for solving linear programming maximisations problems is summarised by (Render *et al*., 2009) as follows:

I. Formulate the linear programming problem's objective function and constraints;
II. Add slack variables to each less-than-or-equal-to constraint and to the problem's objective function;
III. Develop an initial simplex tableau with the slack variables in the basis and the decision variables equal to 0. Compute the Z_j and $C_j - Z_j$ values for this tableau;
IV. Follow these five steps until an optimal solution has been reached:

1 Choose the variable with the greatest positive $C_j - Z_j$ value to enter the solution. This is the pivot column;

2 Determine the solution mix variable to be replaced and the pivot row by selecting the row with the smallest (nonnegative) ratio of the quantity-to-pivot column substitution rate. This row is the pivot row;

3 Calculate the new values for the pivot row;

4 Calculate the new values for the other row(s); and

5 Calculate the Z_j and $C_j - Z_j$ values for this tableau. If there are any $C_j - Z_j$ values greater than 0, return to step 1. If there is no $C_j - Z_j$ values that are greater than 0, an optimal solution has been reached.

Note that the procedure for solving linear programming minimisations problems is similar to the above procedure and that the details can be found in Render *et al*. (2011).

3.3.3 Sensitivity Analysis

The linear programming problem presented in the previous sections assumed that all data are known with certainty. However, in the real world, conditions are dynamic and changing. To handle this apparent discrepancy, sensitivity analysis is often employed. Sensitivity analysis allows decision makers to experiment with changing values of input parameters.

Van der Westhuizen (2011) summarised sensitivity analysis as follows: The basis of sensitivity analysis is the proposition that all parameter values, except for one number in the model are fixed. By determining a range for each parameter, which will not affect the optimal solution, the sensitivity of the solution values can be considered. Sensitivity analysis can be used to determine how much the objective function coefficient of a parameter can change before the objective value changes. A change in the right-hand side values (resources) can cause the feasible region to change and this may lead to a different optimal solution. Sensitivity analysis can indicate how much these values can change without influencing the optimal solution. Most of these answers can be derived from the final simplex tableau.

A more technical and detailed discussion of sensitivity analysis can be found in Render *et al.* (2011).

3.4 Linear Response Surface Analysis

Linear regression models and the interpretation of such models are often not straightforward. Bruwer & Hattingh (1985) stated that in practice problems often arise with the interpretation and use of a given regression model even though researchers may be satisfied with the model.

A regression model such as the one in (3.10) in Section 3.2.2 may not offer sufficient information. It is, for example, difficult (or even impossible) to forecast at the outset that the value of the dependent variable can be increased by increasing those independent variables with positive coefficients and decreasing those with negative coefficients. It would also be incorrect to assume that the dependent variable can be increased by changing only one or two of the independent variables. This is because of the possible interdependence among the independent variables. Interdependence among the independent variables implies that if the value of one of the variables is changed, it may have an influence on the values of one or more of the other independent variables. Bruwer & Hattingh (1985) summarise the potential problems in the following three questions:

- How do we interpret the regression function?
- What is the influence of a specific independent variable?
- How do we use the estimated function when we are interested in forecasting or optimisation of the dependent variable?.

To deal with these potential problems, linear response surface analysis (LRSA) is suggested as an alternative technique for evaluating linear regression models of the form presented in (3.10). LRSA is concerned with the investigation and optimisation of a response function as obtained by fitting the function to raw data (Terblanche, 2001).

The central claim in the suggested technique is that the “area of experience” should be considered when optimising linear models. The area of experience is represented as a convex hull and the linear model is then optimised with the convex hull as a constraint (Bruwer & Hattingh, 1985).

The following subsections will present an overview of the technique and offer an illustrative example.

3.4.1 Illustrative Example

The illustrative example that will be used through the explanation is based on a dataset taken from Wonnacott & Wonnacott (1981). The dataset represents production data together with rainfall and temperature measurements for a specific region. See Table 3.4.

Production (y)	**Rainfall (x_1)**	**Temperature (x_2)**
60	8	56
50	10	47
70	11	53
70	10	53
80	9	56
50	9	47
60	12	44
40	11	44

Table 3.4 Data on production (Wonnacott & Wonnacott, 1981)

The variable production (y) is taken as the dependent variable and the other two variables rainfall (x_1) and temperature (x_2) are the independent variables. By applying the method of least squares, the following estimated regression function is obtained.

$$\hat{y} = -144.6 + 5.71x_1 + 2.95x_2 \tag{3.36}$$

The statistics below indicate a reasonable fit of the model to the data points and both coefficients of the independent variables x_1 and x_2 are positive.
Statistics for the model fitting:

Coefficient of determination = 0.889
t-values:
$b_0 = -2.59$
$b_1 = 2.13$
$b_2 = 4.26$

3.4.1.1 The Area of Experience as a Convex Hull

The area of experience is measured by the existence of data points in this area. For the dataset exampled in Table 3.4, the area of experience for rainfall (x_1) and temperature (x_2) is the convex hull of data points as given in Figure 3.2

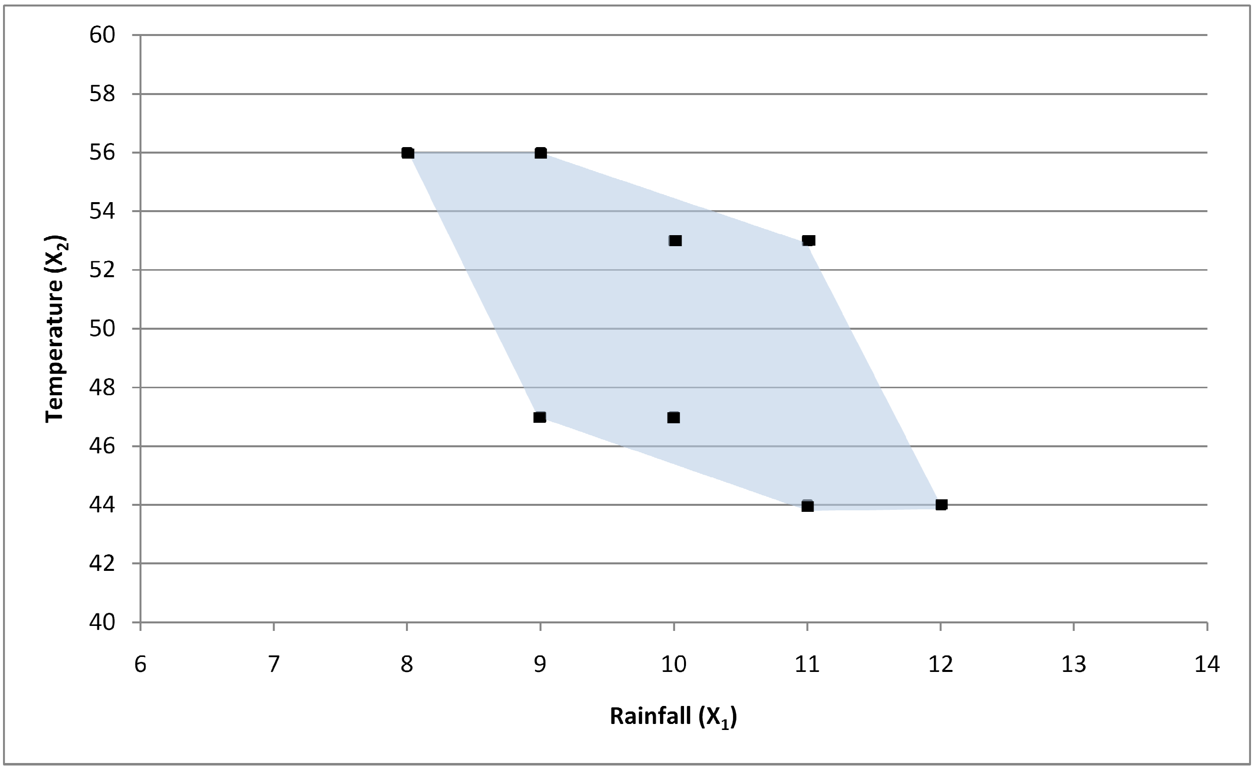


Figure 3.2 Convex hull for production data

The convex hull can formally be defined as follows (Bruwer & Hattingh, 1985).

Suppose the following data points are available:

$V_i = (X_{i1}, X_{i2}, \dots, X_{ik})$ for $i = 1,2,\dots,N$

The convex hull can now be represented as the following set:

$$C = \left\{ Z \,\middle|\, Z \in E^k \; and \; Z = \sum_{i=1}^{N} \lambda_i V_i \; with \; \lambda_i \geq 0 \; and \; \sum_{i=1}^{N} \lambda_i = 1 \right\}$$

E^k denotes a k-dimensional Euclidean space.

3.4.1.2 Optimisation of the Linear Model Over the Convex Hull

Following the definition of the convex hull of the observations, the linear program needs to be formulated. The estimated regression function is taken as the objective function and the convex hull as the constraints. This results in the following linear program.

$$\text{Max/Min} \quad \hat{y} = b_0 + b_1 x_1 + \ldots + b_k x_k, \tag{3.37}$$

subject to

$$\sum_{i=1}^{N} \lambda_i x_{ij} = x_j \; for \; j = 1,2,\ldots,k, \tag{3.38}$$

$$\sum_{i=1}^{N} \lambda_i = 1, \tag{3.39}$$

$$x_p = q_{pr}, \tag{3.40}$$

$$x_j \geq 0 \; for \; j = 1,2,\ldots,k, \tag{3.41}$$

$$\lambda_i \geq 0 \; for \; i = 1,2,\ldots,N, \tag{3.42}$$

where x_{ij} denotes the i-th measurement on variable x_j. $\hat{y}$ denotes the response to be maximised or minimised.

The constraint (3.40) enables the decision maker to determine the influence of a specific variable x_p on the dependent variable $\hat{y}$. By solving the linear program iteratively for a range of values $q_{p1}, q_{p2}, \ldots, q_{ps}$ with $q_{pr} \in \begin{bmatrix} \underset{1 \leq i \leq N}{min}(x_{ij}), \underset{1 \leq i \leq N}{max}(x_{ij}) \end{bmatrix}$ a range of optimal values $z_{p1}, z_{p2}, \ldots, z_{js}$ is generated. Displaying the range of values for q_{pr} against the optimal values z_{jr} represents the behaviour of the linear model within the convex model with respect to x_p.

The solution of the linear program then gives the maximum (or minimum) of $\hat{y}$ as well as the levels of the independent variables where this optimal level is reached.

It should be noted that the solutions may also be obtained by using parametric linear programming techniques (Terblanche, 2001).

3.4.1.3 Generating Graphical Results

Graphical results are generated by limiting one of the independent variables x_1 or x_2 to the values $q_{p1}, q_{p2}, \ldots, q_{ps}$ (3.40), as explained in the previous section, and then solving the linear program (3.37 to 3.42) for each of these values. Suppose the independent variable x_2 is under investigation. The following is then true for the illustrative example:

$$q_{2r} \in \left[\begin{matrix} min\,(x_{i2}) \\ 1 \le i \le 8 \end{matrix}, \begin{matrix} max\,(x_{i2}) \\ 1 \le i \le 8 \end{matrix}\right]$$

$$q_{2r} \in [44{,}56]$$

If 8 equal intervals, for example, are considered then q_{2r} may take on the values 44; 45.5; 47; 48.5; 50; 51.5; 53; 54.5; 56, respectively.

If $r = 1$, the constraint (3.41) becomes $x_2 = q_{21} = 44$. Solving the linear program (3.37 to 3.41) with this constraint, yields an optimal value of $z_{21} = 53.72$.

If $r = 2$, the constraint (3.41) becomes $x_2 = q_{22} = 44.75$ is and the optimal value $z_{22} = 57.19$ is obtained.

By solving the linear program in (3.37) to (3.42) repeatedly for $r = 1,2,\dots,9$, a set of optimal values z_{2r} is obtained. These optimal z_{2r} values are then plotted against q_{2r} as a line graph to produce an estimated maximum response line.

The above procedure is now repeated as a minimisation problem to produce an estimated minimum response line. Figure 3.3 shows the response graph for production (y) against temperature (x_2).

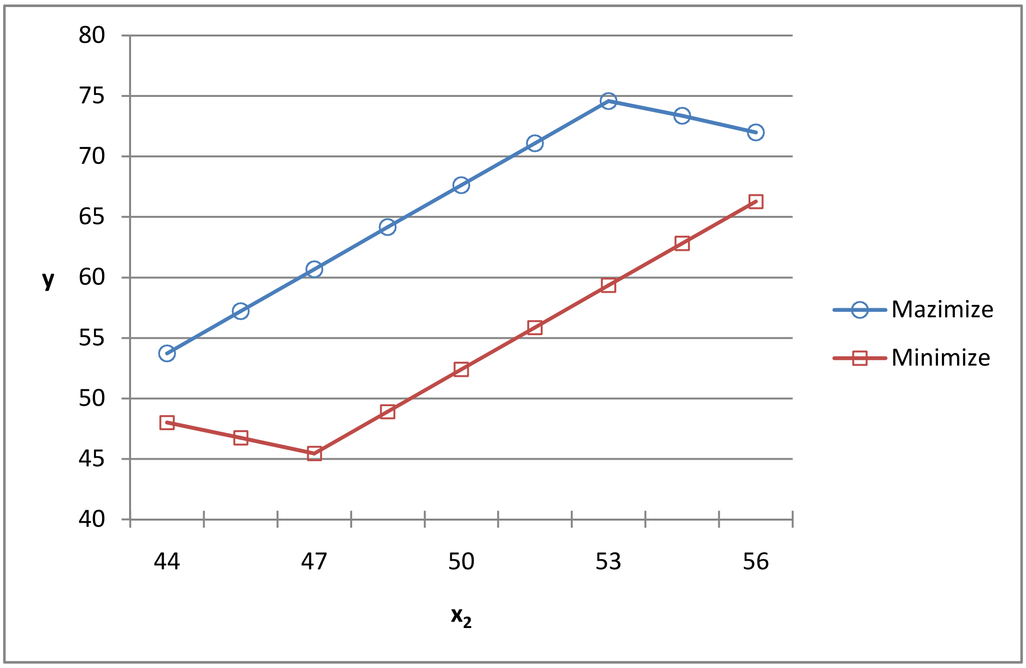


Figure 3.3 Response Graph for Temperature (x_2)

In the discussion above, only one independent variable, x_2, was restricted at particular levels. It is possible to restrict more than one independent variable and then solve the linear programming problem. This is often the case in practice (Bruwer & Hattingh, 1985).

3.4.1.4 Properties of the Graphical Result

Terblanche (2001) explained the properties of the graphical results as follows:
For each solution z_i found, the optimal conditions or values for the independent variables $x_1^*, x_2^*, \ldots, x_k^*$ are also obtained from the solution to the linear program. For example, the solution found with the constraint $x_2 = q_{21} = 44$ was $z_{21} = 53.72$ with the optimal values for the independent variables $x_1^* = 12$ and $x_2^* = 44$.

Another property to notice is that the vertical distances (difference) between the maximum and minimum piecewise linear graphs are an indication of the relative importance of the remaining independent variables that were not constrained. The influence is relatively large when the difference is large and small if the difference is small. To illustrate this particular property, Figure 3.4 shows the result when the variable x_1 is investigated. The response graph is produced in the same way as above with 8 intervals and q_{1r} taking on the 9 values 8; 8.5; 9; 9.5; 10; 10.5; 11; 11.5; 12. It can be seen from Figure 3.4 that the vertical distances between the maximum and minimum graphs are considerably larger than those of x_2 in Figure 3.3 in Section 3.4.1.3. This indicates that the variable x_2 has a greater effect on the response variable.

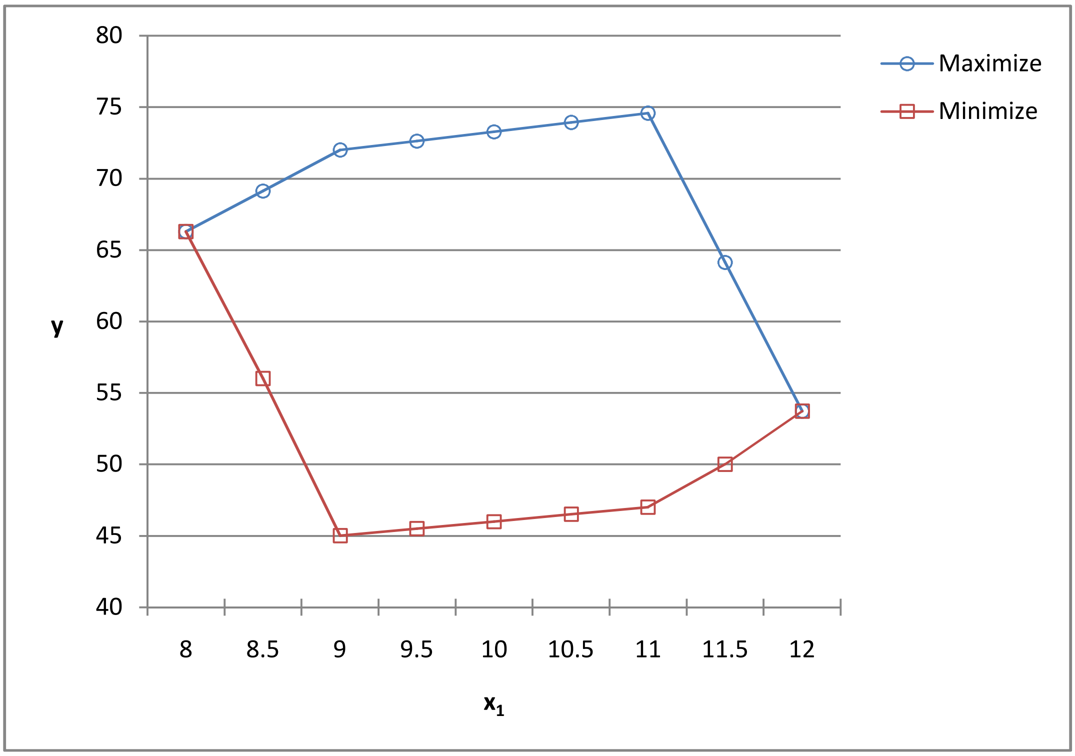


Figure 3.4 Response Graph for Rainfall (x_1)

3.4.2 Linear Response Surface Analysis Summary

To conclude the discussion of linear response surface analysis, a summary of the technique is presented (Bruwer & Hattingh, 1985):

1 Obtain a regression model that is satisfactory.

2 Determine the area of experience of the regression model by identifying the convex hull of the available data points.

3 Identify the state variables whose influence on the dependent variable has to be investigated.

4 Select a specific level for this variable.

5 Optimise the regression function over the area within the convex hull where this variable is at a specific level. Obtain maximum and minimum values. Select anther level and repeat the procedure.

6 Graph the optimum values of the regression function against different levels of the chosen variable.

3.5 Chapter Summary

The purpose of Chapter 3 was to provide a theoretical background to the LRSA technique that will be used in subsequent chapters to evaluate QoS factors in a wireless network. The chapter presented an overview of linear regression, linear programming and the LRSA technique.

The next chapter will detail the construction of the prototype wireless network that was used for evaluation in the study.

Chapter 4

Prototype Wireless Network

4.1 Introduction

In order to generate QoS data for a wireless network that can be analysed with the LRSA technique, a prototype wireless network was constructed. The focus of this chapter is to describe the process of setting up such a wireless network and to discuss specific considerations relating to software and hardware used in the prototype. The configurations used will be presented. The chapter is then concluded with a brief overview of the data used and the performance parameters captured in the empirical experiment.

4.2 Motivation for Prototype Wireless Network

One of the most preferred system analysis methods is simulation (Banks, 1999). This is also a preferable method when an experimenter wishes to investigate the influence of a specific variable. Due to the reasons discussed in the following paragraphs, it was decided to construct a prototype wireless network rather than to use simulation software to perform network experiments.

However, simulations in general suffer from four disadvantages as noted by Banks (1999). Firstly, they require special training; the modelling is an art that is developed over time and through experience. Even if two competent designers model the same situation, they will have similarities but it is highly unlikely that the results will be the same. Results obtained from simulations may be difficult to interpret as the output is essentially random, making it hard to distinguish if an observation is the result of an interrelationship in the model or if it is simply random. Such endeavours can be time consuming and expensive and, if the model and the analysis thereof is not done properly, the results may be insufficient for the task. Lastly, simulation may be used inappropriately in situations where it is better or more preferable to make use of an analytic solution.

In the area of computer networks, simulation as a means of gathering data is not the preferred technique for various reasons. The main reason for avoiding network simulators for testing is the fact that there is no actual network involved (Albrecht, 2007). This makes it difficult to model accurately certain forces such as cross traffic, resource contention or failure in the network. As a result, the researcher is limited in his ability to test QoS under realistic network conditions. Such network simulation software ignores hardware and operating system properties presenting challenges in the evaluation of QoS results in heterogeneous computing environments.

The main motivation for opting to construct a prototype wireless network is to enable the performance of real-world experiments to obtain realistic data on the prototype wireless network's quality of service. Such a network allows for the generation of trustworthy, relevant and specific data on QoS factors that can then be used to perform LRSA analysis. A constructed test platform also enabled control over the parameters and protocols of the monitored network. The constructed prototype network further allows for a controlled environment and enables the controlled injection of network factors such as cross traffic and resource contention.

4.3 Prototype Requirements and Considerations

A constructed wireless network is a good alternative to network simulation software when experimenting on the QoS of a network. This section presents the specific requirements and the factors that were considered during the planning of the prototype wireless network.

4.3.1 Prototype Wireless Network Requirements

In order to perform experiments and capture QoS data for a prototype wireless network, certain requirements of the configuration of the prototype wireless network as well as those of the monitoring software were identified. The prototype wireless network, which was used for this study, had to be able to connect multiple nodes in the infrastructure mode as explained in Section 2.3.2. To comply with this requirement, the network had to make use of an access point, or a wireless router that had the capability to function as an access point.

The computers that formed the sending and receiving nodes had to be able to communicate wirelessly. This particular feature could be part of the computer as an on-board function, an added wireless adapter card or even a USB wireless dongle. Due to limitations on the software used in this study, the nodes were fitted with wireless adapter cards as discussed in Section 4.4.1.

One of the requirements on the access points used was that the network must be extendable to an extended service set (see Section 2.3.2). The network should also be able to manage up to six connections at a particular time. The last requirement for the access point is that it should support the 802.11n protocol and allow for the specification of wireless channel, network security, the public name of the network (SSID) and frequency mode.

Requirements for the monitoring software used with the prototype wireless network were based on the QoS factors evaluated in this study. It was important to use software that had the capability of measuring throughput, delay, packet loss and jitter, or alternatively, provide measurements on values that could be used to calculate these factors. It was also desirable to use as few as possible applications in order to monitor all the necessary variables of the network.

4.3.2 Prototype Wireless Network Considerations

To use a prototype wireless network for research purposes, certain considerations had to be kept in mind to ensure the validity of the experiments performed on the prototype wireless network. For this study, a prototype wireless network needed to be constructed which was similar to other wireless networks in order for the results to be credible, reproducible and repeatable.

4.3.2.1 Credibility

Credibility of scientific research refers to the assurance that the results obtained from the experiments performed are reliable, as is the manner in which these results were obtained. The generalisations and conclusions of a study are based on the obtained results and this makes the reliability of the results an important factor. If the results obtained are not reliable, then the conclusion inferred may be incorrect.

It should be noted that “reliability of results” in this context refers to the reliability of results as obtained from experimental measurements. The trustworthiness of the prototype wireless network to perform as a real-world wireless network underwrites the credibility of the measured QoS results. A credible prototype wireless network ensures that the results obtained are reliable that, in turn, ensures that the conclusions and generalisations of this study will be trustworthy.

4.3.2.2 Reproducibility

Reproducibility of results is defined by NIST (2001) as the “closeness of the agreement of results of measurements of the same measurand carried out under *changed conditions* of measurement”, where the measurand refers to the quantity subject to the measurement.

It must be possible to replicate measurements under different circumstances or conditions in order to ensure reproducibility. A typical example of reproducibility would be if an independent researcher were able to replicate a certain experiment on a different, or the same prototype wireless network, but under different measurement conditions. The prototype wireless network must therefore be designed and described in such a manner that it can be easily replicated, hence facilitating the reproducibility of results (Taylor & Kuyatt, 1994).

4.3.2.3 Repeatability

The repeatability of results can be defined as the “closeness of the agreement between the results of successive measurements of the same measurand carried out under the *same conditions* of measurement” (NIST, 2001).

Repeatability requires that measurements be acquired under the same circumstances or conditions. In a prototype wireless network, this would place the following requirements on an experiment:

- Using the same prototype wireless network for consecutive experiments.
- Running the same experiment method.
- Using the same wireless network nodes for consecutive experiments.
- Repeating experiments over a short period of time.
- Using the same procedure of measurement.

4.4 Overview of Prototype

The prototype network was constructed with the requirements and considerations discussed in Section 4.3. It consisted of a number of desktop computers with wireless adapter cards and one or two wireless routers that functioned as the access points of the network. This section will present a brief overview of the hardware and of the monitoring software used in the prototype wireless network.

4.4.1 Prototype Wireless Network Hardware

In the prototype wireless network between two or six (depending on the configuration), similar computers were used. These computers had the following specifications:

- HP 8200 Elite Convertible Minitower.
- 4GB Ram.
- Intel Core i5 3.3GHz i5-2500 CPU.
- Microsoft Windows 7 Professional 64bit.
- Linksys Dual Band Wireless-N WMP600N PCI Adapter.

Wi-Fi routers that were capable of functioning as access points within a wireless network were used. Depending on the configuration of the prototype wireless network, one or two wireless routers were used. The network made use of Trendnet TEW 691-GR 450mb/s wireless routers for wireless communication.

The routers were set to communicate on the 802.11n protocol only. At the start of the study, it was tested to determine if both the 802.11g and 802.11n protocols should be included in this study. In initial tests, both the protocols were used and it was discovered that result sets of both the protocols presented similar patterns. Due to the similarity in patterns and the time constraints within the study, it was decided that only the 802.11n protocol would be used.

4.4.2 Prototype Wireless Network Software

The software used on the nodes within the prototype wireless network can be categorised into two groups, being general software and the software used for monitoring. This section will briefly present the software that was used in this study.

4.4.2.1 General Software

All the computers in the wireless network used the Windows 7, 64bit operating system. No utility programs were used in order to transmit data over the network. Instead, the nodes depended on functions of the operating system for communicating over the network. The operating systems on all the nodes were configured to use only the TCP/IP4 protocol and the nodes were then grouped into one network with the network mask 255.255.255.0.

4.4.2.2 Monitoring Software

In order to monitor QoS factors such as throughput, delay, jitter and packet loss, the nodes used three applications. For real time monitoring of QoS variables, Colasoft Capsa 7 was used and the captured packets were inspected further with Wireshark. The third application, WirelessNetView, measured average signal strength for the duration of each experiment. These three applications and their role in the experiments will be presented briefly below.

Capsa 7 from Colasoft is a portable network analyser that can be used for LAN and WLAN networks. The software performs real-time packet capturing, network monitoring, advanced protocol analysis as well as in-depth packet decoding and automatic expert diagnosis (Colasoft, 2012). It was used as the main monitoring application. However, to simplify data capturing and cleaning, the results obtained from the application were saved as a *.cap* type file to allow for further inspection using Wireshark. The application was used on both the sending and receiving nodes. At the sending node, it captured data such as transmission duration, data sent (MB) and all sent packets. At the receiving node, the packets received were recorded. Packets were filtered to show only packets that originated from the sender's or receiver's IP address.

Wireshark is a network protocol analyser for Unix and Windows (Wireshark, 2012) and could have been used to capture packet data during transmissions. However, due to the sensitivity of the application when collecting all packets communicated between sender and receiver, including acknowledgements, it was decided not to use the software for live data capture. Instead, its functionality as a protocol analyser was used to extract information, such as the timestamp, when a packet was sent or received, together with the id of the packet.

WirelessNetView is a small background utility used to monitor the activity of wireless networks in an immediate area. It displays relevant information such as the SSID of the networks, as well as the last and average signal quality (Nirsoft, 2012). The software was used to capture the average wireless signal strength during the transmission of a file and was implemented on both the sending and receiving nodes.

4.5 Prototype Wireless Network Configurations

Six different configurations were used to capture data under different situations. These configurations were changed to account for cross talk, distance and obstacles that might present themselves in a real-world wireless network. This section will present the six configurations used in this study.

4.5.1 BSS Basic Configuration

The basic service set (BSS) configuration presents the most basic network with one sending node, one receiving node and one access point (AP). It provides a wireless network with no physical obstacles, minimal resource contention and no cross talk from other nodes. This configuration presents a stable baseline of results to which the results from other configurations can be compared. Figure 4.1 presents the wireless network as configured in the first configuration.

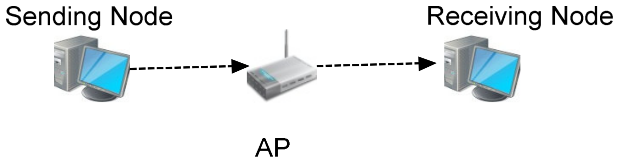


Figure 4.1 Prototype Wireless Network BSS Basic Configuration

4.5.2 BSS With Two Sending/Receiving Pairs

The second configuration introduced a second pair of sending and receiving nodes. It consisted of two sending and two receiving nodes that were connected via a single access point. The setup of this wireless network introduces a small level of cross talk and greater resource contention on the network. The configuration allows for the measurement of the effect of cross talk and resource contention on the QoS provided by a wireless network. Figure 4.2 presents the second configuration.

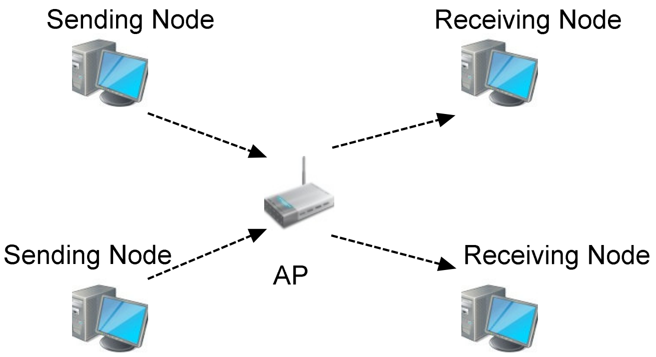


Figure 4.2 Prototype Wireless Network BSS with two Sending/Receiving Pairs

For the instances where two or more sending nodes were used, the sending and receiving nodes were arranged in pairs of one sender and one receiver. Each sending node is allowed to transfer only data to its receiving node to allow for measurements without the possible influence of a bottleneck at a receiving node of two or more sending nodes sending data at the same time.

4.5.3 BSS With Three Sending/Receiving Pairs

The third configuration added another communication pair of sending and receiving nodes to the wireless network. It has three sending and three receiving nodes with one access point controlling the communication. In this network layout, three sending nodes will each be sending data at the same time interval which will allow for the most cross talk and resource contention within the configurations based on basic service sets (BSS) (see Section 2.3.2). See Figure 4.3 for a presentation of this network.

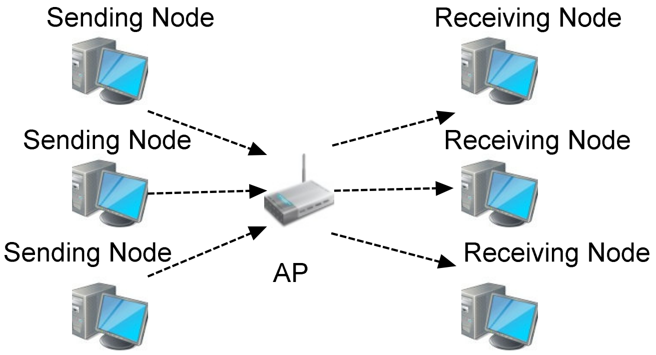


Figure 4.3 Prototype Wireless Network BSS with three Sending/Receiving Pairs

4.5.4 ESS Basic Configuration

The extended service set (ESS) configuration is the first configuration under which the prototype wireless network is expanded from a basic service set (BSS) to and extended service set (ESS) (see Section 2.3.2). The extension of the prototype wireless network allows for the evaluation of the impact that a second access point may have on the QoS provided by the network. The addition of another access point will increase the hop count of the network with a single hop. It is important to evaluate the influence of an additional hop, because, in larger spaces, an ESS is a simple solution for spreading the coverage of the wireless network.

The configuration consists of one sending and one receiving node that are connected over two access points. This configuration will present data for an ESS with minimal resource contention between sending and receiving nodes and no cross talk. Figure 4.4 provides a graphical presentation of the layout.

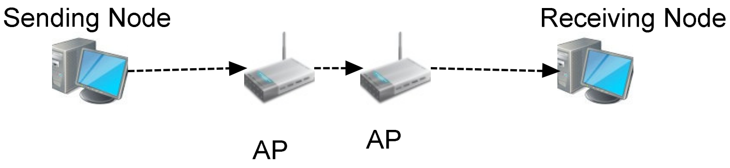


Figure 4.4 Prototype Wireless Network ESS Basic Configuration

It should be noted that when two access points are used in the network, the access points are set to be wireless distribution systems (WDS) to allow for an ESS. The MAC addresses of the senders and receivers were provided to the access points that enabled communication between the sending and receiving nodes.

4.5.5 ESS With Two Sending/Receiving Pairs

This configuration adds a sending and receiving node to the network layout presented in the basic configuration for an ESS. The addition of nodes to the network increases the amount of cross talk and resource contention that may influence the QoS. Refer to Figure 4.5 for a presentation of this configuration.

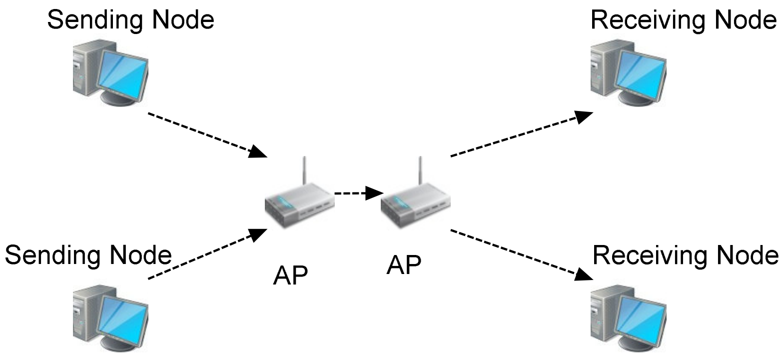


Figure 4.5 Prototype Wireless Network ESS with two Sending/Receiving Pairs

4.5.6 ESS With Two Sending/Receiving Pairs

The sixth configuration is the most elaborate configuration used as the prototype wireless network. It consists of three sending nodes, three receiving nodes and two access points. The sending nodes are all connected to one access point and the receiving nodes to the other (see Figure 4.6). This configuration allows for data gathering under conditions with the most cross talk and resource contention within the prototype wireless network.

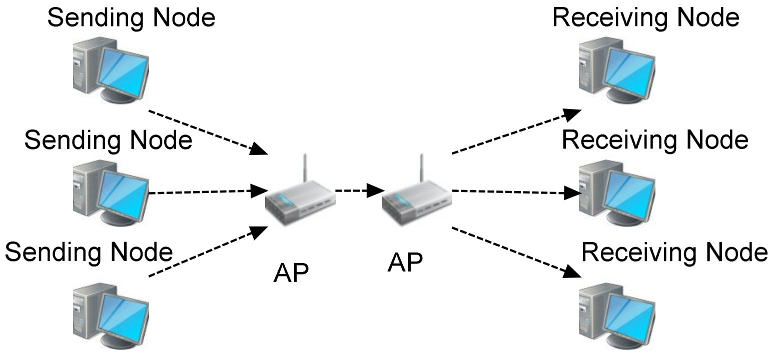
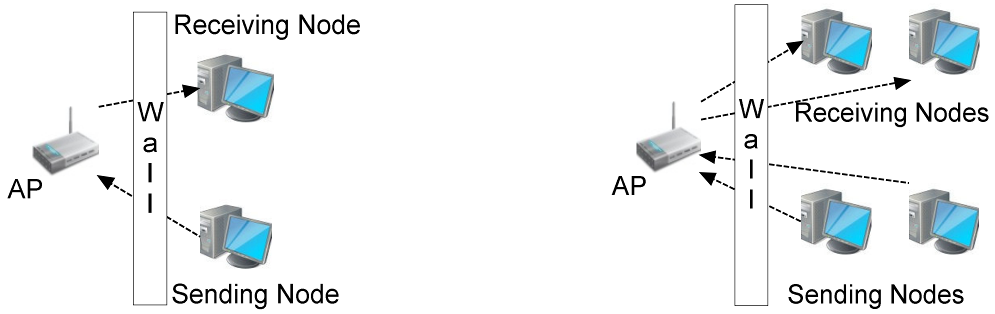


Figure 4.6: Prototype Wireless Network ESS with three Sending/Receiving Pairs

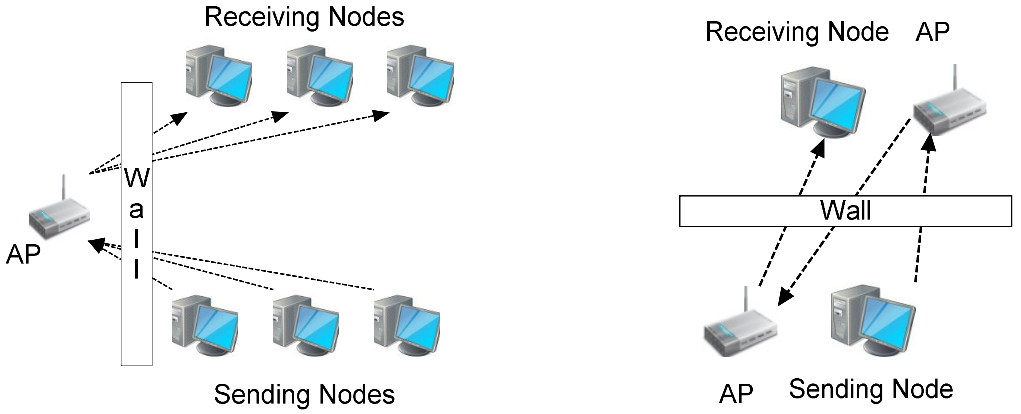
4.5.7 Other Changes

Certain changes to the layout of the wireless network were made on each of the six configurations. The changes present factors that are common in office areas where a wireless network may be used. These included the separation of nodes with a wall as an obstacle and changing the distance between nodes and access points.

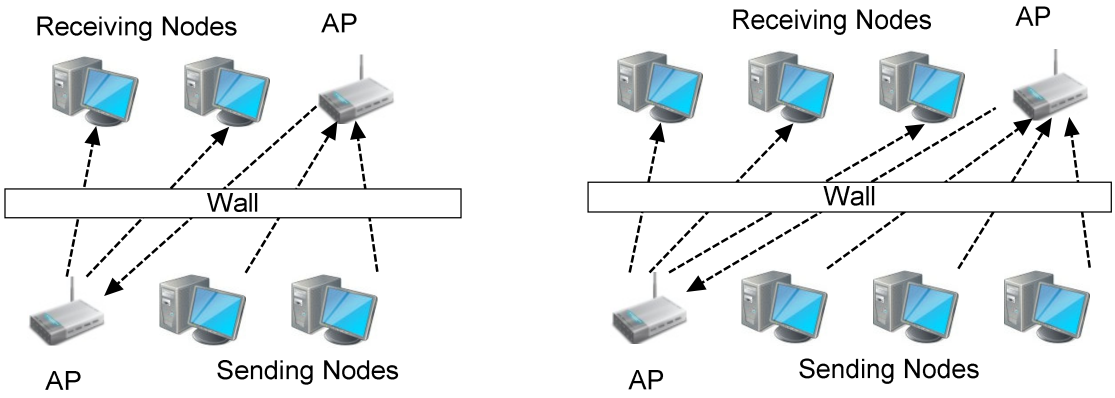
The use of a brick wall as an obstacle enabled the evaluation of the effect a wall in an office building might have on the wireless network. This was achieved by placing the nodes in adjacent rooms. For a graphical presentation of the various network setups with a wall as an added obstacle, see Figure 4.7 (a)-(f).



a) BSS Basic Configuration b) BSS with two Sending/Receiving Pairs



c) BSS with three Sending/Receiving Pairs d) ESS Basic Configuration



e) ESS with two Sending/Receiving Pairs f) ESS with three Sending/Receiving Pairs

Figure 4.7 Network configurations with walled obstacle

The distance between nodes in the network was also varied between 1 and 3 meters. The variance in distance was kept to such short distances due to spatial limitations in the building where the experiments were performed. These limitations became rather apparent during the planning of experiments in adjacent rooms as an increase in the distance between nodes to a larger distance could lead to various numbers of brick walled obstacles in different experiments. The variation in distance was introduced because of two reasons. Firstly, to evaluate the effect that distance may have on the QoS factors, and secondly, an attempt was made to have a weaker signal due to the physical space between a node and access point. However, the signal strength of the access points used and the discussed spatial limitations prevented experiments with weaker signals. For a complete list of the network configurations used during the measurement of QoS factors, refer to Table 4.1.

Setup	**Number of Computers**	**Number of Senders**	**Number of Receivers**	**Number of Access Points**	**Distance Between Nodes (m)**	**Wall Between Nodes**
1	2	1	1	1	1	No
2	4	2	2	1	1	No
3	6	3	3	1	1	No
4	2	1	1	1	2	No
5	4	2	2	1	2	No
6	6	3	3	1	2	No
7	2	1	1	1	3	No
8	4	2	2	1	3	No
9	6	3	3	1	3	No
10	2	1	1	1	1	Yes
11	4	2	2	1	1	Yes
12	6	3	3	1	1	Yes
13	2	1	1	1	2	Yes
14	4	2	2	1	2	Yes
15	6	3	3	1	2	Yes
16	2	1	1	1	3	Yes
17	4	2	2	1	3	Yes
18	6	3	3	1	3	Yes
19	2	1	1	2	1	No
20	4	2	2	2	1	No
21	6	3	3	2	1	No

22	2	1	1	2	2	No
23	4	2	2	2	2	No
24	6	3	3	2	2	No
25	2	1	1	2	3	No
26	4	2	2	2	3	No
27	6	3	3	2	3	No
28	2	1	1	2	1	Yes
29	4	2	2	2	1	Yes
30	6	3	3	2	1	Yes
31	2	1	1	2	2	Yes
32	4	2	2	2	2	Yes
33	6	3	3	2	2	Yes
34	2	1	1	2	3	Yes
35	4	2	2	2	3	Yes
36	6	3	3	2	3	Yes

Table 4.1 Network Configurations

4.6 Data Files Used

During the experiments, nine different data files were used. These files consisted of three data types and three different sizes, resulting in nine different files. In all of the experiments, the same nine files were used in order to prevent any influence that a different file of the same type and size may have on the measurements.

It should also be noted that the QoS factors were measured only on one pair of sending and receiving nodes. This was seen sufficient as the homogenic nature of the nodes and data being transferred should provide the same QoS measurements on all of the nodes. Capturing data on each pair of sending and receiving nodes would only expand the dataset and fill it with redundant data.

The three data file types used included uncompressed text (.txt), uncompressed audio (.avi) and compressed ZIP (.zip) files. The different file types were used to evaluate the possible influence that the data type may have on the QoS factors. Firstly, the file types allow the comparison of compressed files against uncompressed files, and secondly, allow the comparison of the different types of uncompressed files against one another.

The alterations in file size were introduced to evaluate the effect the data size may have on the QoS factors, as different data sizes may cause a change in prioritised QoS, in terms of the routing algorithm applied at the access point. This, in turn, may influence the measured parameterised QoS. The three data file sizes used during experimentation was 20MB, 50MB and 100MB. For a list of the data files used during the experiments, refer to Table 4.2.

File	File Type	Size(MB)
1	Audio	20
2	Audio	50
3	Audio	100
4	Text	20
5	Text	50
6	Text	100
7	ZIP	20
8	ZIP	50
9	ZIP	100

Table 4.2 Data Files

Initially, larger sizes were suggested, but two factors limited the file sizes used for this study. The first factor that had to be taken into account was the time it took to transfer the files from one node to another. Initial experiments with file sizes of 500MB and 1GB files proved to take up to an hour to transfer one file. This would require a lot of time to measure all the data as presented in this study. A further factor that had to be taken into account was the limitation of the software used for monitoring the QoS factors. ColaSoft Capsa 7, used as the monitoring software, stored the captured results into a buffer memory that could be adjusted to a maximum of 500MB. This buffer, even when set to its maximum, was insufficient to store the results of a 500MB file. Lastly, it should also be mentioned that failed transmissions would necessitate a retransfer that would further extend the time needed to measure the QoS factors.

4.7 Data Acquisition, Cleaning and Transformation

As the monitoring software could not store just the required data and not in the required format, the data had to be cleaned and transformed to a dataset that would be appropriate for use in this study. This subsection provides a brief overview of the methods used in data cleaning and transformation.

During the different experiments, 324 data records were created. This number of records is due to three reasons; the number of different network configurations used (see Section 4.5), the three file types and the three different file sizes. Preparing for the final data acquisition and testing possible data sets, such as 802.11g and 802.11n, took four months. The acquisition of the final records took six days due to the delay in transferring the data files between the nodes and therafter saving the captured data. Cleaning and transforming the resulting data took another week.

Not all of the parameters could be measured directly with one of the software packages discussed in Section 4.4.2.2. In order to acquire these parameters, a process involving two self-designed applications and Microsoft Excel was used. The data packages that were captured with ColaSoft Capsa 7 were saved in a *.cap* format. This was because both Wireshark and ColaSoft Capsa 7 use a program (WinPcap) to capture the packets, but the interface of ColaSoft Capsa 7 only presents certain elements of the captured data, whilst Wireshark presents all the captured data and allows for easy export of this data, thus permitting calculation of the desired parameters.

Once the file was opened with Wireshark for each packet, the frame information as well as TCP and IP protocols, was expanded. This allowed for the extraction of information such as arrival time from the packets' information, an identification number, source and destination address from the protocols. The expanded information was then exported to a text file.

In order to simplify and expedite the process of extracting the necessary data from the text, files were scanned with a Java application that was created for the specific needs of this study. The application read through each of the files extracting information such as delay, packet arrival times and packet identification numbers.

This text file was then imported into a different application created with C#. The application was designed to automate the process of transferring the data from the text files into a single Microsoft Excel worksheet. It opened an Excel process in the background and created a connection with this process. It then created a new worksheet into which it could import the text files by making use of Excel's import functions.

To calculate the throughput for each transfer, the Excel data for the delay and for the amount of data that was transferred for the specific record were obtained. The data size was then divided by the delay (see formula 2.4.2) to obtain the throughput of the record.

To calculate jitter, the formula discussed in Section 2.4.2 was inserted into a worksheet along with the sending and receiving time for each packet. The jitter result for each data record was then exported to a text file along with an identification of the data record. The text file was inserted along with the other data into the Excel worksheet where functions of Excel were used to match the delay to the record of the transfer.

Packet loss can occur for various reasons as discussed in Chapter 2. The packet loss was therefore measured not only as the number of packets that was not delivered, but also included the packets that had to be resent. From the *.cap* files, the sequence numbers of the packets involved could be found as discussed in Section 4.7. The sequence numbers were then compared in Excel to find the number of packets sent and those not received or those sequence numbers that occurred more than once. The resulting packet loss for each data record was added to the dataset in the same fashion as the jitter results.

The data was then subjected to regression analysis in order to confirm appropriateness for applying linear regression functions. The results of the analysis were satisfactory and the data set could be used for further analysis using the LRSA technique; refer to Chapter 5 for a brief discussion on the regression analysis and the result thereof. During this analysis, it became apparent that the signal strength as an explanatory variable would be redundant as it presented a 100% signal for almost the entire data set. Table 4.3 presents an example of the data generated for this study.

Throughput	Delay	Jitter	Packet Loss	Data Size (MB)	Hop Count	Wall	Node Pairs	Distance Between Nodes	File Type
5.216	4	0.003	19	20.865	1	Yes	1	1	Audio
0.457	46	0.044	153	21.006	1	Yes	2	1	Text
0.403	52	0.004	18	20.943	1	Yes	2	1	ZIP
0.523	200	0.009	98	104.630	1	Yes	3	1	Audio
0.756	69	0.002	52	52.192	1	Yes	3	2	Text
3.723	14	0.001	192	52.125	1	No	1	2	ZIP
5.216	4	0.001	37	20.864	1	No	1	3	Audio
0.838	25	0.003	56	20.949	2	No	1	3	ZIP
0.54	121	0.005	496	65.377	2	No	2	1	Text

Table 4.3 Example Data Rows

Data sets that are used for modelling purposes are normally subjected to tests to identify possible outliers. An outlier can be defined as observations that do not follow the same model as the rest of the data (Hoeting *et al.,* 1996). The presence of outliers can be attributed to a number of reasons such as human error, malfunction of measuring instruments, fraudulent actions or natural deviation in populations. There are a number of techniques available to detect outliers but for the purpose of this study, it was decided to perform an elementary test to identify possible outliers. The technique is based on the upper and lower quartiles of a data set and was suggested by Seo (2006).The algorithm is as follows:

Sort the data set in ascending order.
Find the lower quartile ($Q1$) and upper quartile ($Q3$) of the data.
Compute the interquartile range (IQR) using the formula $Q3 - Q1$
Calculate the lower and upper outliers with the formulas

$$Upper\ Outliers = Q3 + (IQR * 1.5), \tag{4.1}$$

$$Lower\ Outliers = Q1 - (IQR * 1.5). \tag{4.2}$$

The results obtained when the algorithm was applied to the QoS data indicated that possible outliers might exist for individual parameters (throughput, jitter, delay, packet loss). However, no outliers were present when searching the data set using all parameters simultaneously.

Based on this result, it was decided not to exclude any of the recorded data records for further model building.

4.8 Flow of the Data Acquisition Process

Schematically, the different steps to acquire the QoS data set, which was used in the LRSA technique, can be represented as depicted in Figure 4.8.

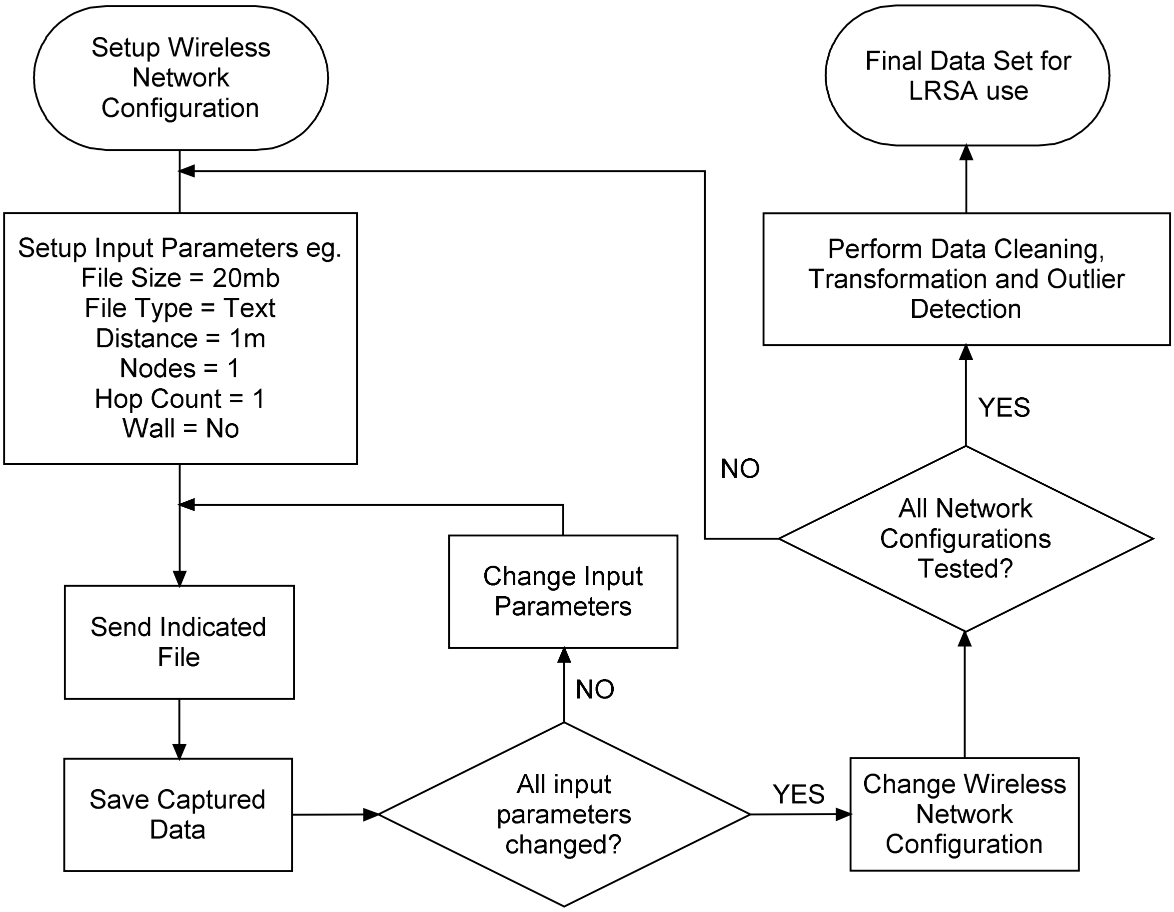


Figure 4.8 Flow of the Data Acquisition Process

4.9 Chapter Summary

The aim of this chapter was to provide some detail regarding the construction of a prototype wireless network for this study as well as of the software used for monitoring the network's performance. The methods used to capture and transform data on the QoS parameters was also presented.

Chapter 5 will graphically present the captured data as well as the ensuing analysis. The chapter includes the results of applying the linear response surface analysis technique to the captured data.

Chapter 5

Empirical Experiments and Results

5.1 Introduction

The focus of this chapter is the application of the LRSA technique on the QoS (quality of service) data generated from the different wireless network configurations presented in Chapter 4. Different multiple linear regression models are formulated and the results are investigated in order to determine the feasibility of the technique and then make recommendations, where applicable, on the improvement of wireless networks.

5.2 Formulation of the LRSA Models

The application of the LRSA technique as discussed in Chapter 3 requires the formulation of linear programming problems with objective functions and constraints as set out in Section 3.4.

The model in general, and presented in Chapter 3, can be formulated as follows:

$$\text{Max/Min} \quad \hat{y} = b_0 + b_1 x_1 + \dots + b_k x_k, \tag{5.1}$$

subject to

$$\sum_{i=1}^{N} \lambda_i x_{ij} = x_j \; for \; j = 1,2,\dots,k, \tag{5.2}$$

$$\sum_{i=1}^{N} \lambda_i = 1, \tag{5.3}$$

$$x_p = q_{pr}, \tag{5.4}$$

$$x_j \geq 0 \; for \; j = 1,2,\dots,k, \tag{5.5}$$

$$\lambda_i \geq 0 \; for \; i = 1,2,\dots,N, \tag{5.6}$$

where x_{ij} denotes the i-th measurement on variable x_j, $\hat{y}$ denotes the response to be maximised or minimised.

A summary of the steps of the LRSA technique was presented in Section 3.4.2.

The data used for the model formulations were presented and discussed in Chapter 4. It was decided for the purpose of this study to focus on *Throughput* and *Delay* as response variables with all the other variables possible candidates for inclusion as explanatory variables.

All models were formulated and solved using SAS system (SAS/OR® PROC OPTMODEL, 2012). A CD is included in the dissertation that contains the SAS programs developed to implement and solve the models as well as the data used by the models.

The following subsections will present the models used in the study.

5.2.1 Throughput as Response Variable

Throughput is seen as one of the more important metrics in QoS evaluations and it was therefore decided to choose *Throughput* as the response variable for the initial analysis.

Using the 323 observations, a multiple linear regression model was formulated by employing a standard least squares technique. The following regression equation was obtained.

$$\begin{aligned} Throughput = {} & 2.825 - 0.683x_1 - 0.00009x_2 + 0.003x_3 - 0.463x_4 + 0.231x_5 \\ & - 0.882x_6 + 0.447x_7 - 0.057x_8 \end{aligned} \tag{5.7}$$

where x_1 – jitter, x_2 - packet loss, x_3 - data sent, x_4 - hop count, x_5 – obstruction, x_6 - communicating node pairs, x_7 - distance between nodes and x_8 - file type.

Regression Statistics	
Multiple R	0.696172603
R^2	0.484656293
Adjusted R^2	0.471526517

Table 5.1 Regression Statistics for Throughput

The R^2 value in Table 5.1 implies that the model does not fit the data as well as might be desired. However, the value was accepted based on literature resources that indicated that it was still statistically significant (Swanepoel *et al.*, 2008). The statistical acceptable ranges given by Swanepoel *et al.* (2008) are given below in Table 5.2.

R^2 Value	Conclusion
< 0.13	Not Meaningful
0.13 – 0.25	Meaningful
> 0.25	Important

Table 5.2 Statistical Acceptable Ranges for R^2 (Swanepoel *et al.*, 2008)

It would be possible to improve the fit (and the R^2 value) by repeating the different data generating exercises and by making use of more sophisticated and expensive equipment. The time and cost constraints of the study, however, prevented the further exploration of these options.

The optimisation of the model in (5.7) was carried out as follows.

To investigate the influence of an independent variable on the optimum values for *Throughput*, each one of them was substituted, in turn, in the constraint $x_p = q_{pr}$ (see 5.4). This means that the r was set sequentially to an appropriate range of values for each variable p investigated. Throughput was then maximised and minimised for each of these values by solving the linear response model presented in equations (5.1) to (5.6).

This procedure resulted in a large number of linear programming problems (depending on the number of r values) for each of the decision variables used in (5.7). It should be noted that no feasible solutions may exist when a decision variable is restricted to a certain level if such a specific combination did not occur in the convex hull of the data.

The results are given in the form of graphic representations of which two (Packet Loss (x_2) and the number of Communicating Node Pairs(x_6)) will be presented here in detail.

Figure 5.1 is the graphical representation of the optimal Throughput values when the variable Packet Loss (x_2) is restricted to values of 120 to 170 with increments of 10. The optimal values for Throughput when minimising (5.7) are presented as zero in both the graph and table in Figure 5.1. This was done for graphical presentation purposes and it should be noted that these values are actually very small positive values close to zero. This is because Throughput is measured in MB/s and that a small throughput rate such as a few kb/s will appear to be zero when rounded.

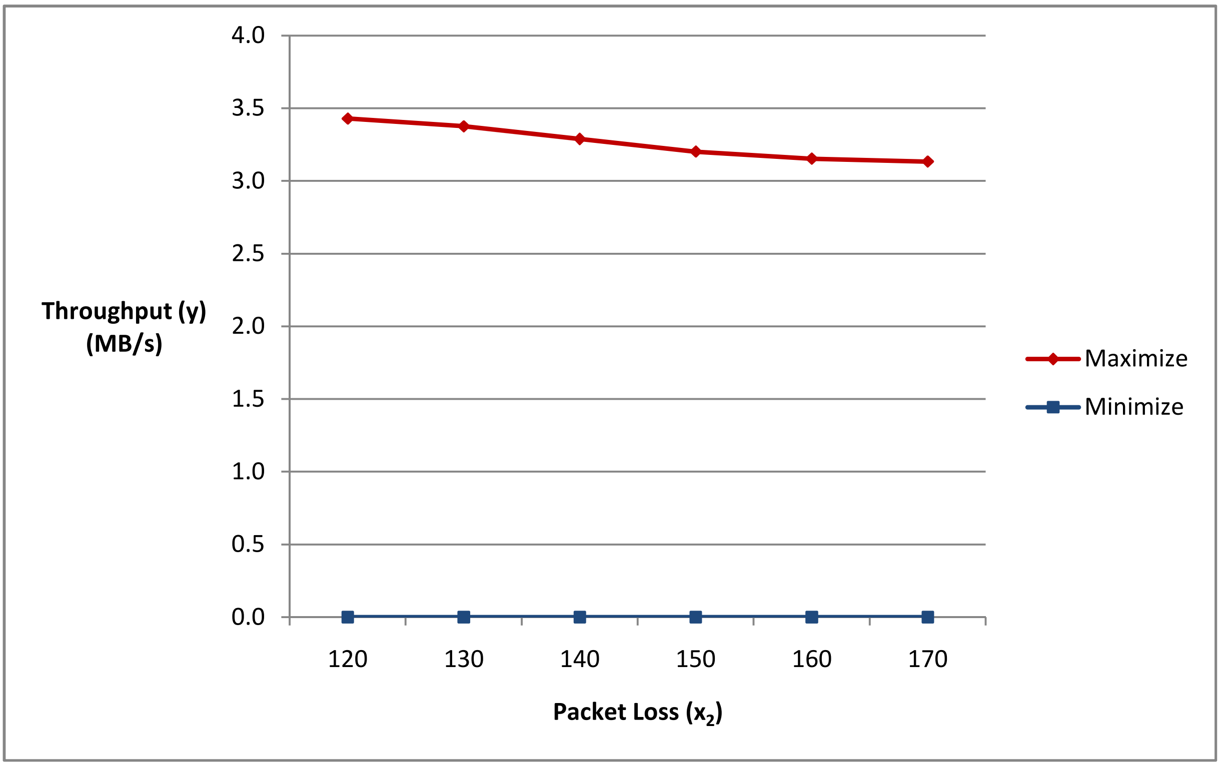
The results on the graph clearly indicate that the variable Packet Loss (x_2) will have an impact on the Throughput. This can be seen as the graph, formed by joining the maximum values, is non-increasing. This is also true for the graph that joins the minimum values. When Packet Loss is high, the optimum value for the response variable, Throughput, is low. The interpretation that can be made is that, at high values of Packet Loss, it is difficult to select values for the other decision variables that will result in high Throughput.

The tables above and below the graph provide suggestions for the levels of the other decision variables that can be employed to find higher (or lower) Throughput. For example, if Packet Loss (x_2) is at a level of 170, it seems to be a good idea to have Hop Count (x_4) at a low level, the distance between the nodes (x_7) at a high level. etc. Similar interpretations can be given to the other levels of Packet Loss. Using this type of analysis and information, it becomes clear that specific recommendations can be made on where to concentrate efforts and cost to improve Throughput.

As mentioned earlier, it should be noted that the optimisation results will not suggest values of variables not contained in the convex hull of the data points. In some cases, it may be difficult to adjust the values for the explanatory variables to the values proposed by the model, as it may be a state variable that is not under the control of the decision maker. The variable x_5 that represents the presence or absence of a physical obstruction can, for example, not be changed easily. This problem can be overcome by simply adding another constraint to the model similar to the one used to restrict Packet Loss to a certain level. The model would then have two constraints of the form presented in (5.4) and can then be solved to suggest levels for the other explanatory variables, given that x_5 has a specific value.

In the next illustration of the LRSA technique, the Number of Communicating Node Pairs (x_6) is restricted to 1, 2 and 3 while optimising Throughput. Figure 5.2 shows the graphical results.

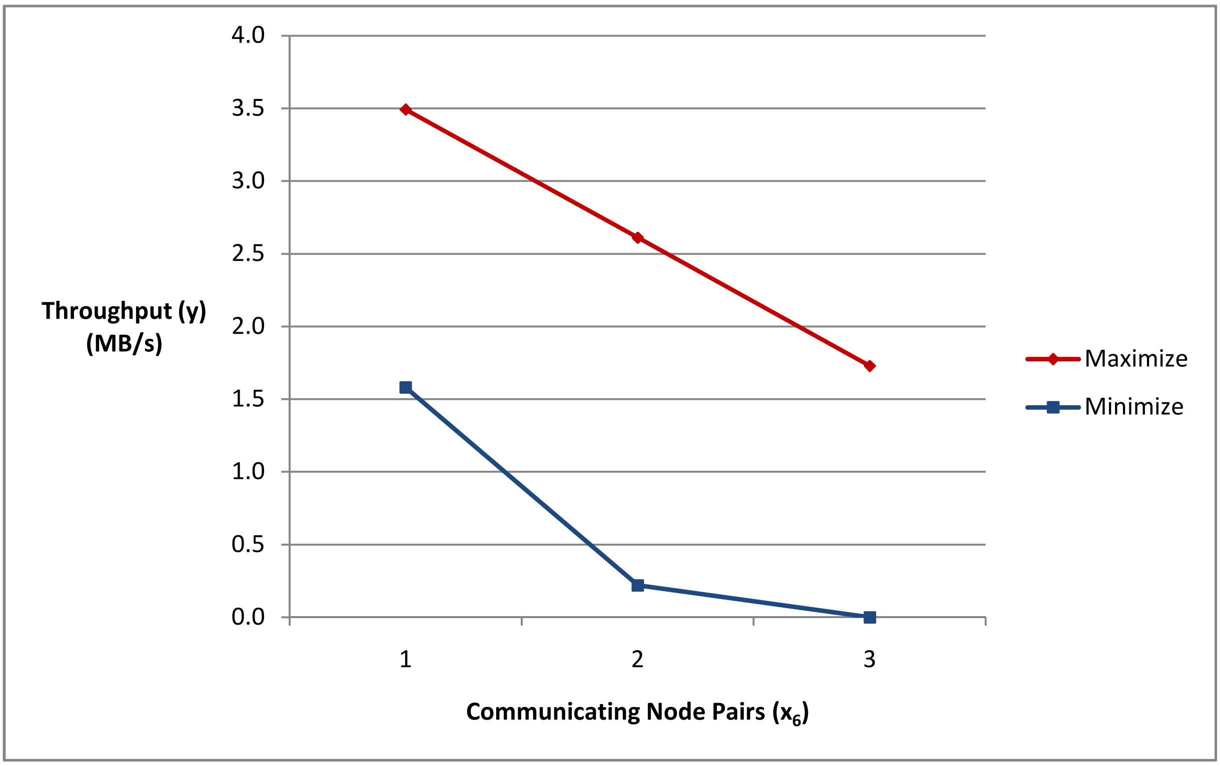
Maximum Value for Throughput (y)	3.4284	3.3757	3.2883	3.2009	3.1522	3.1328
Jitter (x_1)	0.0004	0.0005	0.0005	0.0005	0.0002	0.0002
Packet Loss (x_2)	120	130	140	150	160	170
Data Size (MB) (x_3)	104.64	102.04	97.615	93.195	99.29	89.842
Hop Count (x_4)	1	1	1	1	1	1
Obstruction (x_5)	2	2	2	2	1	1
Communicating Node Pairs (x_6)	1	1	1	1	1	1
Distance Between STA's (x_7)	3	2.8992	2.7311	2.563	2.9367	2.8229
File Type (x_8)	2	2	2	2	2	1



Minimum Value for Throughput (y)	0	0	0	0	0	0
Jitter (x_1)	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002
Packet Loss (x_2)	120	130	140	150	160	170
Data Size (MB) (x_3)	32.556	33.032	33.508	33.984	34.46	34.936
Hop Count (x_4)	2	2	2	2	2	2
Obstruction (x_5)	1	1	1	1	1	1
Communicating Node Pairs (x_6)	3	3	3	3	3	3
Distance Between STA's (x_7)	1.2426	1.2418	1.241	1.2403	1.2395	1.2387
File Type (x_8)	2	2	2	2	2	2

Figure 5.1 Optimum Throughput Values when Restricting Packet Loss

Maximum Value for Throughput (y)	3.491	2.610	1.729
Jitter (x_1)	0.000003	0.000014	0.000025
Packet Loss (x_2)	52	49.5	47
Data Size (MB) (x_3)	104.66	104.68	104.69
Hop Count (x_4)	1	1	1
Obstruction (x_5)	2	2	2
Communicating Node Pairs (x_6)	1	2	3
Distance Between STA's (x_7)	3	3	3
File Type (x_8)	1	1	1



Minimum Value for Throughput (y)	1.58	0.22	0
Jitter (x_1)	0.00009	1.04	0.0001
Packet Loss (x_2)	21	16	93
Data Size (MB) (x_3)	20.94	20.95	57.87
Hop Count (x_4)	2	2	2
Obstruction (x_5)	1	2	1
Communicating Node Pairs (x_6)	1	2	3
Distance Between STA's (x_7)	1	1	1.22
File Type (x_8)	3	3	3

Figure 5.2 Optimum Throughput Values when Restricting Communicating Node Pairs

As in the first case, the results on the graph indicate that the number of computers communicating over the network (x_6) will have an impact on the Throughput. This can again be seen from the non-increasing pattern in the resulting maximum values for Throughput and the similar pattern for the minimum values. Figure 5.2 shows that when the Communicating Node Pairs (x_6) is high, the optimum value for the response variable Throughput is low. The results also correlate with the results in Figure 5.1 and it is clear that whenever there is a high number of Communicating Node Pairs, it would be difficult to select values for the remaining decision variables that will result in high Throughput.

From the tables above and below the graph, it can be seen that, for example, when the Communicating Node Pairs (x_6) is at a high level of 3, Packet Loss (x_2) should be at a lower level to reach the optimum Throughput.

5.2.2 Delay as Response Variable

Delay is seen as another important metric in QoS evaluations and this section will present the LRSA technique using Delay as the response variable.

Using the same data as in Section 5.2.1, the following multiple linear regression model was obtained.

$$\begin{aligned} Delay = & -34.253 + 16.959x_1 + 0.0311x_2 + 0.003x_3 - 6.183x_4 + 3.347x_5 \\ & + 31.684x_6 - 14.044x_7 + 2.521x_8 \end{aligned} \tag{5.8}$$

where x_1 – jitter, x_2 - packet loss, x_3 - data sent, x_4 - hop count, x_5 – obstruction, x_6 - communicating node pairs, x_7 - distance between nodes, x_8 - file type.

Regression Statistics	
Multiple R	0.72584264
R^2	0.526847538
Adjusted R^2	0.514792698

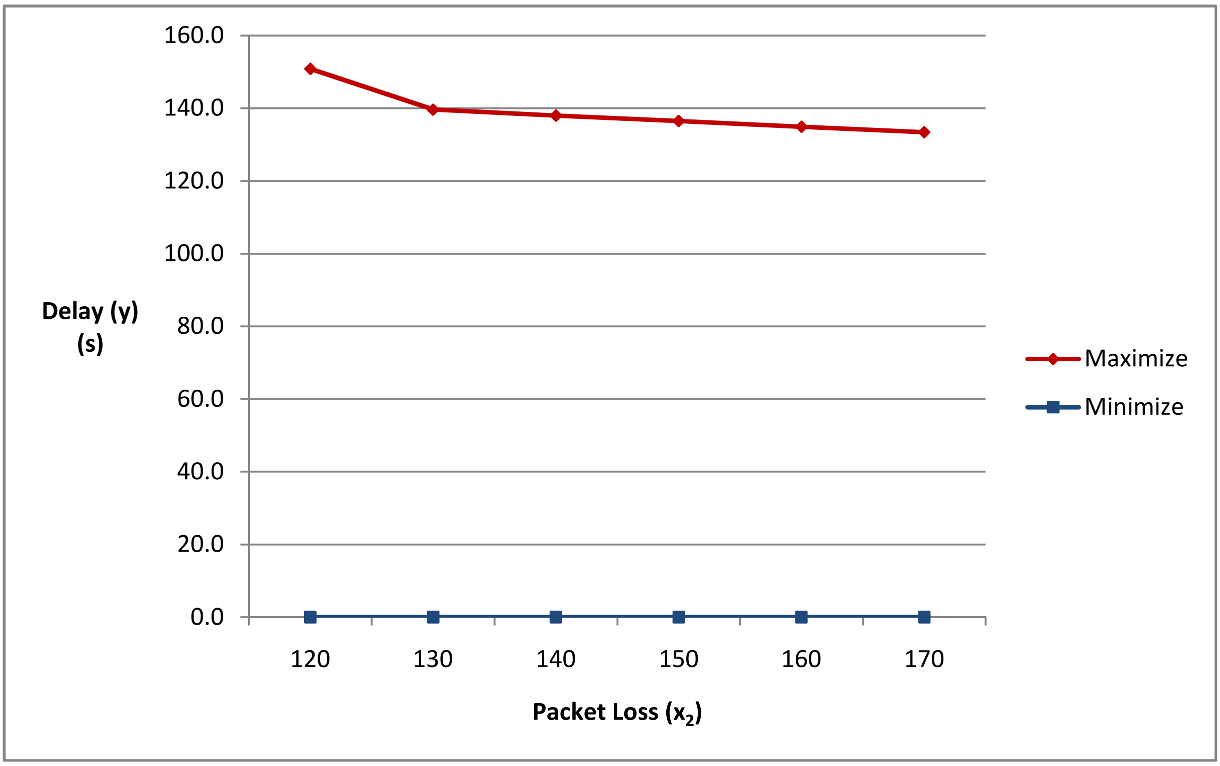
Table 5.3 Regression Statistics for Delay

The R^2 value in Table 5.3 has slightly improved over the Throughput model in the previous section but is still relatively low. Based on the explanation in Section 5.2.1, the R^2 was accepted and the model in (5.8) was optimised. The optimisation was carried out in the same way as explained for the Throughput model (see Section 5.2.1).

The results of two specific evaluations are presented. Firstly, when Packet Loss (x_2) is restricted to certain values, and secondly, when the number of Communicating Node Pairs (x_6) is restricted.

The optimal values for Delay when the variable Packet Loss (x_2) is restricted to values 120 to 170 with increments of 10 is presented graphically in Figure 5.3. As explained earlier, for the Throughput model, the zero minimum values are small positive values that appear to be zero due to the difference in measurements in seconds and milliseconds.

Maximum Value for Delay (y)	150.81	139.58	137.98	136.45	134.91	133.37
Jitter (x_1)	0.0005	0.0036	0.0063	0.0057	0.0051	0.0046
Packet Loss (x_2)	120	130	140	150	160	170
Data Size (MB) (x_3)	104.58	103.92	104.67	104.68	104.69	104.7
Hop Count (x_4)	1	1	1	1	1	1
Obstruction (x_5)	2	1	1	1	1	1
Communicating Node Pairs (x_6)	3	3	3	3	3	3
Distance Between STA's (x_7)	1	1.5441	1.5526	1.6842	1.8158	1.9474
File Type (x_8)	2	2	1	1	1	1



Minimum Value for Delay (y)	0	0	0	0	0	0
Jitter (x_1)	0.0002	0.0002	0.0003	0.0003	0.0003	0.0003
Packet Loss (x_2)	120	130	140	150	160	170
Data Size (MB) (x_3)	24.047	23.35	22.654	21.957	21.26	30.268
Hop Count (x_4)	1	1	1	1	1	1
Obstruction (x_5)	1	1	1	1	1	1
Communicating Node Pairs (x_6)	1	1	1	1	1	1
Distance Between STA's (x_7)	1.7918	1.769	1.7462	1.7235	1.7007	2.1244
File Type (x_8)	2	2	2	2	2	1

Figure 5.3 Optimum Delay Values when Restricting Packet Loss

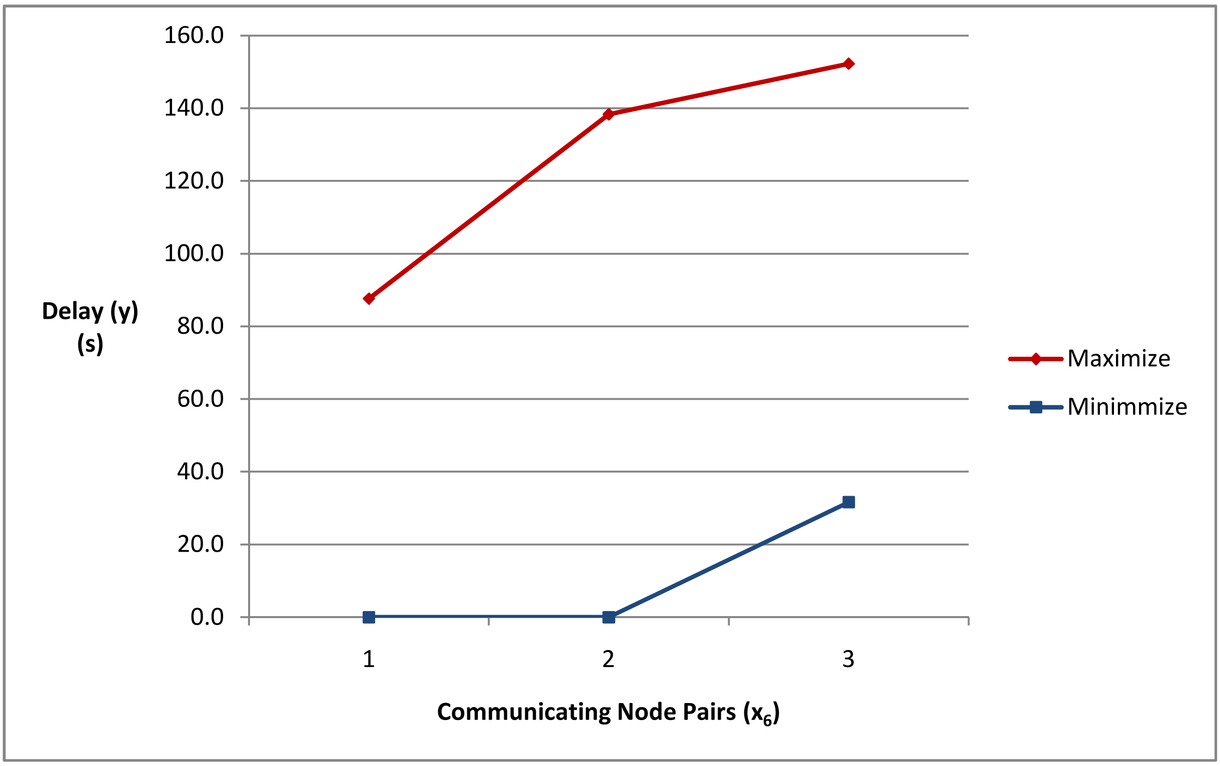
The maximum values for Delay seem to be an anomaly as it would be expected that Delay would increase when Packet Loss increases. The situation as depicted in the model is, however, possible as Delay is also influenced by other prioritised QoS parameters that were not included in the LRSA model. For example, Delay is amongst other things influenced by the specifications of the protocol used. The protocol used may enable a receiving node to infer the correct contents of a corrupted packet by applying a specific algorithm. This means that the receiving node will not necessarily issue a resend request for every lost packet that, in turn, means that the Delay may decrease. The specifications of the protocol will also determine if a specific packet that was not received must be resent or if n packets must be resent, where n is the number of packets including the packet that was not received. This specification may also decrease the Delay.

This type of information and explanations would not have been easily obtainable without the LRSA model, where the influence of a specific variable (Packet Loss) can be investigated with regard to maximum Delay values. It is also possible to see from the graph in Figure 5.3 that the remaining variables will have a significant influence on the Delay. This can be seen from the difference between the maximum and minimum values of Delay – the influence of the other variables is relatively large when the difference (as in Figure 5.3) is large.

In Figure 5.4, the second illustration of the LRSA technique is presented graphically. In this instance, the number of Communicating Node Pairs (x_6) is restricted to 1, 2 and 3 while optimising Delay.

The results on the graph clearly indicate that the variable Communicating Node Pairs (x_6) will have a negative impact on the Delay. This can be seen from both graphs that are non-decreasing. When Communicating Node Pairs is high, the optimum value for the response variable Delay is also high. This means that whenever Communicating Node Pairs are high, it would be difficult to lower the Delay by adjusting the other decision variables. As in the previous illustrations, the tables above and below the graph present suggested values for the other decision variables to find higher or lower Delay values.

Maximum Value for Delay (y)	87.579	138.31	152.25
Jitter (x_1)	0.00008	0.00004	0.00325
Packet Loss (x_2)	86	337	126
Data Size (MB) (x_3)	103.13	125.13	103.13
Hop Count (x_4)	1	2	1
Obstruction (x_5)	2	2	2
Communicating Node Pairs (x_6)	1	2	3
Distance Between STA's (x_7)	1	1	1
File Type (x_8)	3	2	3



Minimum Value for Delay (y)	0	0.00916	31.599
Jitter (x_1)	0.00002	0.00003	0.00004
Packet Loss (x_2)	23.235	18	15
Data Size (MB) (x_3)	20.945	20.929	20.927
Hop Count (x_4)	1	2	2
Obstruction (x_5)	1	1	1
Communicating Node Pairs (x_6)	1	2	3
Distance Between STA's (x_7)	1.5565	3	3
File Type (x_8)	3	1	1

Figure 5.4 Optimum Delay Values when Restricting Communicating Node Pairs

5.2.3 Reconciliation of Conflicting Goals

The previous sections were largely used to explain how factors may influence Throughput and Delay during transmissions in wireless networks. To do this, models in the form of linear regression equations were developed and coefficients were estimated using standard linear regression techniques. These models were then maximised and minimised to investigate the influence of specific factors. However, it is often the case that factors are interdependent and are conflicting in nature. This means that if, for example, efforts or resources are concentrated on one factor, it might improve, or weaken, another factor. In this section, the possible conflict between the two response variables, Throughput and Delay, will be investigated.

Based on the definitions of Throughput and Delay (presented in Section 2.4.2), it is safe to presume that there is an interdependent relationship between the two variables. If Delay increases, there will be a decrease in Throughput and, *vice versa,* if resources are focused in the improvement of Delay, it may also improve Throughput. To make provision for these apparent contradictions, the original LRSA model adapted by adding an additional constraint that can be used to provide for the predetermined level of Throughput or Delay. The adopted model, to optimise Throughput while taking Delay into account, was formulated as follows.

$$\text{Max/Min} \quad Throughput = b_0 + b_1x_1 + \dots + b_kx_k, \tag{5.9}$$

subject to

$$\sum_{i=1}^{N} \lambda_i x_{ij} = x_j \; for \; j = 1,2,\dots,k, \tag{5.10}$$

$$\sum_{i=1}^{N} \lambda_i = 1, \tag{5.11}$$

$$c_0 + c_1x_1 + \dots + c_kx_k = d, \tag{5.12}$$

$$x_p = q_{pr}, \tag{5.13}$$

$$x_j \geq 0 \; for \; j = 1,2,\dots,k, \tag{5.14}$$

$$\lambda_i \geq 0 \; for \; i = 1,2,\dots,N. \tag{5.15}$$

In this formulation, the constraint (5.12) was added and represents the linear regression model for the Delay (see 5.8 in Section 5.2.2)

By solving the linear model (5.9) to (5.15), the Throughput can be maximised with the notion that Delay (5.12) is fixed (given) at a certain level. Constraint (5.13) may also be used to restrict other decision variables to determine what their effect would be on the Throughput given that Delay is at a certain level.

To illustrate the use of the model, it was solved for 9 different values of d. No other decision variables were restricted. The different solutions were as follows (table 5.4).

d	**Maximum Throughput**
20	3.34
35	3.43
50	3.48
65	3.25
80	2.77
95	2.41
110	2.25
125	1.54
140	1.1

Table 5.4 Maximum Throughput when restricting Delay

Graphically, the maximum Throughput can be presented as in figure 5.5.

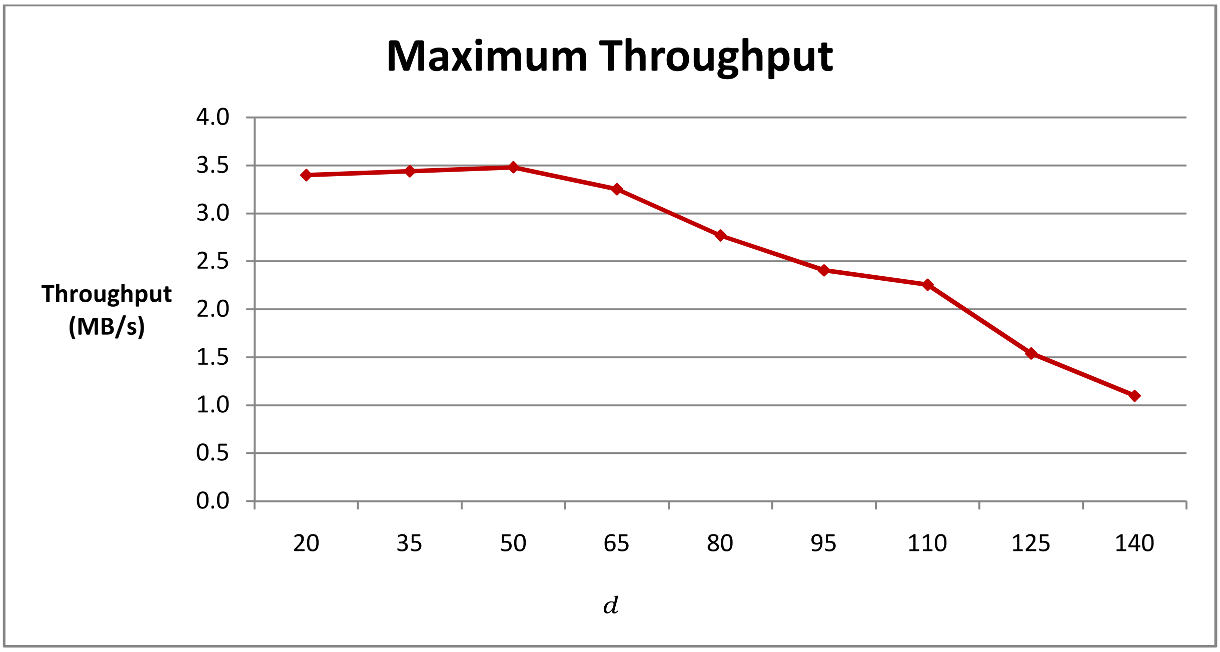


Figure 5.5 Maximum Throughput when restricting Delay

It can be seen from Table 5.4 and from the graph in Figure 5.5 that a certain price in Throughput has to be paid if pre-determined Delay levels are applicable. The maximum Throughput when $d \leq 50$ is 3.48. Whenever d rises above 50, the Throughput will decrease. At $d =$ 140, a maximum Throughput of only 1.1 is achieved. This amounts to a 68% difference (or price to be paid) due to the higher Delay. It is therefore important to concentrate efforts on Delay in a network as there is a certain point (50 seconds in this study) whereafter Throughput will start deteriorating.

The same analysis (not presented here) can be done when Delay is minimised while Throughput is set to be at least at some specific level. In this case, the Delay regression model will be the objective function (5.9) and the Throughput regression model will be substituted into constraint (5.12). For example, it may be decided to maintain a Throughput of at least 3.5MB/s. The constraint would then be formulated as

$$c_0 + c_1x_1 + \ldots + c_kx_k \geq 3.5 \tag{5.16}$$

The model presented in this section has the advantage of taking both Delay and Throughput factors into consideration in an effort to alleviate conflicting interests. It has a built-in mechanism to ensure that no discrimination against Delay has taken place because Delay is forced to be at an accepted pre-determined level.

5.3 Additional Analysis

The nature of the QoS data captured during the experiments provides an opportunity to perform evaluations for specific categories of data. In other words, the LRSA model does not necessarily have to be applied to the entire data set but may be applied to only specific categories of the data set such as specific file types transmitted, distance, hop counts, etc. This can be handled either by simply extracting a specific category to do the analysis or by utilising the constraint $x_p = q_{pr}$ (5.4). In this section, examples of how the analysis was done for a specific file type will be presented.

5.3.1 Throughput as Response Variable

To investigate the influence of Packet Loss (x_2) for specific file types (as opposed to using all the data as in Section 5.2), the original data set was divided into three data sets containing the text, audio and ZIP files, respectively. There were 108 text file records, 107 audio file records and 108 ZIP file records. In this section, two examples of the results obtained are presented. Figure 5.6 shows the results for the maximum and minimum Throughput values for audio files while restricting Packet Loss to values ranging from 120 to 170, in increments of 10. The results for the text file type are presented in Figure 5.7.

The multiple linear regression model formulated for the audio file type was:

$$\begin{aligned} Throughput = {} & 3.087 - 21.206x_1 - 0.0008x_2 + 0.004x_3 - 0.502x_4 + 0.217x_5 \\ & - 1.004x_6 + 0.465x_7 \end{aligned} \tag{5.17}$$

with $R^2 = 0.524$.

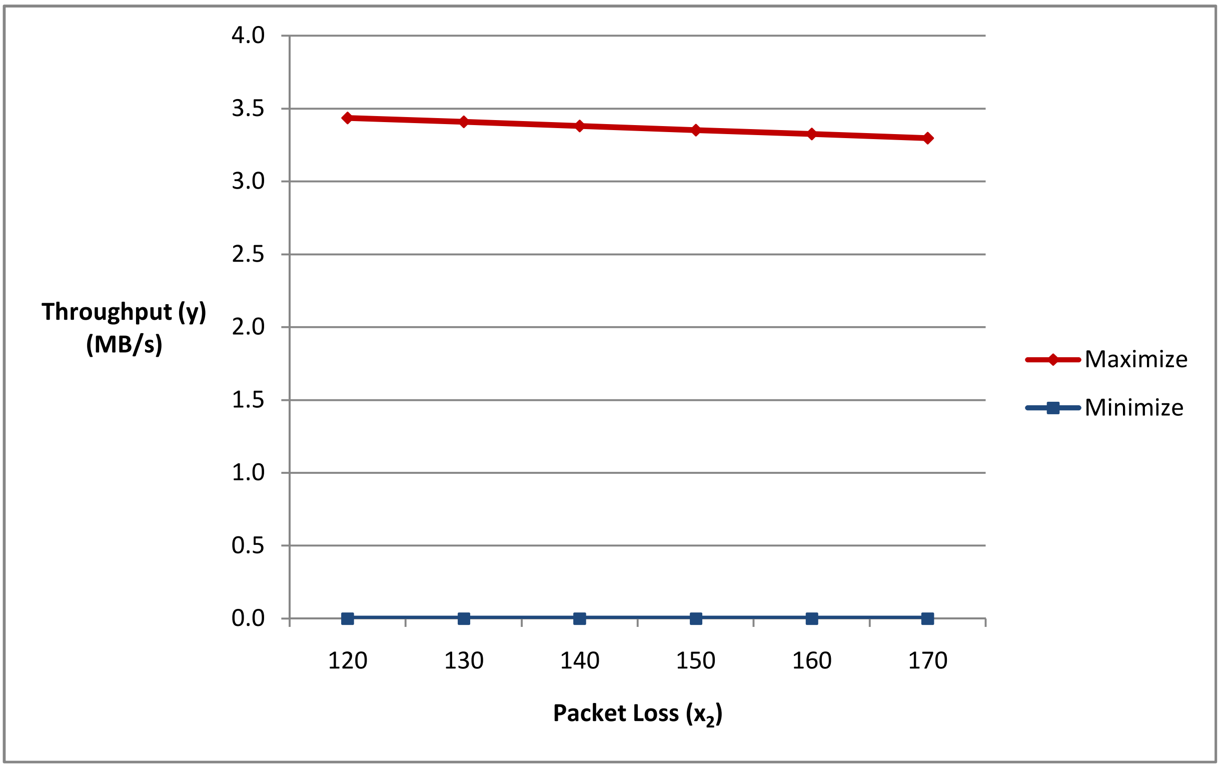
For the text file type, the linear regression model obtained was

$$\begin{aligned} Throughput = {} & 2.843 - 25.516x_1 + 0.0006x_2 + 0.001x_3 - 0.466x_4 + 0.196x_5 \\ & - 0.817x_6 + 0.402x_7 \end{aligned} \tag{5.18}$$

with $R^2 = 0.484$.

In both these cases, the results are in line with the findings of Section 5.2.1 when all the data was used. Packet Loss as a variable has a significant effect on the Throughput for both audio and text files and at high levels of Packet Loss, it would be difficult to obtain high Throughput by simply adjusting the other decision variables. It seems, therefore, that the file type does not play a significant role when treating Packet Loss as a state variable.

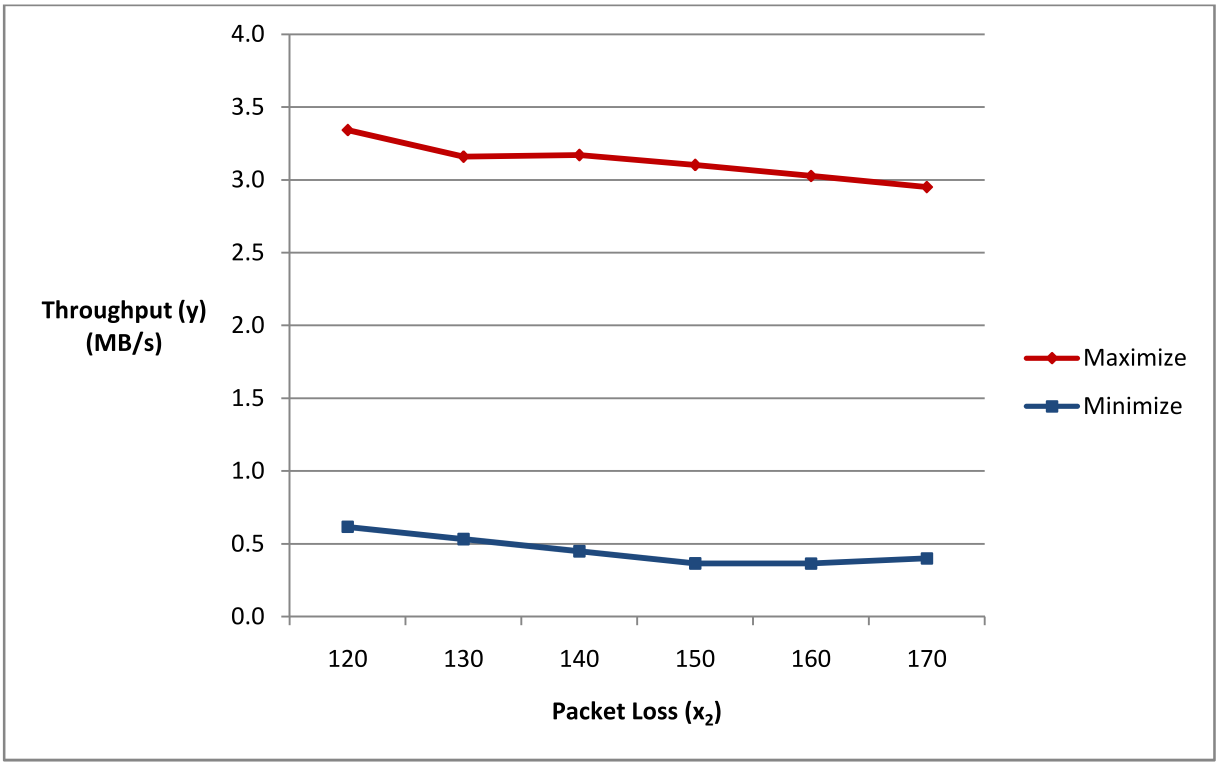
Maximum Value for Throughput (y)	3.4346	3.4068	3.379	3.3512	3.3234	3.2956
Jitter (x_1)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Packet Loss (x_2)	120	130	140	150	160	170
Data Size (MB) (x_3)	100.72	98.543	96.368	94.193	92.017	89.842
Hop Count (x_4)	1	1	1	1	1	1
Obstruction (x_5)	1	1	1	1	1	1
Communicating Node Pairs (x_6)	1	1	1	1	1	1
Distance Between STA's (x_7)	2.9531	2.9271	2.901	2.875	2.849	2.8229



Minimum Value for Throughput (y)	0	0	0	0	0	0
Jitter (x_1)	0.0001	0.0002	0.0002	0.0002	0.0002	0.0002
Packet Loss (x_2)	120	130	140	150	160	170
Data Size (MB) (x_3)	26.497	26.977	27.458	27.939	28.42	28.9
Hop Count (x_4)	2	2	2	2	2	2
Obstruction (x_5)	1	1	1	1	1	1
Communicating Node Pairs (x_6)	3	3	3	3	3	3
Distance Between STA's (x_7)	1.5324	1.5454	1.5584	1.5713	1.5843	1.5973

Figure 5.6 Optimum Throughput Values for Audio File Type when Restricting Packet Loss

Maximum Value for Throughput (y)	3.342	3.1587	3.1703	3.1029	3.0267	2.9504
Jitter (x_1)	0.0004	0.00001	0.00001	0.0002	0.0004	0.0007
Packet Loss (x_2)	120	130	140	150	160	170
Data Size (MB) (x_3)	102.61	99.433	104.2	98.379	91.375	84.371
Hop Count (x_4)	1	1	1	1	1	1
Obstruction (x_5)	2	1	1	1	1	1
Communicating Node Pairs (x_6)	1	1	1	1	1	1
Distance Between STA's (x_7)	3	3	3	2.8487	2.6807	2.5126



Minimum Value for Throughput (y)	0.6162	0.5329	0.4496	0.3663	0.3656	0.4003
Jitter (x_1)	0.0326	0.0359	0.0393	0.0426	0.0432	0.0426
Packet Loss (x_2)	120	130	140	150	160	170
Data Size (MB) (x_3)	29.879	27.19	24.501	21.813	21.846	23.045
Hop Count (x_4)	1	1	1	1	1	1
Obstruction (x_5)	1	1	1	1	1	1
Communicating Node Pairs (x_6)	2	2	2	2	2	2
Distance Between STA's (x_7)	1	1	1	1	1.02	1.0486

Figure 5.7 Optimum Throughput Values for Text File Type when Restricting Packet Loss

5.3.2 Delay as Response Variable

Tests were also performed on specific types with Delay as the response variable. Two examples are again presented and, in this case, the Data Size(x_3) was restricted to 25, 50 and 100 Mega Byte (MB). The multiple linear regression model obtained for the audio file type was

$$\begin{aligned} Delay = & -39.504 + 643.25x_1 + 0.009x_2 + 0.855x_3 - 5.677x_4 + 1.662x_5 \\ & + 32.998x_6 - 8.414x_7 \end{aligned} \tag{5.19}$$

with $R^2 = 0.572$.

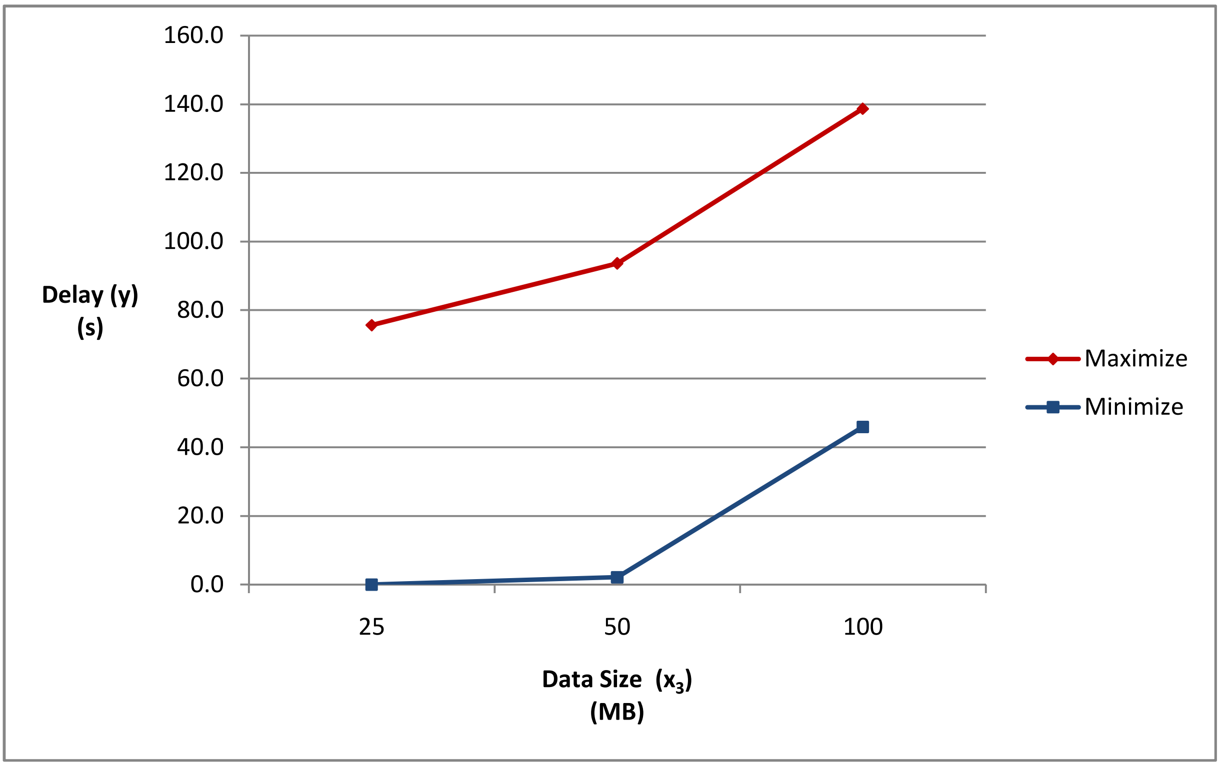
For the text file type, the model was formulated as

$$\begin{aligned} Delay = & -33.487 + 447.153x_1 + 0.025x_2 + 0.877x_3 - 1.836x_4 + 5.683x_5 \\ & + 28.049x_6 - 14.128x_7 \end{aligned} \tag{5.20}$$

with $R^2 = 0.521$.

The results of the optimisation of these models while restricting the variable Data Size (x_3) are presented in Figures 5.8 (audio file type) and 5.9 (text file type). The non-decreasing graphs for both file types indicate that for high values of Data Size (x_3), the optimum value for Delay will also be high. This implies that for high values of Data Size (x_3), it would be difficult to choose values for the remaining decision variables in order to lower the Delay. The tables above and below the graphs give the suggested levels for the other decision variables. The two graphs and the values are very similar, and it appears that the file type does not play a significant role in this instance.

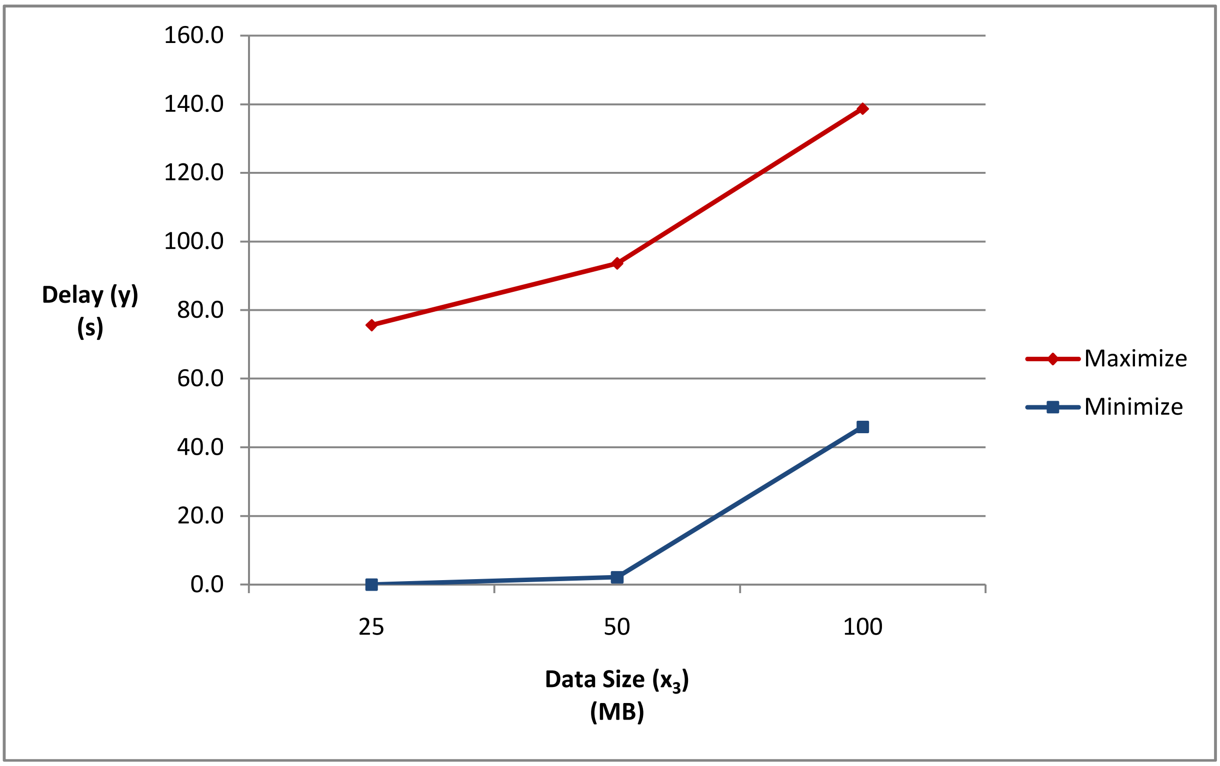
Maximum Value for Delay (y)	75.602	93.614	138.68
Jitter (x_1)	0.0169	0.0117	0.0082
Packet Loss (x_2)	30.481	33.47	93.462
Data Size (MB) (x_3)	25	50	100
Hop Count (x_4)	2	2	1
Obstruction (x_5)	2	2	1
Communicating Node Pairs (x_6)	3	3	3
Distance Between STA's (x_7)	1	1	1



Minimum Value for Delay (y)	0.0000	2.1299	45.9440
Jitter (x_1)	0.0024	0.0004	0.001
Packet Loss (x_2)	27.709	62.644	134.27
Data Size (MB) (x_3)	25	50	100
Hop Count (x_4)	1	2	2
Obstruction (x_5)	1	1	1
Communicating Node Pairs (x_6)	1	1	1
Distance Between STA's (x_7)	1.5043	3	3

Figure 5.8 Optimum Delay Values for Audio File Type when Restricting Data Size

Maximum Value for Delay (y)	69.816	91.528	136.83
Jitter (x_1)	0.0067	0.0002	0.0003
Packet Loss (x_2)	26.767	60.981	117.75
Data Size (MB) (x_3)	25	50	100
Hop Count (x_4)	2	1	1
Obstruction (x_5)	2	2	2
Communicating Node Pairs (x_6)	3	3	3
Distance Between STA's (x_7)	1	1	1



Minimum Value for Delay (y)	0	0	44.009
Jitter (x_1)	0.00002	0.00027	0.00005
Packet Loss (x_2)	26.521	56.399	84.41
Data Size (MB) (x_3)	25	50	100
Hop Count (x_4)	2	2	2
Obstruction (x_5)	1	1	1
Communicating Node Pairs (x_6)	1	1	1
Distance Between STA's (x_7)	1.3566	2.9688	3

Figure 5.9 Optimum Delay Values for Text File Type when Restricting Data Size

5.3.3 File Type Comparison

The previous section presented a few examples of how the LRSA technique was applied to text and audio file types. In those examples, results for only two restricted variables Packet Loss (x_2) and Data Size (x_3) were presented. The analysis was extended to investigate the influence of each one of the QoS factors on all three of the file types. This analysis provided an opportunity to compare the three file types against each another while restricting the QoS variables, one at a time. The comparison is presented in Table 5.5.

The first column in Table 5.5 shows the specific variable that was restricted to different values while optimising Throughput and Delay. For example, the last row in Table 5.5 indicates that while the distance between the nodes (x_7) was restricted, the audio files generally achieved the highest Throughput, the ZIP files generally had the lowest Throughput and the highest Delay, and the text files had the lowest Delay throughout the analysis.

QoS Factor	Highest Throughput	Lowest Throughput	Highest Delay	Lowest Delay
Jitter(x_1)	Audio	ZIP	-	-
Packet Loss(x_2)	Audio	ZIP	ZIP	Text
Data Size(x_3)	Audio	Text	ZIP	Text
Hop Count(x_4)	Audio	ZIP	ZIP	Text
Obstruction(x_5)	Audio	ZIP	ZIP	Audio
Communicating Node Pairs(x_6)	Audio	ZIP	ZIP	Audio
Distance Between Nodes(x_7)	Audio	ZIP	ZIP	Text

Table 5.5 Comparison of File Types Achieving Highest and Lowest Throughput and Delay

From this comparison, it can be concluded that the ZIP files are the most difficult to transmit over a wireless network (low throughput) while the audio files are transmitted more easily (high throughput). The uncompressed audio files and the compressed ZIP files therefore lay at two opposite ends concerning throughput. Concerning Delay, the text files and ZIP files lay at opposite ends. This implies that the compression of a file type does have an effect on the level of Throughput and Delay experienced in a wireless network and that uncompressed file types are transmitted more effectively than are compressed file types.

These results are supported by the different file type's sensitivity or the change in Throughput or Delay when the restricted variable is increased or decreased. The sensitivity results are presented in Table 5.6. Over the seven inspected QoS factors, the ZIP file type is the most sensitive file type in the majority of cases. The text file appears the least sensitive, making it the most stable file type in terms of network dynamics. Concerning Table 5.5, the file type achieving the highest Throughput is the most sensitive and the file type achieving the lowest Throughput is the file type least sensitive to changes in the restricted QoS factor. For example, concerning Throughput, the file type in Table 5.5 achieving the highest throughput was the audio file type while in Table 5.6, it can be seen that it is the most sensitive to changes in the factors. In addition, in Table 5.5, the file type achieving the lowest throughput was the ZIP file type that in Table 5.6 is the file type that is the least sensitive to changes in QoS factors.

QoS Factor	**Most Sensitive (Throughput)**	**Least Sensitive (Throughput)**	**Most Sensitive (Delay)**	**Least Sensitive (Delay)**
Jitter(x_1)	Audio	ZIP	-	-
Packet Loss(x_2)	ZIP	Audio	ZIP	Audio
Data Size(x_3)	Text	ZIP	ZIP	Audio
Hop Count(x_4)	Audio	ZIP	ZIP	Audio
Obstruction(x_5)	ZIP	Audio	Audio	ZIP
Communicating Node Pairs(x_6)	Audio	ZIP	ZIP	Text
Distance Between Nodes(x_7)	Audio	Text	ZIP	Audio

Table 5.6 Comparison of File Types Sensitivity

5.4 Extension to the LRSA Model

A decision to improve the QoS in a wireless network, which may be interpreted as increasing Throughput or lowering Delay, will involve certain costs. Improving the QoS implies that the variables or factors influencing QoS should be changed. The best combination for the various levels factors involved should be determined (with the help of the LRSA) while at the same time, the cost to change each factor to the desired level should be considered. This section will very briefly examine how cost can be incorporated into the LRSA model.

In general, if it is assumed that costs to adjust variables $x_1 \dots x_k$ with one unit are $c_1 \dots c_k$ respectively, and that a total budget, B, is available then the following constraint can be added to the model.

$$c_1x_1 + c_2x_2 + \cdots + c_kx_k \leq \mathrm{B} \tag{5.17}$$

The addition of this constraint implies that the decision maker assumes that the cost for each variable increases linearly - that may not be true in all cases.

Another problem relates to the specification of values for $c_1 \dots c_k$. It is assumed that whenever costs are taken into account that historical data and other relevant cost information would be available to accurately estimate cost figures. Therefore, for any specific case, the following would be available

Factor	Observed performance	Desired performance	Cost to adjust factor with one unit	Total Cost
x_1	Po_1	Pd_1	c_1	$\lvert Pd_1 - Po_1 \rvert c_1$
x_2	Po_2	Pd_2	c_2	$\lvert Pd_2 - Po_2 \rvert c_2$
x_3	Po_3	Pd_3	c_3	$\lvert Pd_3 - Po_3 \rvert c_3$
⋮	⋮	⋮	⋮	⋮
x_k	Po_k	Pd_k	c_k	$\lvert Pd_k - Po_k \rvert c_k$

It would now be possible to once again maximise, for example, Throughput, and to add the following constraint to incorporate the cost of adjusting the factors from their observed values to their desired levels:

$$|Pd_1 - Po_1|c_1 + |Pd_2 - Po_2|c_2 + \cdots + |Pd_k - Po_k|c_k \leq B \tag{5.18}$$

The consideration of costs was not included in this study and the above constraints are only presented for explanatory purposes.

5.5 Recommendations

This subsection will present the main recommendations following the empirical experiments and the application of the LRSA technique. First, some recommendations and general remarks regarding the use of the LRSA technique will be presented. This will be followed by comments that are more specifically related to the performance of the wireless network configurations used in the study.

5.5.1 Linear Response Surface Analysis

The objective of this research project was to investigate the use of the LRSA technique in the evaluation of QoS factors in a wireless network. The following comments, based on the work that has been performed, conclude that the LRSA technique is an appropriate technique to use.

- The technique is suitable for investigating the influence of a specific independent variable. The preceding sections presented examples where specific variables were restricted to different values in order to see what the effect would be on a dependent variable such as Throughput or Delay.

- One of the strengths of the LRSA technique is that it not only provides an indication of the optimum values (for example, the maximum attainable Throughput) for a dependent variable, but the model also suggests levels for the other decision variables in order to achieve the maximum (or minimum) value. This means that the model also provides suggestions of where to concentrate efforts in order to achieve higher Throughput or lower Delay.

- The LRSA technique is particularly suitable for analysing the influence of state variables (a variable not under the control of the decision maker). For example, the variable Obstruction (x_5) can be seen as a state variable – if a physical obstruction exists, it is normally a given and cannot be changed. The constraint (5.4) in the model, as presented in Section 5.2, can be used to restrict the variable to indicate that an obstruction is present or absent.

- Conflicting goals can be analysed and reconciled with the LRSA technique. For example, in Section 5.2.4 it was shown how the model could be adapted to determine the “price” to be paid in Throughput if a certain minimum predetermined level for Delay is required.

- The linear programming model can be extended to make provision for other requirements. In Section 5.4, an extension to include the cost of adjusting factors was presented as an example of just such an extension.

- The LRSA technique is easy to understand and to implement and with modern optimisation software, such as SAS, large problems can be solved in a short time.

The following recommendations should be considered in future studies where the LRSA technique is employed.

- The LRSA technique is based on linear relationships. In studies where there is clearly a non-linear relationship between variables, the LRSA technique should not be used.

- Empirical work to generate data should be conducted in a careful manner. In this study, the R^2-value of the different linear models was around 0.5. This relatively low value can be improved by taking greater care during the data generation process. In this study, it would have meant spending more time to repeat experiments and also using more sophisticated (and therefore expensive) equipment – this was not possible in this study.

- The LRSA technique would be more efficient if more QoS factors were measured and included in the empirical experiments. In addition, it is also recommended that other factors, measured in a continuous way, be included. For example, factors such as signal strength and bit rate can also be considered for inclusion.

5.5.2 Wireless Network Performance

This section presents some general comments and recommendations based on practical experience gained during the construction of the prototype wireless network and the application of the LRSA technique to analyse the QoS in the network.

- There is an interrelationship among the independent variables (as expected) and they influence one another. This means that adjusting one factor (to a level suggested by the LRSA model) will improve or weaken another. Figure 5.10 shows the interrelationship of QoS factors graphically. The factors on lower levels directly influence the next higher level.

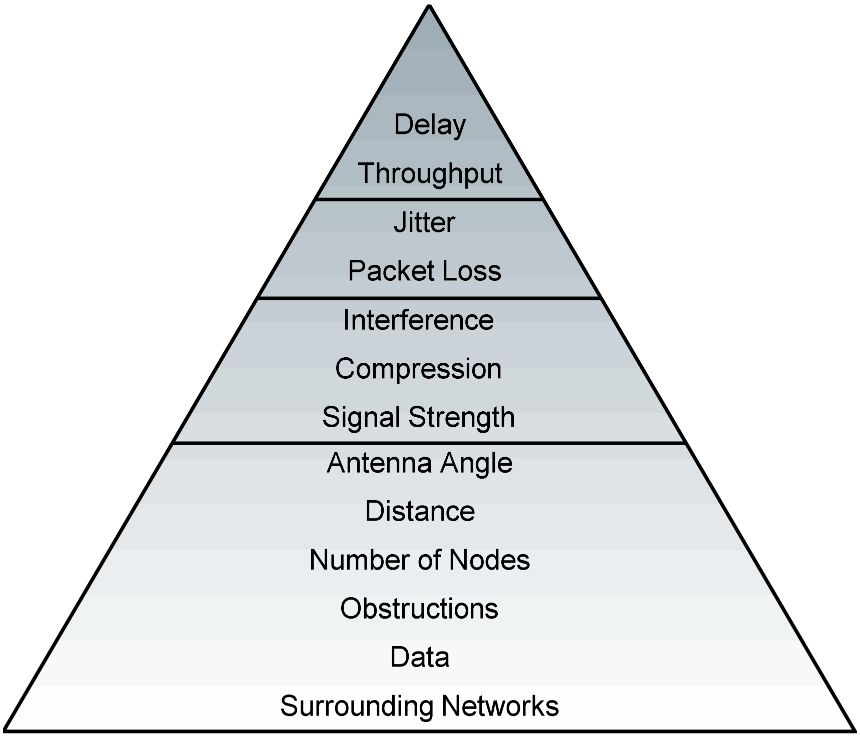


Figure 5.10 Influences of QoS Factors on Each Other

- During the construction of the wireless network and the application of the LRSA technique, it became clear that the factor Packet Loss is influenced by a number of other issues. For example, by the number of nodes in the network as well as by the signal strength. To lower packet loss, and indirectly the jitter, the number of computers in the network should be kept to a minimum. In cases where the networks are large, it should be considered to divide the network into smaller sections that are interconnected via a number of access points.

- Signal strength also plays a role in packet loss and to ensure a sufficient signal strength consideration should be given to aspects such as the distances between nodes and access points, as well as the presence of possible obstructions. Care should also be taken that the antennas of the access points are angled at an optimal angle for the nodes connected to them and for the signal strength.

- The environment in which the wireless network is constructed may also have an influence on the QoS data. Other wireless networks in the surrounding area may influence both the signal strength and the amount of interference experienced. It is therefore important to ensure that the channels used by the different wireless networks are separated sufficiently.

- The results of the analysis for Delay were not always as expected (see, for example, Section 5.2.2). The reason for this is that Delay is further influenced by other factors that were not measured in this study. These factors are related to prioritised quality of service factors such as routing algorithms. For a discussion on these factors, see Ferreira (2009).

- Another factor that may influence the Throughput and Delay is the compression method employed by the protocol used in a network. In this study, the uncompressed audio files and the compressed ZIP files showed large differences in Throughput and Delay (see Section 5.3.3). This was due to the use of the TCP/IP protocol that compresses outgoing data by default (Cisco, 2012). It is recommended that the choice of protocol be based on the type of data that will primarily be sent over the wireless network.

5.6 Chapter Summary

Chapter 5 presented the empirical results of the application of the LRSA technique on the QoS data generated from different wireless network configurations. The results focused on Throughput and Delay as response variables. Various multiple linear regression models were formulated and optimised while restricting the decision variables. An explanation of how the LRSA technique can be used to reconcile conflicting goals was also presented as well as an illustration on how to incorporate cost into the models. The chapter concluded with recommendations and general comments on the use of the LRSA technique on the QoS data.

The next chapter presents the conclusion of the study and will summarise the goals set for the study and how they were achieved.

Chapter 6

Summary and Conclusions

6.1 Introduction

This chapter presents the final comments and concluding remarks of the study. The goals of the study and their achievement will be summarised. Opportunities for further study that presented themselves during the research project will also be outlined.

6.2 Summary of Work Performed

Chapter 1 stated that the primary goal of this study was to investigate the feasibility of a linear response surface analysis technique as an evaluation method for quality of service factors in wireless networks. To achieve the main goal, five secondary goals were identified.

1. Provide an overview of the quality of service factors in wireless networks;
2. Provide an overview of the linear response surface analysis technique;
3. Construct a prototype wireless network (802.11n) to generate appropriate quality of service data;
4. Perform an analysis on the generated quality of service data using the LRSA technique; and
5. Interpret results and make appropriate recommendations on the improvement of wireless network performance.

A summary of how each one of the objectives were addressed and achieved follows.

Provide an overview of the quality of service factors in wireless networks

The goal was addressed by discussing the ISO OSI network model in Sections 2.2 and 2.3 of Chapter 2. The discussion included a review of the 802.11n protocol that was used in the construction of the wireless network. The overview in Chapter 2 also covered various aspects of quality of service (Section 2.4) such as definitions, importance and problems. Finally, an overview of similar studies of QoS and its meaning and evaluation was presented (Section 2.5).

Provide an overview of the linear response surface analysis technique

To achieve this secondary goal, the two techniques on which the linear response surface analysis technique is built, linear regression and linear programming, as well as the methods used to solve linear programming problems, were discussed in Chapter 3, Sections 3.3.1 and 3.3.2. This was followed by an overview of the linear response surface analysis technique with an illustrative example (Chapter 3, Section 3.4).

Construct a prototype wireless network (802.11n) to generate appropriate quality of service data

This objective was achieved by constructing a prototype wireless network that was configurable in six different ways (Chapter 4, Section 4.5). In addition, specific considerations relating to software and hardware (Section 4.3) were also presented. The discussion was concluded with a presentation concerning the data used and the performance parameters calculated in empirical experiments (Sections 4.6 and 4.7).

Perform an analysis on the generated quality of service data using the LRSA technique

The contents show how this objective was achieved. A number of models were formulated and optimised with both Throughput and Delay as response variables (Chapter 5, Sections 5.2 and 5.3). It was also demonstrated how the formulated models can be used to reconcile conflicting goals (Section 5.2.3) or extended to include other issues such as costs (Section 5.4).

Interpret results and make appropriate recommendations on the improvement of wireless network performance

This goal was achieved by analysing, interpreting and explaining the results obtained from the various models (Chapter 5, Sections 5.2 and 5.3). Final comments and recommendations, based on the completed study and its results, were also provided (Chapter 5, Section 5.5).

To summarise, all objectives as set out in Chapter 1 were addressed. Based on the results and discussion presented in Chapter 5, it was concluded that:

- The LRSA technique is appropriate for evaluating QoS levels in a wireless network. It has specific strengths which include:
    - the investigation of the influence of specific independent variables;
    - suggested levels for other variables to maximise or minimise response variables such as Throughput or Delay;
    - the handling of conflicting goals;
    - the possibility of extending the model to include other aspects such as costs; and
    - an easy to understand technique which can be solved easily with optimisation software.

- The interrelationships among QoS factors play important roles in the optimisation of Throughput and Delay

- Other factors also affect the performance of a wireless network. For example, the environment (other networks in the surrounding area), routing algorithms, protocol used (automatic compression of data), etc.

6.3 Problems Experienced

A number of problems, related to the prototype wireless network, were experienced. There were physical problems such as signal loss or no transmission capabilities at certain distances. The major difficulty was the lack of a single application that could be used to capture QoS data in the correct format. Due to this, the data capturing and data preparation phases were difficult, complicated and took an appreciable time to complete.

Fewer problems were experienced with the application of the LRSA technique. Issues such as relatively low R^2 values and the lack of more continuous data did have an impact but these were not serious.

6.4 Recommendations For Future Work

Concerning the LRSA technique, it should be considered to include more QoS factors in further empirical experiments. More factors that can be measured in a continuous manner (as opposed to discrete data) should be included in future studies. The model could also be extended to include other aspects such as costs.

In terms of the prototype wireless network, the following, more technical aspects, may be considered for a follow-up study.

- This study focused on the transmission of entire files across the network using TCP. With the increasing use of handheld devices and the increase of media streaming over wireless networks, the study could be performed on media streaming.

- The IP protocol used in the prototype wireless network is called IPv4. A newer version, known as IPv6, is available and should be used in future studies to determine its possible influence on QoS factors.

- In this study, the 802.11n protocol was used. There is a later variant called 802.11e that can be used to determine if this protocol would influence the QoS factors differently.

6.5 Chapter Summary

Chapter 6 is the final chapter of this study. The chapter presented a summary of the initial goals and of how the main and secondary goals were achieved. Finally, the problems experienced in the study and possible future research opportunities were outlined.

References:

Agharebparast, F. and Leung, V.C.M. 2005. Modelling wireless link layer by network calculus for efficient evaluations of multimedia QoS*. (In* Proc. of IEEE International Conference on Communications May 2005, Hong Kong, China:1256–1260*).*

Albrecht, J.R. 2007. Distributed Application management. San Diego: University of California. (Thesis – PhD).

Aldosari, B. 2012. User acceptance of a picture archiving and communication system (PACS) in a Saudi Arabian hospital radiology department. http://www.biomedcentral.com/1472-6947/12/44 Date of Access 9 Sep. 2012.

Balchunas, A. 2012. OSI Reference Model. http://www.routeralley.com/ra/guides.html. Date of Access: 17 October 2012.

Banks, J. 1999. Introduction to simulation. (In the proc. of the 31st conference on Winter Simulation, New York:USA).

Bazaraa, M.S., Jarvis, J.J. and Sherali, H.D. 2005. Linear programming and network flows. 3rd ed. Hoboken, NJ: Wiley-Interscience.

Belzarena, P. and Aspirot, L. 2010. End-to-end quality of service seen by applications: A statistical learning approach. *Computer Networks,* 54(2010): 3123-3143.

Black, S. 1992. An overview of standards work for radio LANs*.Colloquium Digest- IEEE,* 104:1-4.

Bocij, P., Greasley, A. and Hickie, S. 2008. Business information systems: Technology, development and management. 4th Edition. Harlow, England: Prentice Hall.

Bowerman, B.L., O'Connell, R.T. and Koehler, A.B. 2005. Forecasting, time series, and regression: an applied approach. 4th ed. Belmont, CA: Thomson Brooks/Cole.

Brightman, H.J. 1999. Data analysis in plain English with Microsoft Excel. Pacific Grove, CA: Duxbury Press.

Bruwer, P.J.S. and Hattingh, J.M. 1985. Constrained regression models for optimisation and forecasting. *Orion*, 1(1):2-15.

Chandure, O.V. and Gaikwad, V.T. 2012. Detection & Prevention of Gray Hole Attack in Mobile Ad-Hoc Network using AODV Routing Protocol. *International Journal of Computer Applications*, 41(5):27-32.

Crow, B.P., Widjaja, I., Kim, J.G. and Sakai, P.T. 1997. IEEE 802.11 Wireless Local Area Networks. *IEEE Communications Magazine*, 35*(*9):116-126*.*

Colasoft. http://www.colasoft.com/capsa. Date of Access: 25 Jul 2012.

Cisco. 2012. Cisco IOS IP Application Services Command Reference http://www.cisco.com/en/US/docs/ios-xml/ios/ipapp/command/iap-i2.html. Date of Access: 16 October 2012.

Evans, J.R. 2010. Statistics Data Analysis and Decision Modelling, 4th Edition. Upper Saddle River, NJ: Pearson.

Ferreira, M. and Helberg, A.S.J. 2009. Testbed validation for the evaluation of a delay aware routing metric for ad hoc networks (In Proc. SATNAC Aug 2009, Ezulwini, Swaziland).

Ferreira, M. 2009. Testbed validation for the evaluation of a delay aware routing metric for ad hoc networks. Potchefstrtoom: NWU. (Dissertation – MIng).

Futernik, A., Haimovich, A.M. and Papavassiliou, S. 2003. An analytical model for measuring QoS in ad hoc wireless networks. (In GLOBECOM December 2003, San Francisco, California: 216-220).

Garnal, A. E., Mammen, J., Prabhakar, B. and Shah, D. 2004. Throughput-Delay Trade-off in Wireless Networks (In Proc. IEEE INFOCOM, vol. 1, Mar. 2004, HongKong, China).

Hamidian, A. and Körner, U. 2006. An enhancement to the IEEE 802.11e EDCA providing QoS guarantees. *Telecommunication Systems*, 31 (2-3):195-212.

Hashemi, S.A. 2011. Quality creation in educational systems based on the information and communication technology. (In Proc. International Conference Management, Jun. 2011, Penang, Malaysia).

Hoeting, J., Raftery, A.E. and Madigan, D. 1996. A method for simultaneous variable selection and outlier identification in linear regression. *Computational Statistics & Data Analysis*, 22(3):251-270.

Howard, P.N. 2010. The Digital Origins of Dictatorship and Democracy: Information Technology and Political Islam: Information Technology and Political Islam. Oxford University Press, USA.

IEEE (Institute of Electrical and Electronics Engineers). 2007. IEEE standard for information technology-telecommunications and information exchange between systems-local and metropolitan area networks-specific requirements: Part 11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications: Amendment 8. New York: Institute of Electrical and Electronics Engineers, (IEEE 802.11).

Ivanovich, I., Fitzpatrick, P., Beresford, J.L.M. and Saliba, A. 2003. Measuring quality of service in an experimental wireless data network. (In Proc. Australian Telecommunications Networks and Applications Conference, December 2003, Melbourne, Australia).

Kushwaha, G.S. 2011. Competitive advantage through information and communication technology (ICT) enabled supply chain management practices*. International Journal of Enterprise Computing and Business Systems*, 1 (2).

Kutner, M.H., Nachtsheim, C.J., Neter, J. and Li, W. 2005. Applied linear statistical models. 5th ed. Boston, MA: McGraw-Hill Irwin.

Li, J. 2000. Measurement and in-service monitoring for QoS violations and spare capacity estimations in ATM network. *Computer Communications*, 23(2000): 162-170.

Moore, J.H. and Weatherford, L.R. 2001. Decision modeling with Microsoft Excel. 6th ed. Upper Saddle River, NJ: Prentice-Hall.

National Institute of Standards and Technology (U.S.). 2001. NIST special publication (960-961). The Institute.

Ni, Q., Romdhani, L. and Turletti, T. 2004. A Survey of QoS Enhancements for IEEE 802.11 Wireless LAN. *Journal of Wireless Communications and Mobile Computing*, 4(5):547-566.

Nirsoft. http://www.nirsoft.net/utils/wireless_network_view.html Date of Access: 25 Jul 2012.

Olifer, N. and Olifer, V. 2005. Excerpts from Computer Networks: Principles, Technologies and Protocols for Network Design. Wiley & Sons, Great Brittain.

Peha, J.M. 2009. Sharing Spectrum Through Spectrum Policy Reform and Cognitive Radio. Proceedings of the IEEE, 97(4):708-719.

Render, B., Stair, R.M. and Hanna, M.E. 2008. Quantitative analysis for management. 10th ed. Upper Saddle River, NJ: Pearson Prentice-Hall.

Render, B., Stair, R.M. and Hanna, M.E. 2009. Quantitative analysis for management. 11th ed. Upper Saddle River, NJ: Pearson Prentice-Hall.

Roberts, R.M. 2010. Networking Fundamentals. 2nd Edition. Tinley Park:Goodheart-Willcox.

Salvador, P., Nogueira, A. and Valadas, R. 2007. Predicting QoS characteristics on wireless networks. (In Proc Third International Conference on Networking and Services, 2007).

SAS. 2012. SAS/OR® PROC OPTMODEL www.sas.com. 30 June 2012.

Schiller, H. J. 2000. Mobile Comunications. 1st Edition. Boston: Addison –Wesley.

Schiller, H. J. 2003. Mobile Comunications. 2nd Edition. Boston: Addison –Wesley.

Seo, S. 2006. A review and comparison of methods for detecting outlier in univariate data sets. Pittsburgh: University of Pittsburgh. (Thesis – PhD).

Sharma D. and Singh R.K. 2011. QoS & QoE management in wireless communication system. *International Journal of Engineering Science and Technology* 3(3):2385-2391.

Shrivastava, V., Rayanchu, S., Yoon, J. and Banerjee, S. 2008. 802.11n Under the Microscope. (In Proc. Internet Measurement Conference October 2008, Vouliagmeni, Greece: 20 - 22).

Siler, M. and Walrand, J. 1998. Monitoring quality of service: Measurement and estimation. (In Proc. of the 37th IEEE Conference on Decision and Control, vol. 1, December 1998, Tampa Bay, Florida).

Swanepoel, J.W.H., Swanepoel, C.J., van Graan, F.C., Allison, J.S., Weideman, H.M and Santana, L. 2008. Elementere Statistiese Metodes. 2nd Edtion. Potchefstroom: Platinum Press.

Tanenbaum, A.S. 2003. Computer Networks. 4th Edition. New Jersey: Prentice Hall.

Taylor, B.N. and Kuyatt, C.E. 1994. Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, NIST Technical Note 1297, Sep. 1994.

Terblanche, S.E. 2001. Linear response surface analysis as a technique for visualizing linear models and data. Potchefstrtoom: NWU. (Dissertation – MSc.).

Vassis, D., Kormentzas, G., Rouskas, A., and Maglogiannis, I. 2005. The IEEE 802.11g standard for high data rate WLANs. *IEEE Network*, 21-26.

Vidua, K. and Uthariaraj, V. R. 2011. Throughput optimisation of inter- and intra-domain autonomous systems traffic engineering*. International Journal of Communication Networks and Distributed Systems*, 6(1):45-58.

Wonnacott, T.H. and Wonnacott, R.J. 1972. Introductory Statistics. New York, NY: Wiley.
Weiss, D.M.1998. Community, democracy, and the metaphors of cyberspace. http://faculty.ycp.edu/~dweiss/research/Community,%20Democracy,%20and%20Metaphors%20for%20Cyberspace.pdf. Date of access: 9 Sep. 2012.

Whitman, E.M. and Mattord, H. J. 2012. Principles of Information Security. 4th Int. Edition. China Printing and Translation Services Limited: China.

Wilson, J.H. and Keating, B. 2007. Business Forecasting, 5th ed. Boston, MA: McGraw-Hill.

Wireshark. http://www.wireshark.org/about.html Date of Access: 25 Jul 2012.

Van der Westhuizen, M. 2011. Robust techniques for regression models with minimal assumptions. Potchefstrtoom: NWU. (Dissertation – MSc).

Zhuo, X., Wellman, B., and Yu, J. (2011). Egypt: The First Internet Revolt? *Peace magazine* 27(3), 6-10.