Improving Inter-service Bandwidth Fairness in Wireless Mesh Networks

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As the candidate's supervisors, we have approved this dissertation for submission.

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Declaration

I declare that this dissertation is my own work. Where collaboration with other people has taken place, or material generated by other researchers is included, the parties and/or materials are indicated in the acknowledgements or are explicitly stated with references as appropriate.

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This work is being submitted for the Master of Science in Electrical Engineering at the University of Cape Town. It has not been submitted to any other university for any other degree or examination.

Vusumuzi Moyo

Date

Dedication

To God, for His unending Love and Grace though which we are comforted

I also dedicate this work to my beautiful wife, children and family.

Abstract

We are currently experiencing many technological advances and as a result, a lot of applications and services are developed for use in homes, offices and out in the field. In order to attract users and customers, most applications and / or services are loaded with graphics, pictures and movie clips. This unfortunately means most of these next generation services put a lot of strain on networking resources, namely bandwidth. Efficient management of bandwidth in next generation wireless network is therefore important for ensuring fairness in bandwidth allocation amongst multiple services with diverse quality of service needs.

A number of algorithms have been proposed for fairness in bandwidth allocation in wireless networks, and some researchers have used game theory to model the different aspects of fairness. However, most of the existing algorithms only ensure fairness for individual requests and disregard fairness among the classes of services while some other algorithms ensure fairness for the classes of services and disregard fairness among individual requests.

To achieve ubiquitous connectivity, the Wireless Mesh Network is one of the technologies ideal for customers to access the growing array of services in the last kilometre where wired networks are prohibitively expensive to set up or simply inappropriate. Thus, this work focuses on improving bandwidth fairness where a number of different services are competing in the access link of the wireless mesh networks. Game theory has been used to model the game arguments where the services are agents / players strategising to get optimum payoffs in order to achieve fairness.

In wireless networks, it is important to ensure fairness among individual requests as well as fairness among the classes of services. Therefore, this dissertation introduces an algorithm that enhances the fairness of bandwidth allocation at the access link of the wireless mesh networks. The proposed algorithm ensures fairness for service classes as well as for the requests, as opposed to existing algorithms that only ensure fairness for individual requests while disregarding the classes of services or some other algorithms that ensure fairness for classes of services while disregarding fairness for individual requests. The proposed algorithm thus ensures equitable resource allocation amongst different service classes with respect to the number of requests in each class of service.

The performance of the algorithm is evaluated using java multithreading where the request of a player gets a thread and hence resources for processing the request. Once the processing of the request is complete, the resources are returned to the thread pool to be used by other requests.

Simulations results show that the algorithm improves the fairness of different service types when compared with other schemes in the research community. Furthermore, the results show than with more services considered, the allocation of resources amongst all the services considered is comparable, with no skewing of channel capacities.

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Finally, all the praise, honour and glory to the Almighty God for all that I have achieved.

Table of Contents

List of Figures

List of Tables

Glossary

8ta: 8ta is the mobile telephone branch of Telkom.

Bandwidth: The amount of data that can be transmitted from one point to another in a given amount of time, usually seconds.

Channel: It is a physical or a logical communication path, used as a medium to transport information from the sender to the receiver.

Duopoly: A duopoly is a special type of oligopoly in which two players instead of a few players dominate the market.

Fairness: Fairness is the absence of bias or a condition of being fair. Depending upon the context, fairness may have different connotations.

FTTx: These are various fibre distribution infrastructures that include Fibre To The Office (FTTO), Fibre To The Home (FTTH), Fibre To The Building (FTTB), Fibre To The Curb (FTTC) and Fibre To The Node (FTTN), all of which are wired high bandwidth technologies.

Game Theory: It is the study of mathematical models that can be used for strategic decision making where conflicts and co operations between decision makers are analysed.

IANA: Internet Assigned Numbers Authority controls the assignment of IP addresses and other IP resources globally.

ICASA: Independent Communications Authority of South Africa is an authority that issues and regulates spectrum licenses in South Africa, as from 2000.

IEEE: The Institute of Electrical and Electronic Engineers is the world's largest professional association for the advancement of technological innovation and excellence, as well as being a major publisher of scientific journals and organiser of conferences, workshops and symposia.

IP: Internet Protocol is the main communications protocol that is used by internet hosts. The main standards are the 32 bit IPv4, which should become a legacy standard soon and the 128 bit IPv6, which forms the heart of the next generation network connectivity.

ISDN: Integrated Services Digital Networks is a technology that makes use of digital transmission for any two combination of voice, fax and data signal over twisted pair copper cable.

ISO: International Organization for Standardization is a standard setting body composed of representatives from country standards organizations with a mandate of setting international standards to ensure products and services are of high quality, safety and reliability.

ISP: Internet Service Provider is a company that provides internet access. There could be up to three tiers of internet service providers, where the top tier is defined as the ISP who does not pay anyone to access the internet. Tier 2 ISPs pay tier 1 ISPs and tier 3 ISPs pay tier 2 ISPs. Ordinary customers can be connected to tier 2 or tier 3 ISPs and in some cases even tier 4 ISPs, who form part of the last kilometre of the telecommunications network.

Jain's fairness index: Jain's fairness index rates the fairness of a set of values. The index ranges from $\frac{1}{n}$ (the least fair index) to 1 (the fairest index) where there are n users.

Last kilometre: This is the final connection from a telecommunications service provider to the customer. The physical distance of last kilometre varies with the technology used as well as the geographic location of the service. The last kilometre can range from a few meters in densely populated urban areas to a few kilometres in rural areas and sparsely populated communities. Wired and wireless technologies can be employed in the last kilometre.

MIMO: Multiple Inputs Multiple Outputs is a technology that makes use of multiple antennas at both the receiver ad transmitter in order to improve communication performance.

OSI: Open Systems Interconnection is a standard for communications systems that is divided into seven logical layers that provide abstraction and encapsulation.

Pareto Optimality: This is an economic concept originally in economics but applicable in many disciplines, including engineering, where in allocating resources, the allocating algorithm is said to be Pareto optimal or Pareto efficient if and only if there is no individual that is made better off without making at least one individual worse off.

PSTN: Public Switched Telephone Network is the international collection of interconnected voice based public telephone networks, which is sometimes referred to as the plain old telephone service (POTS).

QoS: The Quality of Service is a metric that measures the ability of a network to deliver predictable results that are of high quality and reliability.

RIR: A Regional Internet Registry is an organization that manages the allocation of internet number resources within a particular region. There are five RIRs, broadly for Africa, North America, South America, Europe and Asia.

TCP: Transmission Control Protocol.

Throughput: It is the average rate of successful delivery of packets through a communication node.

VOIP: Voice Over Internet Protocol refers to the communication protocols and technologies used in the delivery of voice communications using the internet.

WiMax: The Worldwide Interoperability for Microwave Access is part of 4G wireless technology that can be used in the last kilometre for communication.

WMN:Wireless Mesh Network is a communications network made up of mobile and stationary nodes that are set up in a mesh physical topology.

xDSL: These are the various technologies of the Digital Subscriber Lines, with the X standing for any of the categories in question. The most common one is the Asynchronous Digital Subscriber Line (ADSL), which is the most commonly used copper broadband access technology. The other types include the Synchronous Digital Subscriber Line (SDSL), High Data Rate digital Subscriber Line (HDSL) and the Very High Data Rate Digital Subscriber Line (VDSL).

1 Introduction

Wireless mesh networks (WMN) have emerged as one of the most promising and practical technology for the next generation wireless networks as it realizes the vision of ubiquitous Internet access with a large coverage and comparably low deployment cost (Akyildiz, Wang, & Wang, 2005), (Jae-Yong & Won, 2008), (Vasilakis, Perantinos, Askoxylakis, Mechin, Spitadakis, & Traganitis, 2009), (Ahmed, Mohamed, Fouly, & Hu, 2011). WMN are more ideal where wired networks are prohibitively expensive to setup or simply inappropriate. Over the years, WMN has become more desirable owing to some of the properties inherited from ad hoc networks such as self-organizing, self-configuring, easy maintenance and broadband access (Sichitiu, 2006), (Kumar & Hegde, 2009), (Olwal T. O., Wyk, Ntlatlapa, Djounai, Siarry, & Hamam, 2009), (Hoblos, 2011). However, the mesh routers still face bandwidth limitations as all other switching and routing devices in the network (Yong, Na, Mugen, & Wenbo, 2010), (Verlini, 2012), (Hou, Lui, Baker, & Li, 2012). The limitation of bandwidth can cause the services to share it unfairly; hence, it is important to develop a scheme that would enhance the fairness of bandwidth sharing at the access router of the WMN (Moyo, Falowo, & Dlodlo, 2012).

Although an essential resource in telecommunications networks, bandwidth is also often a source of bottlenecks in wireless information highways (Isogai, Funabiki, Isshiki, & Nakanishi, 2008), (Yin, Zhang, Zhou, & Wu, 2009). More so, with the proliferation of various services (loaded with graphics and videos) in the next generation of wireless networks that needs to share this limited resource. To achieve ubiquitous connectivity, the WMN is ideal for customers to access the growing array of services in the last kilometre[1] even where wired networks like Fibre To The Home (FTTH) are connected. Figure 1.1 illustrates the last kilometre in telecommunications. Wireless technologies generally do not need a large initial capital outlay and are thus desirable; also, they introduce mobility that the modern user assumes and craves for (Boukerche, Zhang, & Samarah, 2009).

[1] The last kilometre is the access link / distribution portion of the telecommunications network. (Levin, 2011)

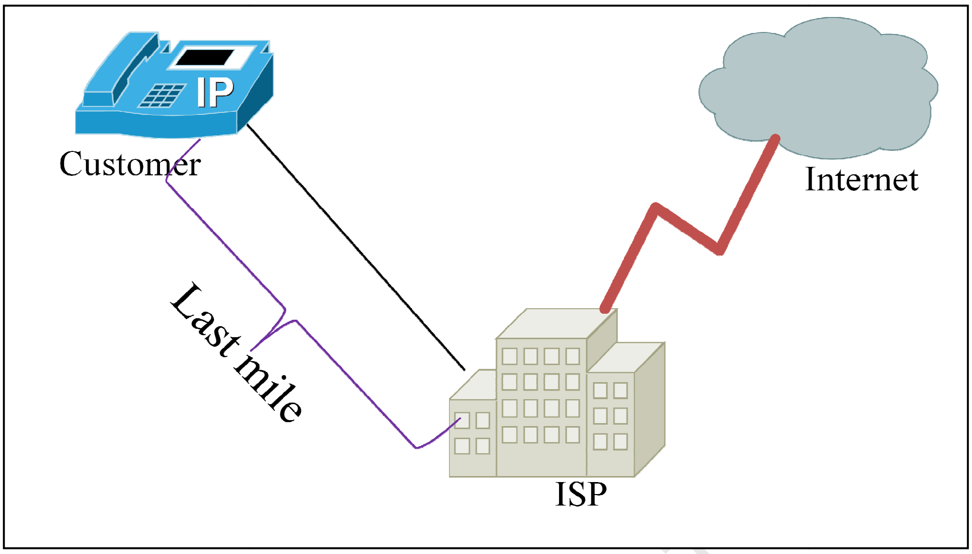

Figure 1: Last kilometre illustration.

Some of the last kilometre services include Portable / Mobile Premium Service, Best-Effort Low-Delay Service, Portable / Mobile Olympic Service, Best Effort Service (BE) and Background applications (Diederich, Doll, & Zitterbart, 2003). While WMN have become ideal for the last kilometre as they incorporate WiFi, WiMax, sensor and ad hoc networks, they still lack scalability, and the absence of centralized control still poses unfairness for the services at the access network (Hoblos, 2011).

Some of the main fairness criteria with respect to WMN have been identified as semi hard fairness that makes use of round robin resource allocation schemes, max-min fairness, proportional fairness and mixed bias (Li W. , Cui, Cheng, Al-Rodhaan, & Al-Dhelaan, 2011). This work focuses on improving bandwidth fairness where a number of different services are competing in the access link of the wireless mesh networks, which is a form of proportional fairness. Game theory is used to model arguments where the services are agents / players that reach equilibrium to achieve fairness. An algorithm is developed, the resulting logic implemented, and seen to offer an improvement by achieving a minimal rejection percentage, assuming the minimum quality of service (QoS) requirements are met for all accepted requests.

Section 2.2 outlines the overview of game theory and Section 2.3 further discusses definitions of the various types of fairness.

A number of authors have researched on ways of managing bandwidth in WMNs (Wang, Cui, Xu, Huang, & Liu, 2009), (Zhu Y. , Liu, Guo, & Zeng, 2009), (Visoottiviseth, Trunganont, & Siwamogsatham, 2010), (Ziermann, Muhleis, Wildermann, & Teich, 2010). In Chapter 4, a theoretical framework is proposed for improving the bandwidth fairness of different services at the access node of WMN. The framework incorporates the number of requests in a service and the various services. This is the main proposition of this research, which is different from the traditional approaches that look at fairness of requests, regardless of the services that those requests come from. As the requests arrive, (assumed to follow a Poisson distribution) they dynamically determine the sizes of virtual channels for the respective classes of service and thereby ensuring that the channels share bandwidth equitably. The various classes of services thus share the bandwidth fairly.

1.1 Background of study

FTTH is an excellent way of delivering broadband internet to fixed and wired clients as optic fibre can carry theoretically huge bandwidths that are not comparable to any other cable based data transmission media (Seibert, 2009), (Jun, 2010), (Elahmadi, Srinath, Rajan, & Haberman, 2012). However, to achieve true ubiquitous networks, there is need to include the mobile wireless networks, and these wireless networks bring with them bandwidth limitations. Amongst the current technologies, WMN have emerged as one of the best last kilometre solution to extend broadband internet (Ahmed, Mohamed, Fouly, & Hu, 2011), (Hoblos, 2011). At the time of writing, Kenya is the only African country to have FTTH (Editor, 2011), although other countries have plans to implement it. True broadband ubiquity still needs a last kilometre wireless access, as even in Kenya, only the affluent suburbs have FTTH connectivity, with the rest of the capital city still on xDSL, not to mention rural areas were most of the population lives in sparse communities with little to no access to reliable means of telecommunication. This is typical of most developing countries as indicated by the case of Malaysia (Omar, Hassan, & Shabli, 2010), where the prohibitive expense of a wired network installation and maintenance in rural areas make the wireless alternative more appealing for the communities. This research will thus be useful in the foreseeable future, as implementing WMN is comparatively cheaper compared to the wired alternatives of FTTH and xDSL, especially in rural areas with sparse populations (Panigrahi, Duttat, Jaiswal, Naidu, & Rastogi, 2008), since wireless technologies do not have the expense of cables and the associated civil works that wired networks require.

1.2 Definition of Fairness

Fairness is a symbiotic relationship for the mutual benefit of all in a setup. The best examples are exhibited by the animal kingdom, for example the bumblebees and the flowers, who need each other for their survival. If various services at the access link of the WMN can forge such a relationship in sharing resources, then such a scheme would be the most ideal as all the users of the respective services would have a fair distribution of resources at all times. If equally shared, unless an uneven allocation is to the advantage of the least favoured at all times, then all those sharing the resources would be treated fairly (Rawls, 2001). Chapter 2 explores the various types of fairness with respect to wireless networks.

1.3 Statement of the problem and motivation for the research

In past years (2001 - 2011), the size of average global broadband telecommunications networks has grown more than five times over (500 000 to 2 500 000 subscriptions), and continues to increase (ITU, 2012). This is because of a very high rate of change of technology as shown by Figure 2, where broadband subscription and internet users show an upward trend. With WMN poised to be one of the de facto last kilometre access technology in the next generation networks (Vasilakis, Perantinos, Askoxylakis, Mechin, Spitadakis, & Traganitis, 2009), (Ahmed, Mohamed, Fouly, & Hu, 2011), further research on bandwidth allocation needs to be done in order to accommodate all the upcoming different services that customers would want to enjoy. This is because while optic fibre may have a large bandwidth, at most of the wireless networking elements, bandwidth can be a finite resource because of limited spectrum (Verlini, 2012) and if not managed properly may limit or degrade the network connectivity. The USA Federal

Communications Commission has projected that spectrum will run out in America by 2013 (Pretz, 2012).

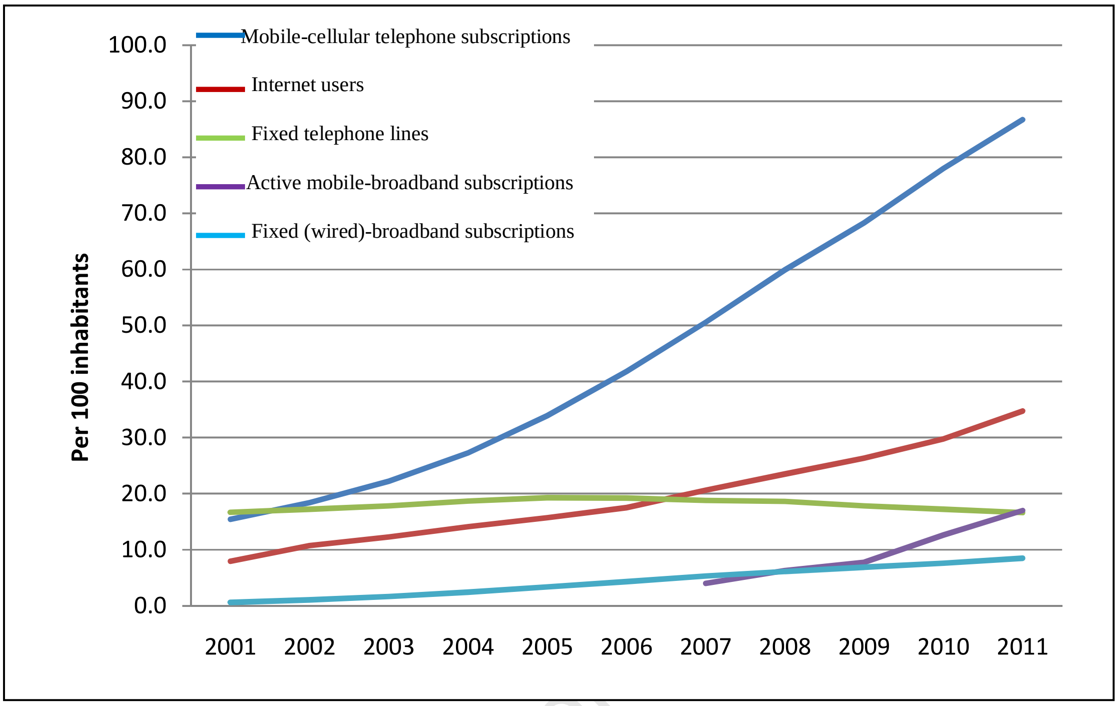

Figure 2: Global ICT developments, 2000 – 2011 (ITU, 2012)

Figure 3 shows the anticipated demand of telecommunications services versus capacity, where the projections clearly show a deficit on available capacity with respect to demand. It is for this reason that there is a need to ensure fair sharing of the capacity as the projected demand surpasses the projected capacity. Peer to peer sharing and download managers are on the increase and these further deplete the already limited wireless bandwidth (Visoottiviseth, Trunganont, & Siwamogsatham, 2010), (Sharma, Kumar, & Thakur, 2011).

This dissertation addresses the problem of how to allocate limited bandwidth among different classes of service in a fair manner, in wireless mesh network.

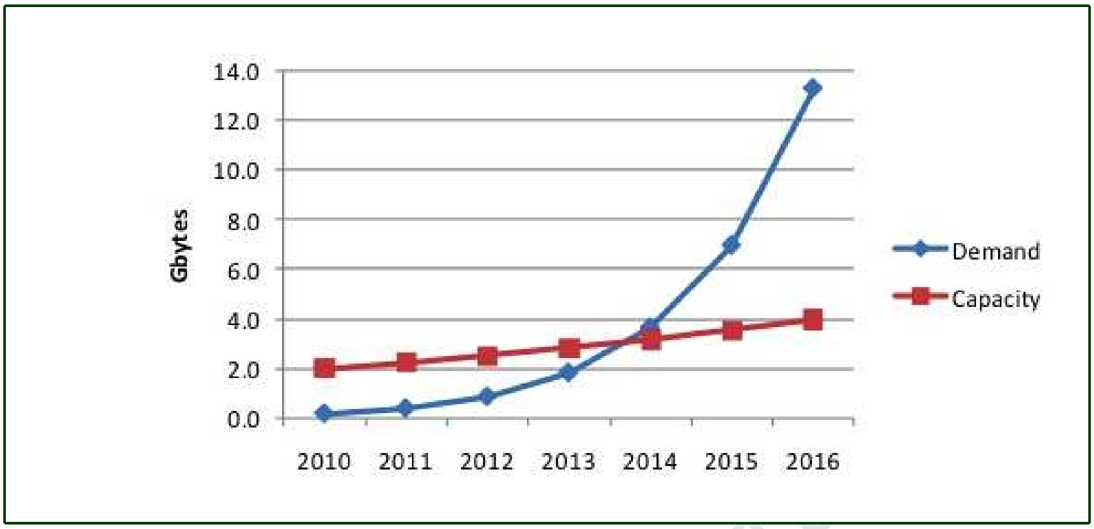

Figure 3: Demand versus Capacity projections (Higginbotham, 2010)

A simple search on Google would reveal that recent media content has a lot of graphics, video and audio in order to attract users and clients. This unfortunately translates to a lot of bandwidth use when exchanging this kind of information over networks, and hence the need for research to improve on bandwidth sharing amongst many diverse services in the network. Wireless Local Area Network (WLAN) has a limited bandwidth compared to its wired LAN counterpart, thus it is imperative that bandwidth should be shared fairly among the wireless clients, and hence the continued research on bandwidth management in wireless networks (Alejos, Sanchez, & Cuiñas, 2012), (Plummer, Taghizadeh, & Biswas, 2012).

1.4 Research Questions

Some of the leading questions that will shape this research are:

- What are the limitations of the existing bandwidth allocation schemes?
- Is a new technique or approach required, or we need to improve upon the current schemes?
- On existing bandwidth allocation schemes, can we make any fairness improvements?

The issues raised in these research questions are investigated and the results of these investigations are collated into a conference paper, which is tested via the research community for the results' validity in order to answer the statement of the problem as well as prove or disprove the hypothesis.

1.5 Hypothesis

During the 1940s, Arthur Fremont Rider calculated that library space would need to double every 16 years to accommodate the increasing number of books (Steele, 2005), but now we can house large volumes of books, journals and other reference resources in electronic form in hard drives which do not need as much space when compared with book shelves. In addition, there are other forms of electronic media like music, radio, television, movies, voice, video and data that need to be stored and shared through the converged internet. More information is added onto the networks everyday and with the advent of the Internet Protocol version 6, where there are an abundance of IP addresses, more terminal and intermediate equipment can be added onto the internet. This continued addition of services, nodes and information into the internet needs to be met with equally adaptive and improved ways of dealing with the distribution of resources. The capacity and hence the bandwidth on which to traffic all the media content does not increase linearly as the demand as shown in Figure 3. This notion results in the first hypothesis, which is:

"It is possible for a number of services to have an equilibrium bandwidth based on the number of requests in each service that will be such that each of the services has an optimum bandwidth. The strategy that gives these bandwidths would be the most fair for services sharing the bandwidth resource. “

Most applications are going wireless, as indicated in the research that shows a 133% global mobile data traffic growth for the year 2010 to 2011 (CISCO, 2012), done by the world’s leading internetworking equipment provider, CISCO. AT&T, America’s second largest wireless carrier has seen a 20000% wireless data growth since 2007 (Velazco, 2012). All these increases in data growth point to a need to manage the network resources properly in terms of infrastructure and the network intelligence. This leads to the second hypothesis, which is:

“It is possible to improve the fairness of bandwidth allocation for different services that compete for resources in the access link of WMN by having virtual channels for each service. The virtual channels will be in such a way that the services can make use of free space in each other’s virtual channels and avoid skewing of bandwidth use, which is a source of unfairness and bandwidth waste.”

1.6 Objectives of study

The main objectives of this research are:

- To establish a mathematical model using game theory principles to demonstrate that it is possible to improve bandwidth fairness in the last kilometre access link of WMN.
- To develop an algorithm that will efficiently allocate bandwidth among various classes of service in WMNs.
- Compare the fairness of the developed algorithm with that of other schemes in the research community.

1.7 Justification of the study

Last kilometre internet access is an integral part of achieving universal connectivity. In an ideal situation, we would have FTTH for all fixed customers. However, with the expense of connecting optic fibre to every home especially in developing countries, this is still a pipe dream (Omar, Hassan, & Shabli, 2010). A more realistic approach would be to make use of wireless connectivity, WMN in this case.

Bandwidth is one of the bottlenecks that can hinder many customers that are connected wirelessly from enjoying the various network services (Huang & Li, 2010). If bandwidth sharing is improved for wireless nodes, all without favour can enjoy services. It is based on this background that an attempt at improving bandwidth sharing is undertaken in this research. If all clients that access a limited resource are treated fairly, then possibly there would be no complaints and the sharing clients can co-exist without any major problems.

According to Moore's law, data density doubles every 2 years (MacVittie, 2007), and as a result, applications that end users require keep on increasing in detail since more information can possibly be added into fixed and mobile equipment. This translates to more bandwidth required for transmission. With the high rate of change of technology, we need an equally adaptive network to meet the ever-increasing demand for bandwidth. It is therefore imperative that all services in the network share this finite resource fairly and efficiently. There is therefore an ongoing need to refine the bandwidth sharing capability at all levels of the network. Bandwidth allocation schemes therefore have a wide application within the entire network, from the sender of information to the receiver of information and through all the communication nodes in between.

1.8 Application of the research

Some of the last kilometre access points that need enhancing the fairness of bandwidth management are where the WMN access router is serving:

- Law enforcement
- Cities and municipalities
- Intelligent transportation systems
- Military usage
- Emergency response
- Households (multimedia home networking)
- Internet cafes
- Isolated locations and rugged terrains
- Colleges and universities
- Temporary venues
- Gas stations
- Warehouses

(Olwal T. O., Wyk, Ntlatlapa, Djounai, Siarry, & Hamam, 2010), (Kum, Park, Cho, Cheon, & Cho, 2010), (Roos, 2011)

1.9 Peer reviewed Publications

1. **Vusumuzi Moyo**, Olabisi Falowo and Mqhele Dlodlo. "Improving Inter service Bandwidth Fairness in Wireless Mesh Networks". The 16th IEEE Mediterranean Electro technical Conference MELECON 2012. 25 – 28 March, 2012. Medina Yasmine Hammame, Tunisia. Page(s): 1013 - 1016
   This publication focused on improving bandwidth fairness where a number of different services compete in the access link of the wireless mesh networks. Game theory was used to model the arguments where the services were agents / players that reach equilibrium to achieve fairness. The weighted request dominance

algorithm was found to improve the fairness of resource allocation. Chapter 4 and Chapter 5 detail most of the work.

2. Mthulisi Velempini, **Vusumuzi Moyo** and Mqhele Dlodlo. "Improving local and collaborative spectrum sensing in cognitive networks through the implementation of cognitive collaborators" The 16th IEEE Mediterranean Electro technical Conference MELECON 2012. 25 – 28 March, 2012. Medina Yasmine Hammame, Tunisia. Page(s): 1045 – 1048
The paper shows that cognitive collaborators can improve spectrum sensing, thus allowing more capacity to be available for services to share in wireless mesh networks.

1.10 Dissertation outline

The dissertation is outlined follows:

Chapter 1 gives an introduction and background insights to this research work. The statement of the problem and motivation for the research are given. Some leading and guiding questions that set the tone and basis for the research are established and the hypothesis is put forward. Key objectives for the research are set forward and the justification for the whole research is given. Finally, some of the applications where the results of the research can be used are identified.

Chapter 2 outlines the research methodology, where some game theory models and basics are detailed. The principles of fairness are overviewed as well as bandwidth fairness metrics that researchers use. WMNs, the next generation of networks as well as converged networks and their contribution and relation to this research are also overviewed. OSI and TCP/IP basic descriptions wind up the chapter where the perspective of the layered models with regards to this research is outlined.

Chapter 3 reviews some of the relevant theory, where work done by other researchers concerning fairness in wireless networks is looked at. The research questions from Chapter 1 are used as guidelines, from where the limitations to existing work are identified, which then lead to the introduction of this research's contributions.

Chapter 4 looks at the operational overview of the proposed scheme. Game theory equations and the algorithm to be used are established, from which the results that lead to publications are analysed in Chapter 5.

In Chapter 5, a look at the simulations and evaluation of results is made. The results were compared and tested with related work via the MELECON 2012 conference proceedings.

Chapter 6 concludes the work, where a revisit to the leading research questions from Chapter 1 is made, in order to ascertain the justification of the research effort. A synopsis for future work in relation to the researcher's research area in general is also made.

2 Background and Literature Review

2.1 Foreword

This chapter gives the underlying methodology on which this research is based, as well as outlines the background to the research.

There is a steady trend in the next generation wireless networks to move from the traditional centrally controlled architectures towards distributed control architectures (Attar, Debbah, Poor, & Zha, 2012). Game theory gives insights into network nodes that are able to make their decisions based on the information at hand without communication from the central control, making game theory modelling ideal for distributed control analysis.

2.2 Game Theory Background

In this research, game theory is used to model the allocation of resources, where the different classes are cooperative players (Fudenberg & Tirole, 1991). Game theory players are assumed to be rational, and this assumption holds well for network elements, whose rationality is brought about by the logic that is implemented in the network elements by designers (Fallah, 2010). A comprehensive overview of game theory and its usage in wireless communication networks is provided in (Saad, Han, Debbah, Hjørungnes, & Başar, 2009). Saad *et al* introduce a novel classification of coalitional games by grouping the various games that players can engage into three distinct classes. This research leans more on one of the classes, the coalition formation games, in that the call requests investigated in this research are grouped into distinct services. Game theory principles can be used to model and study network formation; network stability and network fairness of a diversity of wireless network problems. The use of game theory as a modelling tool is increasing in wireless telecommunications (Canzian, Badia, & Zorzi, 2011), where networking nodes can form coalitions to take advantages of rationalisability. Rational nodes work together for the general good of the entire network.

2.2.1 Overview of Game Theory

The use of Game Theory concepts started in the early 20th century and authors such as von Neumann and Morgenstern later made Game Theory very famous. The most celebrated work on game theory is by Nash in what become popularly known as the Nash equilibrium (Vasilakos, Kannan, Hossain, & Kintis, 2010). Game theory has led to amazing changes mainly in Economics, and has also found very important applications in Engineering as well, where the theoretic models help us to understand and predict the performance of complex systems that would have been otherwise difficult to model using the traditional optimisation tools (DaSilva, Bogucka, & MacKenzie, 2011).

There are four basic common elements in all games (Zhang, Sue, Peng, & Yao, 2010), (Caelen & Xuereb, 2011).

- **Players**: These are the participating entities in any game, and each player will have at least one or more strategies that they can play. Players are assumed to be rational, which means a player will choose a strategy that any other player would have chosen given similar circumstances.
- **Strategy set**: These are all the options available from which each player can select. Depending upon which strategy a player will have selected, the player will receive various payoffs. A player's number of strategies can be infinite or they can be finite, hence we have finite games and infinite games respectively.
- **Payoff functions**: This is the main motivation for playing a game by each player. The payoff is what a player gets after they have chosen a particular strategy. The whole idea behind playing a game is to maximize a player's payoff. Players try to select a strategy that will give them the maximum possible payoff.
- **Orders**: In some games players choose their strategies at the same time, in some games players choose strategies one after the other and in some games players choose strategies a number of times before a consensus is reached. The order in

which players choose their strategies is important, as it defines the type of game played and hence set the parameters of the type of game.

There are various types of games that payers can mix and play (Fudenberg & Tirole, 1991):

- **Cooperative / non-cooperative game**: In cooperative games, groups of players can form coalitions so that coalitions then compete in lieu of the individual players. Players in non-cooperative games form independent decisions regarding their strategies.
- **Repeated games**: In repeated games, players can engage with each other a number of times before a consensus is made. A player may select a strategy that may not seem favourable at the time, but in future, the player can get a great payoff because of an earlier investment.
- **Complete information / incomplete information**: For a game to be in complete information all players have to know the strategies and payoffs of all other players in the game, otherwise the game is considered an incomplete information game. The prisoner's dilemma in Section 2.2.2 is an example of a complete information game as each player knows the strategies and payoff of the other player.
- **Perfect information / imperfect information**: Information can be critical in repeated games. In perfect information, players know all the moves previously made by other players, for example in playing chase. How other players have moved or their utilities are hidden in imperfect information games, even though that information is known.
- **Zero sum game / non-zero sum game**: In zero sum games, what one player loses the other gains in equal magnitude. Such games are strictly competitive, where one player competes against the other like in a cup final soccer match[2]. In non-

[2] In a cup final, two teams keep on playing until one of the teams is the clear winner. If the teams are tied after regulation time, they are given extra time. If they are still tied after extra time, they go to penalty shoot outs until one of the teams wins the game and takes the cup.

zero sum games, what one player loses is not necessarily what the other player wins. The utilities of the players can vary, for example in the prisoner's dilemma in Section 2.2.2.

2.2.2 Prisoners Dilemma

The example of prisoner's dilemma gives a brief insight into the game theory. Two criminals, John and Joe, involved in a bank heist are arrested and put in separate cells. The prosecutor approaches each of the criminals with a proposition. He tells John that the prosecution does not have enough evidence to incarcerate them, however, if John can agree to turn state witness, then all the charges against him will be dropped and Joe will be put behind bars for the maximum of 10 years. If on the other hand Joe also agrees to turn state witness he will have both convictions and can arrange for both of them to be out on parole after 7 years. However, if John refuses to turn state witness and Joe also refuses, then both will only be in prison for gun possession, which attracts a maximum of 1 year in prison. The prosecutor tells John that he has given Joe the same offer and they both have to sleep on it and decide by the next day. Table 1 shows the possible choice that John and Joe have (Wenjie, Jingfa, Mengmeng, & Ming, 2010), (Wang, Nakao, Vasilakos, & Ma, 2011), (Caelen & Xuereb, 2011).

Table 1: The Prisoner's Dilemma

		John's choices			
		Silent		**Confess**	
Joe's choices	**Silent**	**1**	**1**	**10**	**0**
	Confess	**0**	**10**	**7**	**7**

In Table 1, if John chooses to confess, then Joe will have 7 years in jail if he too chooses to confess or 10 years in jail if he chooses to be silent. If John chooses to be silent, Joe will go free if he confesses or get 1 year in jail if he too chooses to be silent. Joe has exactly the same prospects if John chooses to confess or be silent. From Table 1, if both players could work together and choose to be silent, they get off lightly with 1 year of prison each. However, they are both enclosed and do not know what the other player will choose. If John assumes Joe will confess, then he can have 10 years if he remains silent or 7 years if he also confesses, from this logic, he should choose to confess. If on the other hand John assumes Joe will be silent, then he can have 1 year if he also remains silent or get off free if he confesses, again it makes more sense to confess. The other prisoner, Joe, has exactly the same prospects and if he uses the same logic he will also end up choosing the confess strategy. From the payoffs, if both prisoners choose the confess strategy, they end up with 7 years in jail each. This is a worse payoff than if they had chosen to be both silent, where they would have each ended up with a mere 1 year sentence. This is the prisoner's dilemma, a case where the two players can benefit if they share information, but could be worse off since they do not share information.

The two prisoners are players in the prisoner's dilemma game, each with two strategies that they can play. In the game, each player can choose the silent strategy or they can choose the confess strategy. In the game, players are trying to get the maximum payoff possible, where in Table 1, it should be when each prisoner goes to jail for the minimum possible number of years. In the prisoner's dilemma game of Table 1, the order is assumed to be simultaneous, as the players do not see each other's choices. However, there are other variations of the prisoner's dilemma game where various orders are implemented.

2.3 Overview of Fairness

Fairness is generally the absence of bias. This definition is broad; therefore this dissertation will only look at some of the specific measures of fairness. This section focuses on fairness to establish whether some services, users or applications receive equitable system resources compared with other services, users or applications.

If resources are fairly shared and allocated amongst multiple users, it will not only be an ideal and desirable goal, but one that comes with many practical benefits. Traffic management as a result of fair bandwidth sharing can improve traffic flow and minimize user isolation, eliminate most bottle necks, offer more predictable performance and bring about contentment to both users and service providers, thus resulting in a more stable service quality and happier customers (Zhou & Sethu, 2005), (Lin, Chou, & Lin, 2011).

What is fair in a given situation may not be fair in a different situation, depending upon the context in which fairness is viewed. In the research community, there are many angles from which fairness can be looked at, and some of these may at times appear to be contradictory with each other. The types of fairness include max-min fairness, proportional fairness, weighted fairness, utility fairness, and inter service fairness, which is what this research explores.

2.3.1 Principle of Justice

The principle of justice from Rawls (Rawls, 2001) states that for a distribution of resources to be deemed fair the resources must be shared from a premise of a veil of ignorance. This way, the sharing will maximize the minimum, for it is not known where each of the sharing entities will end up. The veil of ignorance assumes that all the sharing entities are equal before the sharing and need to remain equal after the sharing as well. An unequal original share is allowed only if in doing so the entity with the least share is not disadvantaged. Differential treatment should only be considered if in doing so, none of the other entities are disadvantaged and the entity receiving an advantage would have also accepted the differentiated treatment if the odds were not in their favour. A simple illustration is when a father has one orange to be shared between his two rational[3] children. If the first child is to cut the orange in half, and is told that the second child will be the first to choose a piece, then the first child will always cut the orange in the fairest manner he can. This is because the first child would not want to disadvantage himself, as the second child will always choose the bigger of the slices if he can identify it between the

[3] Both children equally want the orange and none may volunteer his share to his sibling.

two slices. It is not easy to enforce these principles in humans, but the principles can be enforced in the design of telecommunication networks and devices.

2.3.2 Pareto Optimality

A Pareto optimal solution (Brownstein, 1980) is one where it should not be possible to improve the outcome of one player while not disadvantaging at least one other player in the system. A Pareto optimal distribution is thus automatically fair with respect to Rawls's principle of justice. For resources to be shared fairly, the resource distribution must be Pareto optimal. In this research, the bandwidth-sharing scheme is such that all the services at the access point of the WMN router have a Pareto optimal distribution.

2.3.3 Max min fairness

Max-min fairness has some optimality properties as it maximizes the minimum and in doing so, ensuring that none of the services that are already receiving a minimum allocation are disadvantaged. In telecommunications, it has been argued that max min fairness favours too much long connections and does not make efficient use of available bandwidth as its objective is to provide the best possible performance to requests with the worst performance (Touati, Altman, & Galtier, 2001). Generally, an allocation vector $\mathbf{r} = (\mathbf{r}_0, \mathbf{r}_1 \ldots \mathbf{r}_{n-1})$ is max-min fair when any component $\mathbf{r}_i$ of $\mathbf{r}$ cannot be increased without decreasing some already smaller or equal component $\mathbf{r}_k$ ($\mathbf{r}_k \leq \mathbf{r}_i$) (Chou & Lin, 2009). A number of flavours of the max-min fairness have been researched, all of which are a variant of the original max-min established by Rawls in 1971 (Rawls, 2001). The max min generally assumes that each and every participating service or user request in the system at hand has the same willingness to pay, and is thus ideal for players with an equal weighting.

2.3.4 Proportional Fairness

Proportional fairness looks at a parameter that is present in all the services. Different services will have different proportions of the parameter and this can be used to allocate resources to the services. Proportional fairness is achieved if any change in the distribution of the assigned rates would result in the sum of the proportional changes to be non-positive. A scheduling algorithm *p* is thus proportionally fair if for any scheduling *s*, the following equation is satisfied (Kim & Han, 2005):

$$\sum_{i \in U} \cdot (R_i^{(s)} - R_i^{(p)}) / R_i^{(p)} \leq 0$$

Where *U* is the user set and $R_i^{(p)}$ is the average rate of user *i* by scheduler *p*.

2.3.5 Fairness Index

A scalable approach to improve the quality of service of data and multimedia applications in IP networks makes use of the fairness Index (FI) equation (Sudha, Maddipati, & Ammasaigounden, 2008):

$$(\Sigma i \chi i)^2 / N * \Sigma i \chi i^2$$

Where the index should be between 0 and 1 and N is the total number of aggregates under consideration and χ is the excess bandwidth obtained by an aggregate divided by the committed information rate of the aggregate.

According to this definition, the closer the fairness index is to unity, the fairer is the distribution of the excess bandwidth between aggregates.

2.3.6 Multicast max min fairness

Multicasting is when one host communicates to a number of other hosts at the same time in a given domain. This is distinctly different from say a unicast communication, where one host communicates with only one other host or on broadcast where one host communicates with all hosts in a given domain. Multicast is used more by streaming media applications, peer-to-peer services and newscasts. To achieve multicast max min fairness, each of the flows must have fully utilized receiver fairness, same path receiver fairness, per receiver link fairness and per session link fairness (Zhang, Österberg, & Xu, 2005).

2.3.7 Weighted max min fairness

Weighting is establishing a parameter that is deemed to be important amongst all the other parameters of the services. The parameter's quantity is analysed in each service and the service's max min fairness with respect to that quantity is then rated. With differentiated quality of service, some users may be willing to pay more than others may; hence, it will make more business sense to allocate more bandwidth to such users. In this case, priority can be the parameter of most importance, where services with a higher priority get more resource allocation (Yu & MacGregor, 2011).

2.3.8 Utility max min fairness

The fairness concept can also be defined directly in terms of the utilities of the users rather than in terms of the throughputs they are assigned. A utility is an object of interest that gives a measure of relative satisfaction. Once the designers for the competing services have decided upon that, the utility can be used as a measure of max min fairness. The rapid growth of multimedia applications has been one of the major triggers for utility max min fairness as the various multimedia applications have various bandwidth requirements, leading to the different utilities of the applications (Cho & Chong, 2007).

2.3.9 Temporal fairness

In (So-In, Jain, & Al Tamimi, 2010), temporal fairness is ideal for requests that are nearest to the base station, as equal numbers of slots are allocated to all users. Requests nearest to the base station are assumed to get good links compared to users some distant from the base station. The good links would usually translate to a good throughput.

$$Time\ Slots = \sum_{i=1}^{N} (S_i)$$

$$S_i = S_j$$

Where both *i* and *j* are less than *N*, that is, the number of slots allocated for any two requests is the same. *Si* is the number of slots allocated to mobile station *i* and *N* is the number of active mobile stations. Si = Sj

2.3.10 Throughput fairness

Throughput is the amount of content that actually passes through in a network node regardless of the maximum capacity of the system (So-In, Jain, & Al Tamimi, 2010). In throughput fairness, we consider the throughput of each of the services. If users are allocated equal bytes, bytes / throughput, then the users near the base station would not need as much slots as those that are some distance from the base station

$$Time\ Slots = \sum_{i=1}^{N} (S_i)$$

$$B_i = B_j$$

$$B_i = b_i S_i$$

Where both *i* and *j* are less than N, that is, the bytes allocated to any two requests is the same, and *Bi* is the number of bytes allocated to mobile station *i*, *bi* is the number of bytes per slot for mobile station *i*

2.3.11 Inter service fairness

This research concentrates on inter service fairness, where the whole service with respect to the requests in that service is looked at. The fairness here would be to ensure all services have equitable resources. A number of metrics (Lowekamp, Tierney, Cottrell, Hughes-Jones, Kielmann, & Swany, 2003) like bulk transfer capacity, bandwidth capacity, end to end delay, data drop, available bandwidth, achievable bandwidth and bandwidth utilization can be used to measure fairness of inter service bandwidth fairness as listed and discussed in Section 2.4.

2.4 Bandwidth Fairness Metrics

Bandwidth has been defined as the speed that any network element can forward traffic (Jin & Tierney, 2003). It can also be understood as the amount of data that can be carried through a network, usually measured in bits per second. The later definition suits the development of bandwidth allocation schemes and will be assumed in the rest of the research. An increase in bandwidth does not necessarily mean an increase in performance as other things like latency and service type need to be considered. Wireless bandwidth is a scarce resource that is dwindling because of depleted spectrum (Rancy, 2011), (Verlini, 2012). As such, this limited resource needs to be continually managed in order to be shared equitably.

Optic fibre currently presents a theoretical limitless bandwidth between any two points (Corcoran, et al., 2010).The user can have an abundance of bandwidth between any two optic fibre connected points; however, terminal equipment tends to constrain the bandwidth. On the other hand, the radio frequency spectrum bandwidth is a limited and finite resource (Rancy, 2011), hence the need to monitor the allocation, licensing and use of spectrum bands for various industries in most countries. This is the ambiguity of bandwidth. In South Africa, the role of regulating and licensing of the spectrum falls under the mandate of the Independent Communications Authority of South Africa (ICASA).

Routing protocols use a number of different metrics in order to decide how to send the packets from source to destination. Vector protocols like Routing Information Protocol (RIP) make use of the number of hops between the source and the destination as the metric to use. Link state protocols like the Open Shortest Path First (OSPF) use bandwidth between the source and destination as the metric to use. Some routing protocols make use of a number of metrics like delay and bandwidth to determine the route that will be ultimately used when forwarding packets. This research concentrates on bandwidth as the metric to be used when deciding the paths to be followed by packets, which is why the scheme is ideally suited for layer three of the OSI. The OSI layers are detailed in Section 2.9 of this chapter.

2.4.1 Bandwidth Capacity

Capacity is the maximum data per time that is made available to the services at the network nodes in the path (Prasad, Dovrolis, Murray, & Claffy, 2003). Each of the various services competing for bandwidth at the access link can have its own required bandwidth, which ideally should be smaller than the capacity of wireless router servicing all the services. The required bandwidth for each of the services can be used as a metric to allocate resources to the competing services. If the number of users of a service were always constant, an allocation using the required bandwidth of the services would be fair; however, the number of users of a service can vary, resulting in an unfair distribution of resources if only service capacities are used to share resources. The installation of optic fibre around major routes of the world should have an effect of generally decreasing the prices of communications, as more capacity is made available. The decrease in prices has however not been linear amongst the different regions as indicated in Figure 4 by the first quarter results of 2012 (Higginbotham , 2012).

This ultimately has an impact on the prices of services as the ISPs pass down the expense of acquiring capacity from the top tier ISPs to bottom level ISPs and the cost is ultimately passed to the customers. Developing countries pay higher prices as indicated by the price of the London–Mumbai link compared to the LA–Tokyo link in Figure 4, which is why we should optimally use the available bandwidth and hence the need to keep on improving algorithms that share resources. Proper and fair management of bandwidth in the wireless networks will allow more services and applications to be added onto the network whilst maintaining low prices so that the third world customer will only be required to pay a moderate cost for the services.

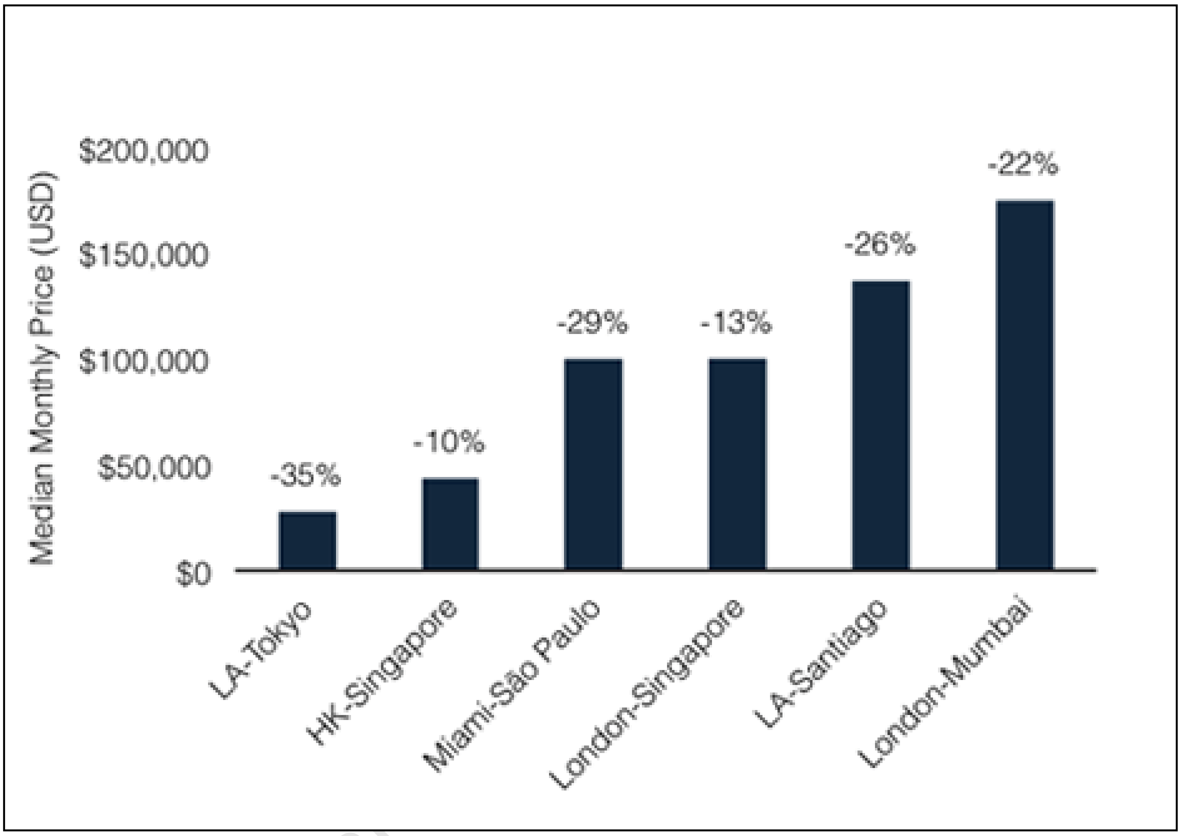

Figure 4: Bandwidth Capacity Prices in various paths (Higginbotham , 2012).

2.4.2 Achievable Bandwidth / throughput

Throughput is the actual amount of data successfully carried through a network and the Round Trip Time (RTT) may adversely affect it. An increase in RTT can reduce the throughput, even though the bandwidth is still the same.

Achievable bandwidth is thus the maximum amount of data per time that a path can provide to an application, regardless of the maximum capacity. If the bandwidth is high, but the signal loss is also high, then the throughput will remain low. Conversely, even if the bandwidth is low the throughput can be high if the signal loss is low. For most system designers and users, throughput is of utmost importance as designers want to optimize the expected performance of the system, while end users want to ensure they have the greatest possible throughput for the least possible cost.

2.4.3 Available Bandwidth

Available bandwidth is the maximum amount of data per time that a path can provide to an application, given current utilization (Prasad, Dovrolis, Murray, & Claffy, 2003). Available bandwidth can give a true reflection of actual capacity, as it does not include bandwidth that has been used, but it is the portion of the capacity that can be acquired by a request (Harfoush, Bestavros, & Byers, 2009). In this research, the available bandwidth is used as a metric for establishing the channel that an incoming request would use because available bandwidth provides a dynamic measure of the capacity that changes with access link load requirements.

2.4.4 Bandwidth Utilization

Utilization is the aggregate capacity currently being consumed on a link or path by some or all of the services in the path. Some services like VOIP do not make use of the bandwidth all the time as there are periods of silence during normal transmission. It should be possible to redirect idle bandwidth at these silence periods to other services with a higher demand in order to improve efficiency and mitigate congestion (Chang & Liao, 2011).

2.4.5 Call Blocking Probability

The call blocking probability (CBP) generally describes the probability that a call cannot be taken, or the loss of a call in switched circuit network calls. The definition can be expanded to include other networks where there is queuing. Metrics like bandwidth capacity, bandwidth availability and bandwidth utilization can be used to determine CBP. In this research, CBP is used where the users/requests arrival rates are assumed to follow a Poisson distribution. As the requests arrive at the access link and are processed, it should be possible that some requests will be processed quicker than others will. The requests that cannot be allocated resources are queued. The request that would have been queued because of the call blocking should thereafter find capacity to be processed once other requests have been completely processed. It is from the measurement of the queued requests that the fairness of the scheme is calculated. The call blocking probability of all the various services in the access link must converge, for the distribution of resources to be fair.

2.5 Overview of Wireless Mesh Networks

A wireless mesh network is a telecommunication network on which the interconnecting radio nodes are organized in a physical mesh topology. The WMN has mesh routers that form the backbone of the network, mobile clients, stationary clients, and mesh gateways that connect to the internet, as illustrated in Figure 5.

The mesh router physical topology can be in a triangular format, a square format or a hexagonal format, where the triangular format is favoured over the hexagonal and square formats as it results in less uncovered spots and thus needs less node density to achieve worst coverage guarantees (Benyamina, Hafid, & Gendreau, 2010), (Iraqi, 2011). The mesh nodes are able to configure automatically, always enabling to maintain connection. The mesh nodes can also dynamically reconfigure according to the network constraints, and hence they are always self-forming and self-healing in response to the network conditions without any need for central management (Johnson, Matthee, Sokoya, Mboweni, Makan, & Kotze, 2007).

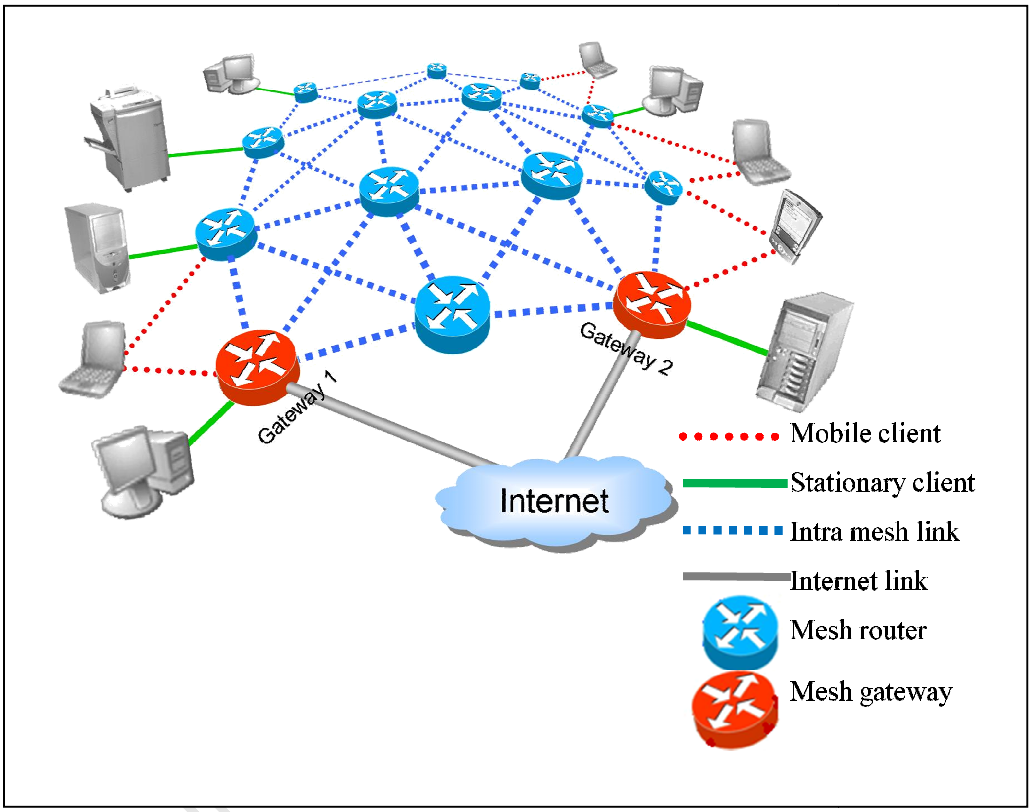

Figure 5: Overview of Wireless Mesh Network (Sichitiu, 2006)

The wireless mesh architecture can be divided into three fundamental groups according to how the mesh nodes are connected (Kumaran & Semapondo, 2010), (Ghahremanloo, 2011). First, the client mesh architecture provides ad – hoc connectivity amongst the mesh clients that can be connected in partial mesh topology. The second group is that of the mesh routers interconnecting amongst themselves in full mesh topology and hence forming a self-healing, self-configuring backbone known as infrastructure mesh architecture. Finally, the architecture as a whole presents a hybrid mesh architecture in that mesh clients can connect to the mesh routers as well as being able to connect amongst themselves as indicated in Figure 6.

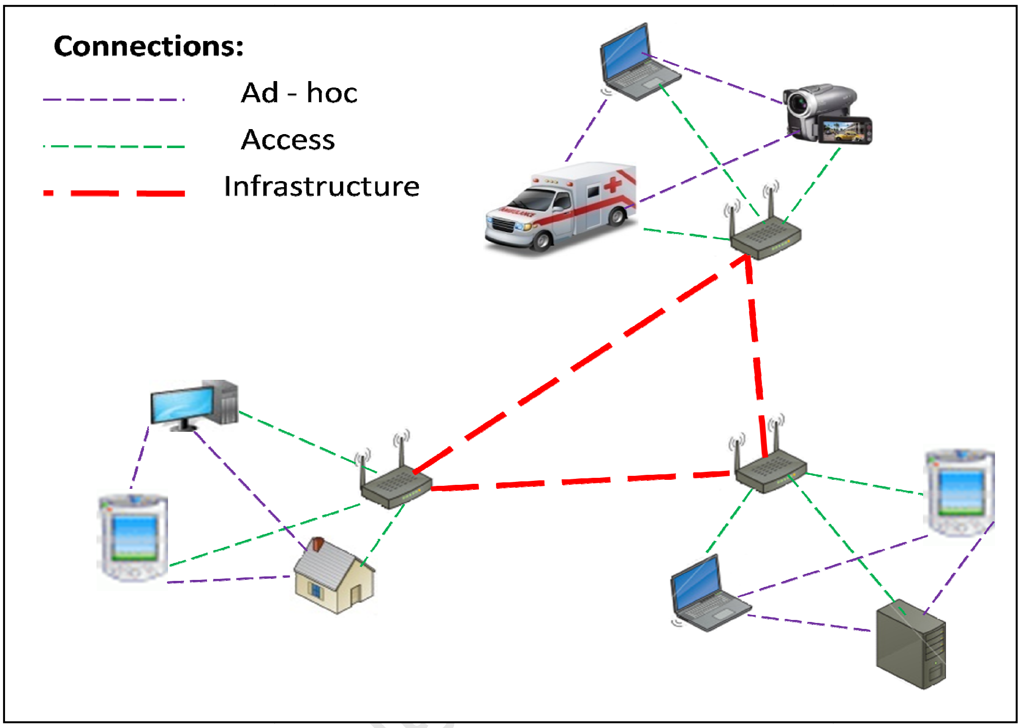

Figure 6: Interconnectivity in the WMN

Each mesh router can thus have a varied number of services that need to share the bandwidth that is available at the mesh router as it can connect to completely different types of nodes and end devices that will have different types of bandwidth needs. The provision of services to different nodes brings about the need to ensure that these varied types of services have an equitable amount of bandwidth, commensurate with all other requests that need to be serviced by the wireless mesh router.

2.5.1 Advantages of WMN

There are a number of advantages (Jackson, 2011) of using the wireless mesh networks, some of which are:

- Dynamic self organizing, self healing and self configuring to meet the changing network demands, and hence can be very ideal for non line of sight network configurations
- They are very easy to install and dismantle, resulting to good coverage extension and very easy adaptability and scalability
- WMN use fewer wires than traditional cable intense networks and do not need major infrastructure support, resulting to less costs for network setup especially in large areas of coverage
- Very convenient were Ethernet wall connections are not there or cannot be used, like outdoor venues, or legacy buildings

Hence WMN are ideal to use in sparsely populated areas, for example African rural areas where there is little wired networks and unreliable power for the mesh backbone (Seth, Gankotiya, & Jindal, 2010), (Mudali, Mutanga, Adigun, & Ntlatlapa, 2011). We are currently in the era of next generation of networks, as indicated by the Internet Assigned Numbers Authority (IANA) report on the depletion of IPv4 addresses in Figure 7 (Huston, 2011). Amongst all the five IANA Regional Internet Registries (RIR), densely populated as well as sparsely populated communities need to be connected. WMN can be used for most of the connections, owing to some attractive advantages like low cost to set up.

From Figure 7, AFRINIC covers the whole of Africa and portions of the Indian Ocean. APNIC covers portions of Asia and portions of Oceania. ARIN covers the United States of America, Canada, many Caribbean and North Atlantic islands. LACNIC covers all of Latin America and portions of the Caribbean. RIPE NCC covers all of Europe, the Middle East and Central Asia. The RIRs administer and register the Internet Protocol address space and Autonomous System numbers within their defined regions. With the depletion of IPv4 address space, we should be moving to the IPv6 address space and some big internet companies like Google, Yahoo and Facebook have already successfully tested this transition (Cowley, 2011).

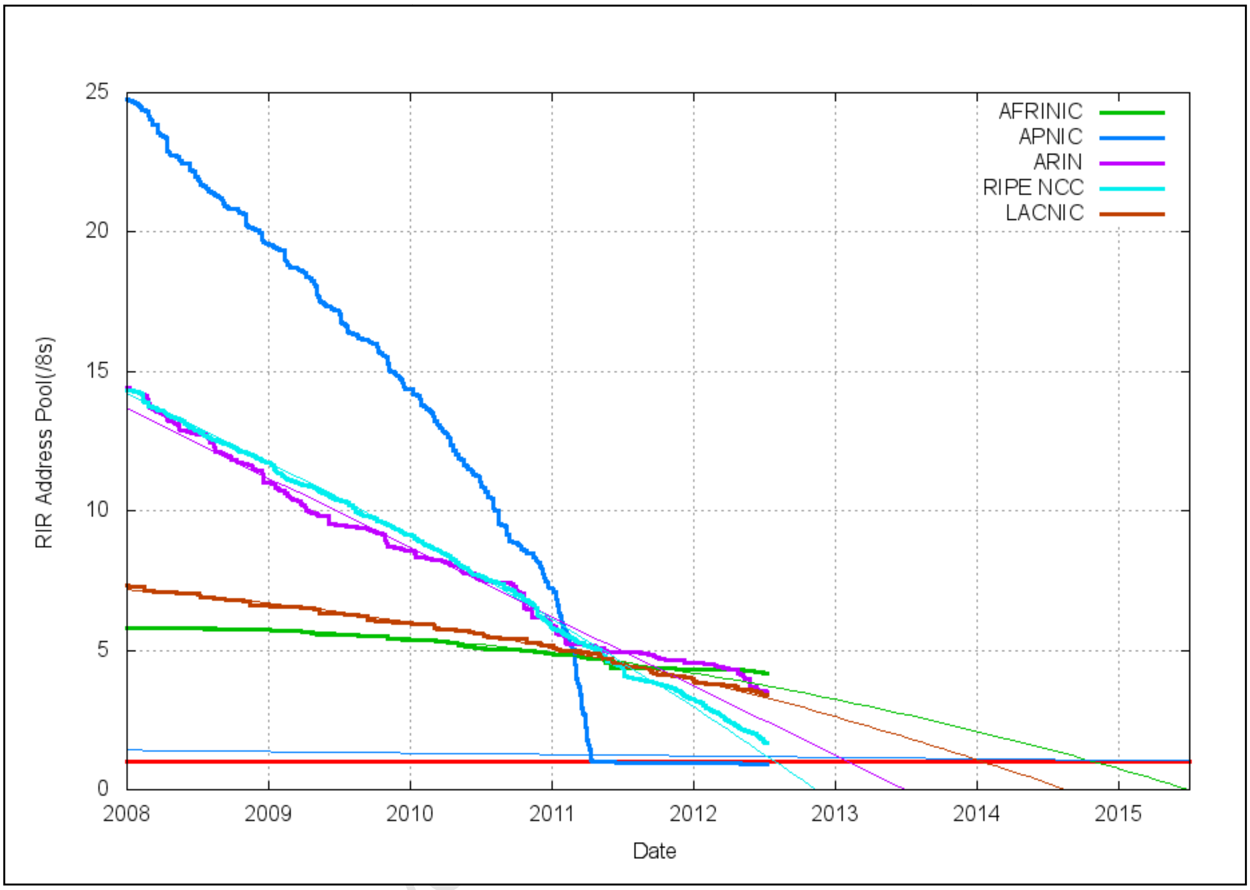

Figure 7: Depletion of IPv4 address space (Huston, 2011).

2.5.2 Challenges of WMN

One of the biggest challenges of wireless networking is capacity, which is linked with limited bandwidth (Marwaha, Indulska, & Portmann, 2009), (Samuel, 2009), (Su, Chan, & Manton, 2010), (Southeastern, 2011). Hopefully, with recent developments and continuous research, limited bandwidth will be a problem of the past as some researchers (Anthony, 2012) have managed to achieve speeds up to 2.5 terabits per second, albeit in the laboratory and within a line of sight of 1 metre distance. These results are exciting and promising, and will be in line with the next generation technology of ubiquitous networks, making provision for increased wireless bandwidth to users of all kinds of networking services.

In their paper (Seth, Gankotiya, & Jindal, 2010), Seth *et al* identify a number of challenges in the physical layer, media access layer and network layer of wireless mesh network designs. At the physical layer, the wireless transmission medium is more vulnerable to interference, signal loss and signal distortion, and is not very reliable when compared to the wired transmission. Household appliances like microwaves can also adversely affect the signal of wireless transmission. Main issues in the MAC layer are quality of service support, heterogeneous access support, and scalability, where Velempini has contributed measures to improve the scalability of MAC protocols in a number of peer reviewed papers (Velempini M. , 2010). This research looks at the issues identified under the network layer, mainly those that deal with routing because allocating the right bandwidth to the various services is complementary to the routing problem. EIGRP and OSPF use bandwidth as part of the metric to determine the cost of a path. It is important therefore to ensure that bandwidth is shared fairly amongst the various services, which is the focus of this research.

2.6 Overview of Wired Technologies

Wireless networks increase the mobility for users and is becoming the preferred means of communication when compared with landline phone. Figure 9 shows the evidence of an increase in mobile phone connections against fixed line connections. While this is true, there is still some amount of wired network that is needed as the backbone for most wireless networks. For this reason, optic fibre and copper-wired connections are reviewed in this section.

2.6.1 Fibre technologies

A number of FTTx distributions are currently in use in the access network of telecommunications networks, with FTTH being used in densely populated areas where cables with as much as 400 fibres are being used (Hogari, Yamada, & Toge, 2010). With FTTH, a customer can have fibre all the way to their home, meaning one can potentially have as much bandwidth at home as at a small work office, hence the proliferation of home offices.

FTTO is a variant of FTTH, but specifically targeted at corporate offices, where the bandwidth requirements are typically much higher compared to the bandwidth requirements of a household or a small office. The terminal equipment provided for the FTTO is much more sophisticated to be able to support the higher bandwidth requirements.

FTTB has fibre all the way to the building or basement. This is ideal in apartment blocks with a number of floors, where the fibre terminal equipment is installed at the basement of the building, with copper or wireless connectivity from the fibre terminal point to the customer. In this case, the last kilometre is a combination of fibre with copper or fibre with wireless.

In FTTC, the fibre terminal equipment is connected at the curb, to serve a couple of buildings and apartment blocks. The final leg of the combination network can also be either copper of wireless.

Table 2: Fibre access network technologies summary (ZTE, 2009)

Technology	Distance to customer	Bandwidth to customer
FTTO	Typically less than 50m	100M to Gigabit Ethernet
FTTH	Typically less than 50m	More than 100M
FTTB	Typically less than 100m	50M to 100M
FTTC	Typically less than 300m	25M to 50M
FTTN	Typically more than 300m	Less than 25M

FTTN has fibre up to a node, where the node could be a concentrator. Here the distance from the fibre terminal point to the customer is greatest, and resultantly the bandwidth that a customer can have the least of all the FTTx technologies. Table 2 summarizes the various fibre access technologies by comparing the bandwidths available to customers.

2.6.2 Copper technologies

Most of the FTTx technologies use copper wire at some point of the access network as shown in Figure 8. Some of the copper wire technologies used are ISDN, xDSL, and CAT 5. XDSL and ISDN use twisted pair while CAT5 uses up to four twisted pairs (Forouzan & Fegan, 2007).

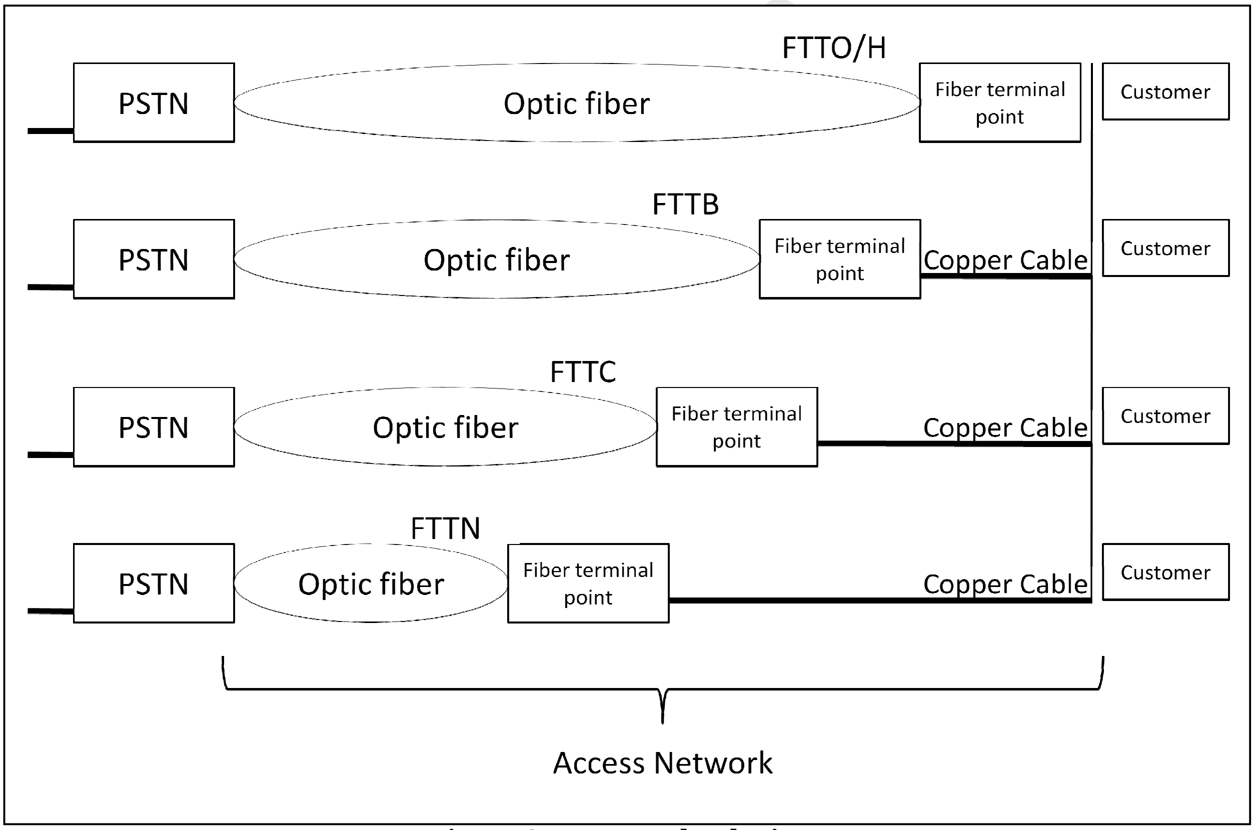

Figure 8: FTTx technologies

Dial up allows speeds of up to 56K using the twisted pair of a fixed landline telephone. While using the dial up, one cannot use the telephone to communicate. Only one of the two services can be used at any given time.

ISDN offers a capacity of up to 2M for its primary rate interface using the POTS, but the basic rate interface commonly used by households can have a capacity of up to 128K, an improvement from the dial up capacity of 56K. Users can use any two services simultaneously, where the service can be voice, fax, internet and data (Telkom, 2012).

XDSL are a range of copper-wired technologies that enhance the capacity of twisted pair. They are an improvement from the 128K that is offered by ISDN as they can provide up to 24M (Bota, Khuhawar, Mellia, & Munafo, 2011) to a household customer, depending upon the DSL technology used and the line conditions. In ADSL, the commonly used DSL technology in South Africa (Telkom, 2012), users can be on the phone whilst simultaneously using the internet.

CAT 5 is category 5, the commonly used local area network cable. CAT 5 can support Fast Ethernet speeds of up to 100M using two of the four pairs. An enhancement of CAT 5 is CAT 5e, which can support up to 1000M and uses all the four pairs of the Ethernet cable, the so-called Gigabit Ethernet. CAT 5 cable is also backward compatible to the legacy Ethernet, with speeds of up to 10M. Research is currently in progress for CAT 6 and CAT 7 cables that will support even higher bandwidths and higher frequencies ideal for data centre backbones (c2g, 2012).

2.7 Overview of Next generation networks

The International Telecommunications Union in their website (ITUngn, 2010) defines the next generation network as a packet based network that offers services independent of the transport related technologies, offering unrestricted access to users from various service providers. We are already experiencing some of the advantages and conveniences of the next generation networks, a common example being the proliferation of VOIP technologies like Skype that share the same transport technologies as the internet. Internet and cell phone banking is in the process of revolutionising the way we do business in urban centres, whereby we can now do most business transactions at home or in transit.

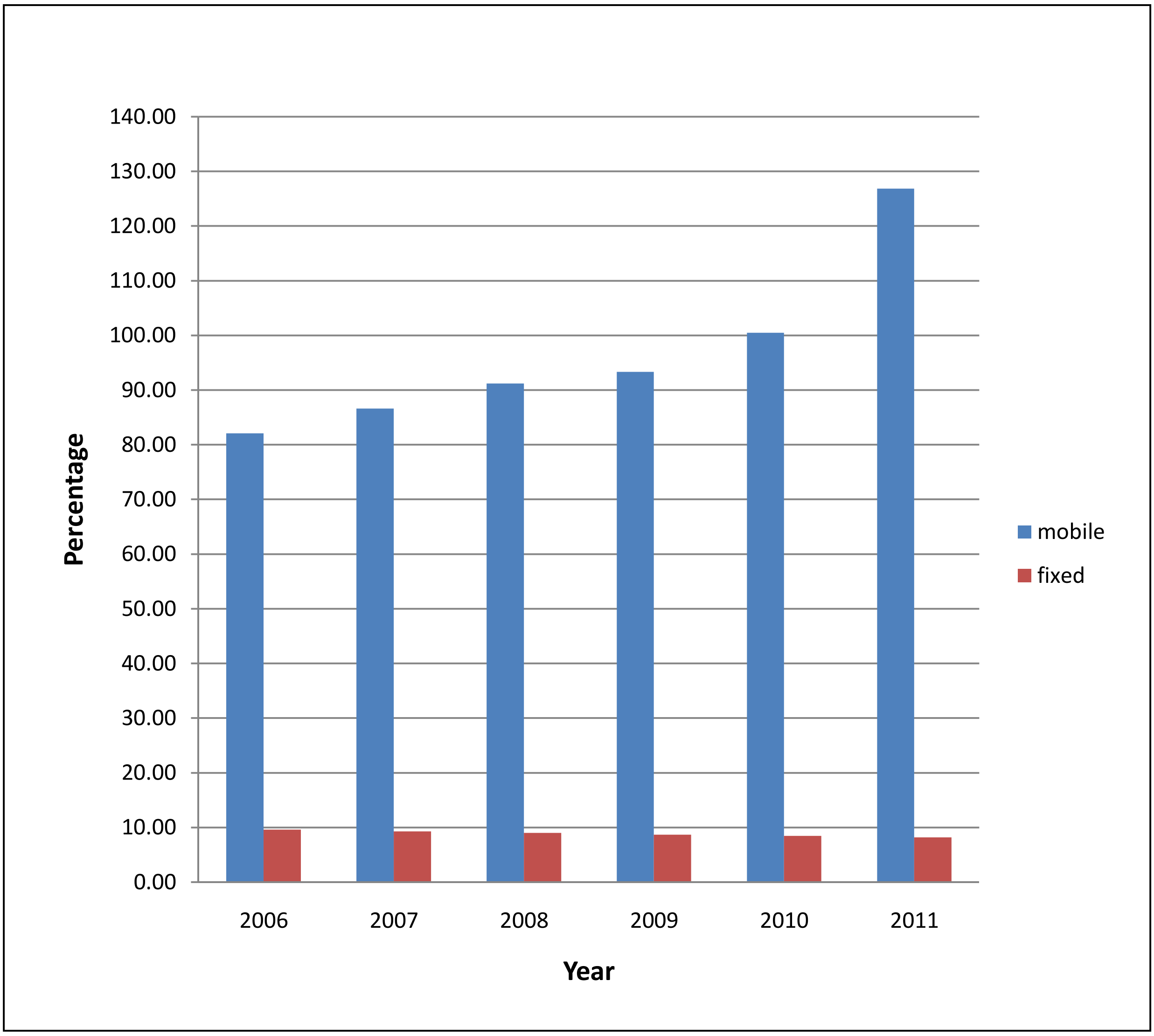

Figure 9: Telephone penetration ratios in South Africa (ITU, 2012)

IPv6 addresses have 128 bits compared to the paltry 32 bits for IPv4, providing for trillions of trillion possible hosts, enough for all seven billion inhabitants of the world to have trillions of IP addresses at their disposal. This should enable a host of gadgets to have IP addresses and thus be networked. It is the provision of these potentially numerous hosts into the network that are becoming more intelligent and faster, needing more bandwidth (Bernier, 2011), which necessitates the need for them to share the resources fairly; otherwise their presence may be futile.

The penetration ratios of telecommunications services have always been with respect to a number of units per household or a number of units per business. Figure 9 shows the fixed line and mobile penetration ratios in South Africa; where the number of fixed lines remains low and slightly decrementing while the number of mobile phones increases annually by an average of more than 5%. The growth rate of the mobile phone, a wireless technology, can be mapped onto WMN since both are largely wireless technologies that do not need a large initial capital when compared to the growth of the wired fixed network. The South African scenario of fixed telephone connections displayed in Figure 9 is slightly better compared to most African countries that even though are endowed with natural resources seem to be handicapped economically, the case of Zimbabwe and Botswana compared against Japan in Appendix B being reference, showing the relatively small numbers of fixed telephone connections. South Africa has a population of 49 million compared to Zimbabwe's 13 million and Botswana's 2 million (CIA, 2012).

WMN would thus be ideal to be used for the next generation of networks in Africa, owing to the poor fixed telephone connectivity. For the next generation networks, we look at a number of telecommunications units per individual, as a single person can have up to four units like a desktop computer, a smart phone, a pager, and a notebook computer as illustrated in Figure 10. It is possible to have cameras to view ones home, zoom and look around, open windows and curtains for fresh air, water the loan and a host of other activities which are enabled by IP connectivity from anywhere as long as they have a network connection. Machine to machine communications (Kripalani, 2009), (Fukahori, 2011) is already on the rise with intelligent fridges, intelligent wardrobes, smart cars and other intelligent gadgets all competing for bandwidth in the network and in the last kilometre.

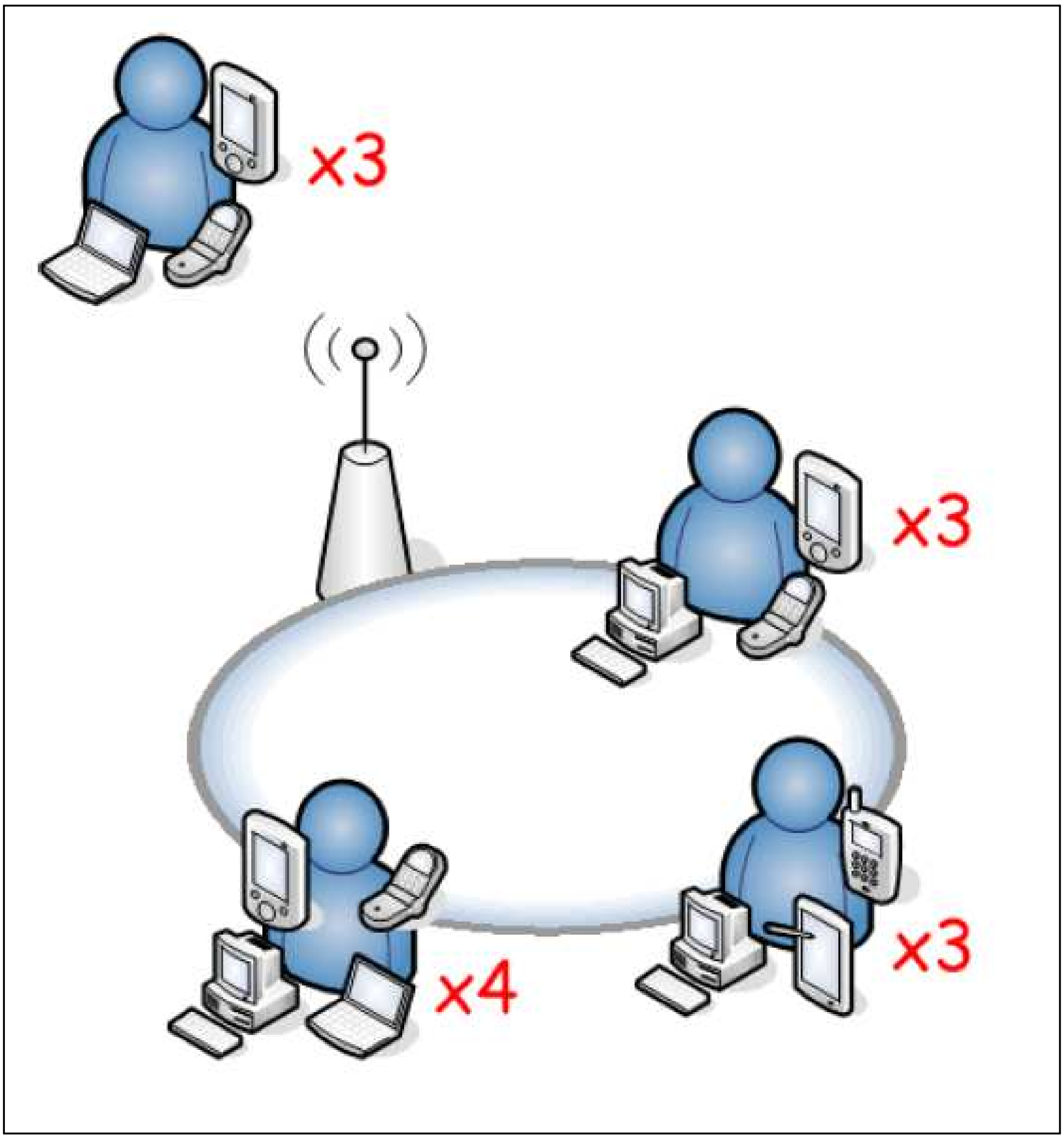

Figure 10: Illustration of services in the next generation networks (RealTimePublishers, 2005)

2.8 Overview of Converged networks

In their early developments, IP networks used to be best effort and thus could not be ideal for the stringent QoS demands of real-time applications. However, with enhancements and improvement on the QoS, IP networks are becoming the cornerstone on which to base all applications, wired or wireless (Yerima, Parr, McCLean, & Morrow, 2011). In the olden days, data circuits, voice circuits, television circuits, radio circuits and cable circuits were all different and discrete networks. The next generation networks carry all these forms of traffic in a single network (Sarrocco & Ypsilanti, 2008), (Anonymous , 2012). This again brings the notion of fairness that needs to be ensured so that all the requests from the various services can interwork with minimal complaints. Sarrocco & Ypsilanti further identify economic, technological and social drivers for the next generation of network and converged networks, some of which are shown in Table 3.

Table 3: Next Generation and Converged Networks drivers (Sarrocco & Ypsilanti, 2008)

Technological Drivers	Social Drivers	Economic Drivers
Obsolescence of legacy networks, plus cost and complexity of managing multiple legacy networks.	Demand for innovative, high bandwidth services	Erosion of fixed line voice calls revenues.
Evolution and convergence of terminal equipment.	Demand for increased interactivity, possibility to interact actively with the service, growing interest for user-created content	Competitive pleasure from new entrants in high margin sectors of the market and from vertically integrated operators.
IP-based networks enable the provision of cheaper VOIP service as a replacement for PSTN voice services.	Demand for more targeted or personalized content	Retain and expand user's base, lower customer churn and ability to expand into new market segments
IP-based networks enable the provision of a wider range of services and allow bundling of services	Demand for evolved and more flexible forms of communications, including instant messaging, P2P, etc	Saturation of both fixed and mobile telephone services
Lower capital and operational expenses. Increased centralization of routing, switching and transmission, lower transmission costs over optical networks	Business demand for integrated services, in particular in case of multi-national structures, which need to link different national branches, guaranteeing a flexible and secure access to centralized resources and intelligence.	Possibility of "ladder of investment", i.e. a phased approach of investment, initially targeting more densely populated areas, and then gradually expanding in other areas.

From the service provider’s perspective, the economic drivers are of prime importance as these are what keep them from going under. As indicated in Figure 9, the revenue from fixed telephone is not growing owing to the lack of more customer connections. This has prompted traditional fixed telephone companies to also venture into the mobile telephone phone sector, for example the South African Telkom Company that has birthed a mobile telephone network called 8ta (8ta, 2012). As equipment gets older, it becomes more expensive to maintain and operate it; hence the need to replace it with new technologically advanced equipment that is relevant to the era. Customers also become more informed and thus would expect better services from service providers. All the points drive the need for the next generation network as a solution to all the drivers, where the entire network can be carried by a single platform that will converge voice, data, television and radio into a single converged network.

2.9 OSI and TCP/IP

The Open System Interconnection (OSI) provides an architectural reference model on which to model networking standards and protocols, and is maintained by the International Organization for Standardization (ISO) (Lewis, 2005), (Forouzan & Fegan, 2007), (Li Y. , Cui, Li, & Zhang, 2011). The seven layers of the model provide an abstraction on which different standards and protocols can provide encapsulation within the layers. The abstraction provides a platform on which the different standards and protocols from a plethora of companies and countries can work together. The Transmission Control Protocol Internet Protocol (TCP/IP) is also a layered model providing four abstract layers. TCP/IP is used to specify how the end-to-end data should be formatted at the application layer, how data should be transported at the transport layer, how data should be addresses and routed at the internet layer and how data should be transmitted at the network access layer. The TCP/IP and OSI models are related in that the highest three layers of the OSI form the application layer of the TCP/IP. Layer four of the OSI is the same as layer two of the TCP/IP. The network layer in OSI is known as the internet layer in TCP/IP and finally the lowest two layers of the OSI form the fourth layer of TCP/IP, the network access layer (Lewis, 2005), (Li Y. , Cui, Li, & Zhang, 2011).

2.9.1 Application layer

The application layer is the topmost layer of the OSI and the TCP/IP (Lewis, 2005), (Forouzan & Fegan, 2007), (Li Y. , Cui, Li, & Zhang, 2011). In the TCP/IP, the application layer separates the application software from the transport layer and contains higher-level protocols that most applications use for networking. In the OSI, the application layer supports end-to-end user applications and processes. Some of the commonly supported applications in the application layer include the file transfer protocol, the hypertext transmission protocol, the simple mail transfer protocol and the dynamic host control protocol.

2.9.2 Presentation layer

The presentation layer of the OSI formats and encrypts data to be sent into the network as well as decrypting data from the network into the application (Lewis, 2005), (Li Y. , Cui, Li, & Zhang, 2011). Protocol conversion is done in the presentation layer, particularly the semantics and syntax of the information, making communication between any two communicating hosts possible. Secure socket layer and transport layer security are the common protocols in the presentation layer.

2.9.3 Session layer

The session layer helps establish, synchronise and maintain the communication between the two communicating hosts (Forouzan & Fegan, 2007). A common service in the session layer is the Network Basic Input/output System (NETBIOS) used in the local area networks for allowing separate hosts to communicate in small networks.

2.9.4 Transport layer

The transport layer guarantees error free communication without any losses or duplications between the communicating hosts. Connectionless and connection oriented protocols are provided in the transport layer. The Transport Control protocol (TCP) and User Datagram Protocol (UDP) of the TCP/IP are the most common transport layer protocols (Lewis, 2005), (Li Y. , Cui, Li, & Zhang, 2011). The transport layer provides flow control.

2.9.5 Network layer

In the network layer of the OSI or the internet layer of the TCP/IP, host identifying and addressing, determining the routes, and switching is done (Lewis, 2005), (Li Y. , Cui, Li, & Zhang, 2011). The network layer also provides for creating of logical paths, thereby creating virtual circuits that can be used to send information from one node to the next. In this research, the scheme will operate at the network layer as the scheme makes use of the virtual channels that are with respect to the services at the wireless mesh router. Some of the common protocols of the network layer are the Internet Protocol (both version 4 and version 6), the Internet Control Message Protocol and the Address Resolution Protocol.

2.9.6 Data link layer

The data link layer is separated into two sub layers of the Logical Link Control (LLC) and the Media Access Control (MAC) (Lewis, 2005), (Li Y. , Cui, Li, & Zhang, 2011). The LLC controls flow control and error checking as well as synchronisation of data towards the network layer. The MAC layer controls how a host on the network manages its interaction with the shared medium. The MAC thus works closely towards the physical layer. Some of the common protocols found in the data link layer include the Point-to-Point Protocol, the Asynchronous Transfer Mode, the Frame Relay and the X25. Velempini’s (Velempini M. , 2010) focus is on the MAC sub layer, where he identified improvements on algorithms that mitigate the multi channel switching cost (MSC), which had been identified as the main cause for MAC protocols failing to schedule data transmissions to all the available data channels simultaneously, resulting in bandwidth wastages.

2.9.7 Physical layer

The lowest layer in the layered model, the physical layer, deals with transmitting the stream of bits from one host to the other as electrical pulses in the network (Lewis, 2005), (Li Y. , Cui, Li, & Zhang, 2011). The transmission medium could be copper cable, optic fibre cable or wireless transmission. Physical and electrical specifications of the networking devices are defined in the physical layer. Some of the more common protocols and standards for the physical layer include the Plain Old Telephone Service, the IEEE 802.11, the Universal Serial Bus, the RS232 and Bluetooth.

2.10 Chapter summary

The groundwork on which this research is based has been set in Chapter 2. Also identified is where and how the improvements to existing bandwidth schemes can be implemented. Fundamental concepts that lay the foundation on which the research arguments are based have been explored especially on Section 2.2 and Section 2.3, where game theory basics and the fairness overview were discussed respectively.

3 Review of relevant research theory

3.1 Foreword

This chapter reviews what other researchers have done with regard to fairness in wireless networks as well as how other researchers have used game theory to improve fairness in wireless networks, and identify missing gaps. The limitations identified are what form the crux of the next chapter, where ways of mitigating the highlighted limitations are explored, thus enhancing fairness in wireless networks.

3.2 Wireless Technologies

Figure 11 summarises the growth of WLAN and cellular access technologies by looking at the bandwidths available to customers over the past 20 years. With ongoing research, it should not be long when we will be using up to 1G in WLAN (Raychaudhuri & Mandayam, 2012).

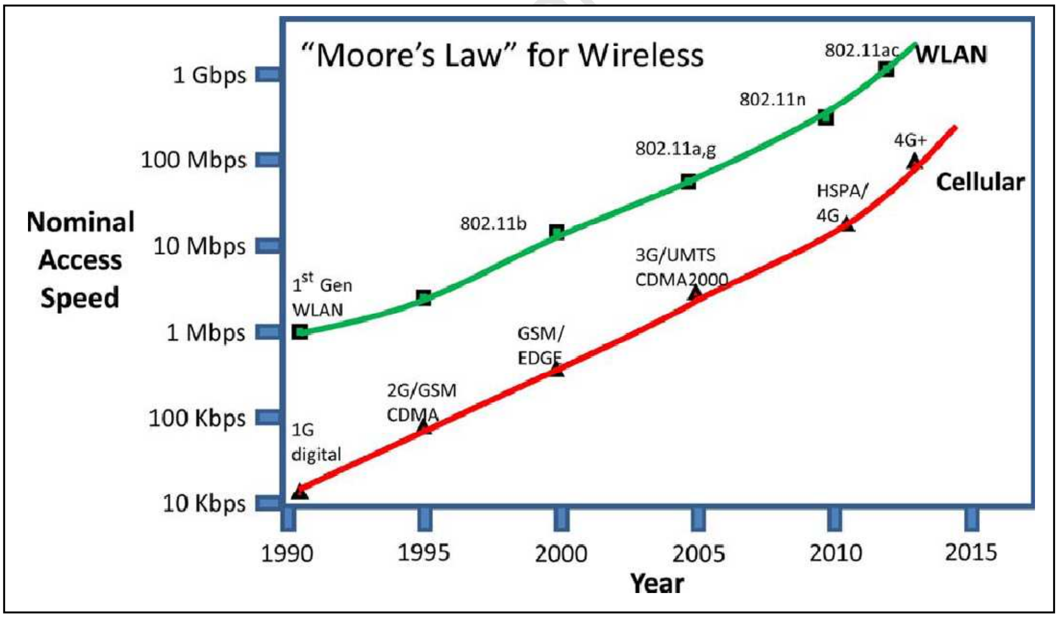

Figure 11: Increase in WLAN and cellular access speeds (Raychaudhuri & Mandayam, 2012)

Bluetooth is a short-range personal area network technology that enables up to 3M of data transfer between the communicating devices and up to 24M on the Bluetooth v3.0 (Bluetooth, 2012). Future research is anticipated to increase the bandwidth up to 100M.

Ad hoc networks do not rely on a fixed structure, but the hosts self-configure and can be mobile, forming mobile ad hoc networks (MANET). In reality, part of a WMN can actually be a MANET if composed of mobile devices. The absence of fixed structure in ad hoc networks makes this local area network technology to be unable to guarantee bandwidth (Du & Yang, 2010).

Wi-Fi is a local area network technology that is based on the IEEE802.11 standards. The first generation started with a modest bandwidth of 1M as shown in Figure 11. We should be achieving bandwidths of up to 1G in the near future as current research makes use of MIMO, a technology that uses multiple antennas at each end of the communication path to optimize data speed by minimizing errors (Zheng, Gao, Zhang, & Feng, 2012).

WiMax is a metropolitan area network technology based on the IEEE802.16 standard that provides broadband access with high mobility that has much more coverage radius that can be as much as 50km, compared to the hot spot radius of less than 100m that is provided by the WiFi (Liao, et al., 2012).

While research is ongoing to improve the speeds for most of the wireless technologies discussed in the above section, there are still limits for bandwidth, hence the need also to continue refining bandwidth fairness for services as well as for hosts.

3.3 Wireless Mesh Networks

Ye, Wang & Huang, (2011) propose a solution to the counter starvation problem among TCP flows in WMN. The scheme works on layer four of the OSI model and thus would complement the work of this research, which is primarily in layer three of the OSI model. The cross layer explicit congestion notification of Ye *et al* accurately assigns the bandwidth and hence improves the QoS for proportional fairness.

The chief advantage of the layered OSI model is that an improvement on an upper layer filters to all the other lower layers as each layer is encapsulated. The authors (Tang, Hincapie, Xue, Zhang, & Bustamante, 2010) in their work on WMN achieve a trade-off between fairness and throughput. The algorithms produced by Tang *et al* achieve the fairest bandwidth allocation in according to Jain's fairness index.

3.4 Game theory in wireless communications

A number of papers have been written on game theory in wireless communications. In their paper (Krishna, Cumanan, Xiong, & Lambotharan, 2009), the authors propose a scheme that uses a cooperative relaying strategy that minimises transmit power at the relay layer while satisfying QoS constraints. The cooperative and non-cooperative stratagems compared are game theory characteristics.

The authors in (Roy, Wu, & Zawodniok, 2011) make use of adaptive control and game theory to produce a guaranteed fair sharing of channels produced by an optimal radio resource allocation that also achieves Pareto optimality.

A scenario where mobile users can force the service providers to provide premium QoS is outlined by the authors (Hassan, Hassan, & Das, 2010), where game theory and Monte Carlo simulations are used.

Though theoretical, the game theory analysis provides an understanding for network designers so that wireless networks service providers can improve their quality of service in order to remain competitive and viable as well as offer their customers the latest technologies.

3.5 Fairness in wireless communications

A scheme with four classes in developed in (Al-Manthari, Ali, & Hassanein, 2008) for bandwidth fairness with revenue considerations. This is ideal for business purposes to maximise on profit. The class weighting determines its utility, which then determines the bandwidth share.

The utility is static, and if there are not requests on a class, bandwidth is still reserved, which can be a waste. Table 4 shows the weightings and their utilities.

Table 4 : The average utilities

w_1	w_2	w_3	w_4	U_1	U_2	U_3	U_4
9	5	3	1	0.68	0.43	0.19	0.05
7	4	2	1	0.561	0.39	0.263	0.19
4	3	2	1	0.442	0.41	0.331	0.295

In Table 4, the weightings W1 … W4 determine the utilities U1 … U4 respectively.

A number of bandwidth allocation schemes have been proposed in the literature. In their work, Zhu *et al* present bandwidth allocation that is done for clients regardless of the kind of service they transmit in the access links (Zhu Y. , Liu, Guo, & Zeng, 2009). Figure 5 shows the access link, the path between the access router nodes and the client nodes where wireless clients are indicated by dotted lines while wired clients are indicated by solid lines.

Zhu *et al* investigate a congested streaming scenario and a distributed bandwidth allocation method for fair multimedia streaming in CSMA/CD-based WMN proposed. While the solution improves the fairness of streaming flows, it does not consider all possible services that a WMN node may be exposed to. If services are not separated, unfairness may result as the access router would simply allocate bandwidth according to the bandwidth needs of each mesh client within its periphery.

In (Wang, Cui, Xu, Huang, & Liu, 2009), bandwidth thresholds are calculated for each of the two services using proportional fairness. An increase in the call arrival of one service results in the increase of CBP for both services as shown in Figure 12 and Figure 13

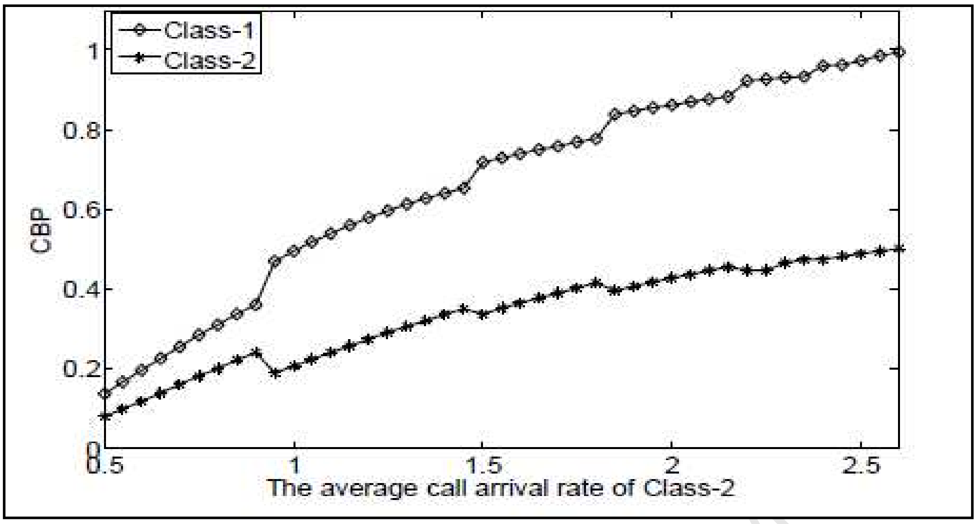

Figure 12: CBP versus average call arrival rate of 1.5

The average call arrival rate of 1.5 is the average call arrival rate where λ is 1.5. Lambda (λ) is the Poisson rate parameter that indicates the expected number of events or arrivals that occur per unit time. The graphs of Figure 12 and Figure 13 can result in unfairness to the service that has an increased call arriving rate as it means more of its requests share the same amount of resources by proportion compared to the service with fewer requests. Ideally, this research looks at a situation where the CBP is commensurate with the call arrival rate of a service.

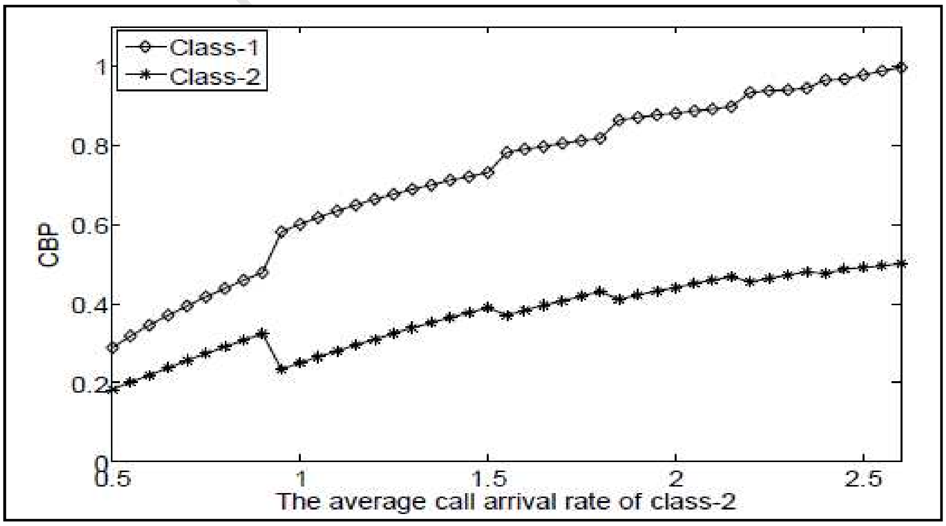

Figure 13: CBP versus average call arrival rate of 2

A fair TCP and UDP bandwidth allocation has been proposed by then authors (Visoottiviseth, Trunganont, & Siwamogsatham, 2010). Their scheme also reduces unused / remaining bandwidth and hence helps increase utilization whereby adjustments between the uplink and downlink traffic can be made if bandwidth is required in either direction. This works well but it is limited by the wireless capacity value, a parameter the authors define as the specific and constant value which conflicts with the fact that wireless capacity is unstable.

Ziermann, Muhleis, Wildermann, & Teich (2010), propose penalising nodes that claim too much bandwidth at the expense of other nodes, this way a greedy node would not have a monopoly of the bandwidth. The proposed algorithm induces penalties for greedy nodes, and hence enforces a fair bandwidth distribution. However, the assumption is that all the nodes have messages of the same length. This research considers a network having varying channels for different services that may not have the same length and priorities. The algorithm of Ziermann *et al* uses game theory players that converge at a Nash equilibrium, which is equivalent to the bandwidth available to all the players in the system.

A strategy vector **s*** is Nash equilibrium if:

$$\mathbf{u_i}(\mathbf{s_i}, \boldsymbol{s^*_{-i}}) \leq \mathbf{u_i}(\boldsymbol{s^*_i}, \mathbf{s_{-i}}), \forall \mathbf{s_i} \in \mathbf{S_i}$$

where **u** is the utility of each player ***i***, with ***s*** being the strategy that can be taken by the player. The utility of player ***i*** is given by the Cartesian product of its probability and the probability of other players not sending.

The probability of any player getting access to the medium would be

$$\boldsymbol{u}_i(\boldsymbol{p}) = \boldsymbol{p}_i \prod_{j \neq i}^{n} (1 - \boldsymbol{p}_j)$$

Where $\mathbf{p}_i$ is the probability of player **i** sending data and (1-$\mathbf{p}_i$) is the probability of player ***i*** not sending data.

If player ***j*** is any player with a higher priority than player **i**, then player **i** will always send when player ***j*** does not send, that is j(**p**)>i(**p**). For any player with a probability less than that of it, ***i*** will send regardless. If for all the players there exists a strategy vector **p** such that

$\mathbf{u}1(p) = \mathbf{u}2(p)=\ldots=\mathbf{u}n(p)$

Then all the users have the same probability to have access to the channel and the strategy vector is said to be fair.

In their work (Li W. , Cui, Cheng, Al-Rodhaan, & Al-Dhelaan, 2011), the authors introduce a proportional fairness scheme that provides a good trade-off between throughput and fairness via power control in multi rate WLANs. Their power control for access-point performance algorithm compares better to other power and signal algorithms as it posts better throughput.

3.6 Chapter summary

In all the reviewed work on Chapter 3, a consistent limitation was encountered, that of schemes not addressing the issue of incorporating the service type in dealing with the fairness of users such that the number of requests on each service type has an effect on the allocation of resources. This issue thus begs a redress, which is the focus of the next chapter where a scheme that overcomes the limitations of existing schemes is introduced.

This research is limited to the fairness in access link of a single router without putting into consideration other routers. The advantage that this kind of work brings is encapsulation, in that the router makes decisions not based on the outcomes of other routers, which is in line with Zinin’s routing laws (Zinin, 2001).

4 Operational Overview

4.1 Foreword

This chapter follows up on the limitations identified in Chapter 3 and uses an analytical model with game theory to establish and describe the proposed solution. Once the mathematical solution has been established, it is mapped into an algorithm that is used for the inter service bandwidth scheme.

4.2 Background

The proposed scheme is broadly divided into two phases. The first phase allocates the virtual channel sizes with respect to the number of requests in each service using game theory principles. In the second phase, requests are serviced in each channel in such a way that if any of the channels fills up, its requests can use other channels as long as service thresholds allow.

In this research the following services are considered for inter service fairness: Mobile Premium Service, Mobile Olympic Service, Best Effort Low delay Service, Best Effort Service and Background applications (Diederich, Doll, & Zitterbart, 2003). For a multi agent game, these are the services that can be used, each with a number of strategies that it can play, yielding various payoffs depending on what strategies the other players play (Moyo, Falowo, & Dlodlo, 2012). The key would be to reach a strategy that will be the most fair for all the players. This would be the equilibrium strategy.

The Portable / Mobile Premium Service offers low loss, low jitter, and low delay for high quality of service applications, for example high end wireless IP telephony and real time video, these applications are extremely sensitive to jitter, loss and delay. The Best Effort Low delay Service is ideal for loss adaptive applications with low delay requirements which can tolerate a certain amount of packet loss, these applications are sensitive to loss, jitter and delay, for example low cost IP telephony. The Portable / Mobile Olympic service provides no assurances on delay or jitter, ideal for streaming applications, as they can be adaptive. Best Effort applications require no minimum quality of service guarantees and are tolerant to delay, for example HTML applications, and some are very tolerant to delay, for example SMTP, Telnet and FTP (Diederich, Doll, & Zitterbart, 2003) (Navda, Kashyap, & Das, 2005), (Carlson, Prehofer, Bettstetter, Karl, & Wolisz, 2006).

Looking at the OSI layers, layer four through layer seven are bulked as host layer and layer one and layer two as media layer. The assumption here is that by the time all the protocol data units (PDUs) of the host layer arrive at the network layer, they would have been encapsulated, implying the network layer protocols would not distinguish them; hence all the fairness improvements at the host layer should complement this research. This also applies to the media layer protocols, so that any improvements on media layer protocols complements this research scheme as provided for by the layered structure of the OSI.

The first huddle is to establish the equilibrium bandwidth that each of these services would get. Once the equilibrium bandwidth has been computed, on the next step, which will enhance the fairness of the services, an algorithm that will ensure equitable resource sharing after the equilibrium bandwidths have been established is used.

The words player, class, channel and service are used interchangeably, and the words request and users are also used interchangeably.

4.3 Computing the equilibrium bandwidth

A strategic form game is a tuple (A, S, u) for multi agents. Where: A = {1,2,…,a} is the set of agents from the first agent to the a^{th} agent; S = {S_1,S_2,…,S_a} where Si is the set of actions available to agent i; u = {u_1,u_2,…u_a} where u_i is the utility function for agent i (Fudenberg & Tirole, 1991). Such a game will yield an enormous number of payoffs that will be difficult to model if all the players A = {1,2,…a} have more than two strategies, as the total number of combinations in such a game will be a^n where a is the total number of players and n is the number of strategies available for each player. From their descriptions, the services can be broadly grouped into two, namely Time-sensitive (TS) services and Best Effort (BE) services, from which a two-player game is used to model the resulting arguments. For this first case, a two-agent game is modelled where each of the players has five strategies. Figure 14 shows a graph with up to five players, where each player has up to five strategies that they can play, and the resulting number of total payoffs for the entire system is well over 3000. A clearer picture is shown in Figure 15 where a logarithmic scale is used for the number of payoffs axes.

As the number of strategies increases, the total possible number of payoffs for the whole game increases exponentially. If there are two players each with two strategies, they will have a maximum of 4 possible payoffs, while the five players with five strategies each will have a maximum of 3125 possible payoffs as shown in Figure 15. Players TS and BE are used to model a two player game.

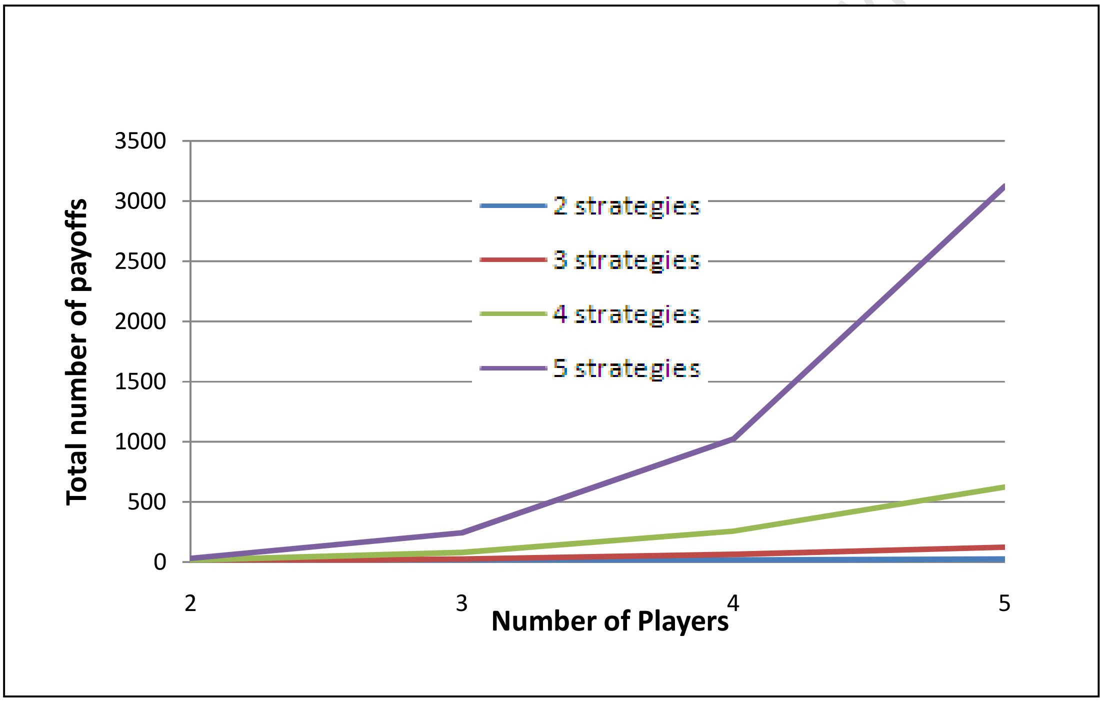

Figure 14: Total Number of payoffs on Players.

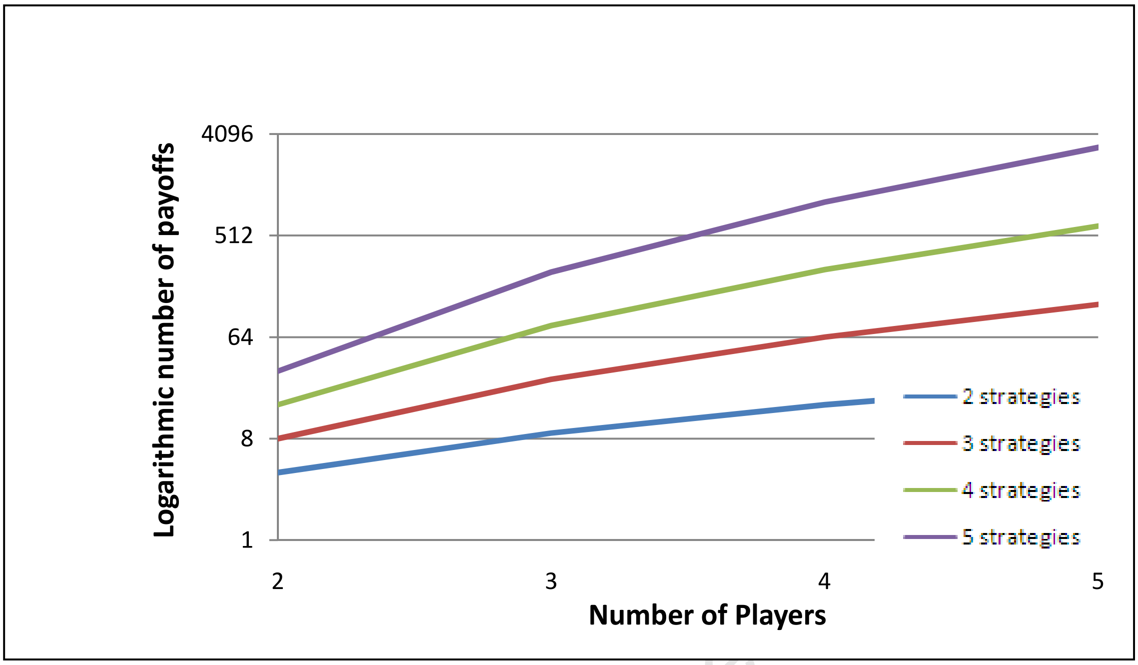

Figure 15: Logarithmic number of payoffs on Players

Treating the two TS and BE players as a duopoly (Gintis, 1997), (Rind, Shahzad, & Qadir, 2006), the TS player is established as duopoly leader and BE player as duopoly follower. Given the same number of requests, BE player thus is given 45% of the total bandwidth (this is arbitrary so as to establish TS service as the leader of the duopoly). This results with the relations: $S_1 = 0.45*TotalBandwidth$ and

$S_2 = 0.55*TotalBandwidth$, from where

$S_1 = 0.82S2$ (1)

At any given time, the total bandwidth available to both the players must be such that:

$S_1 + S_2 = TotalBandwidth$ (2)

Where S_1 is the bandwidth of BE player and S_2 is the bandwidth of TS player and TotalBandwidth is the maximum capacity available at the wireless router. By using the number of users as a determining factor for the allocation of fair bandwidth for the services at equilibrium, the bandwidth of the duopoly follower will be given by

$S_1 = Bt – Bt(r_2)/(r_1+r_2)$ (3)

Where Bt is the total bandwidth available at the wireless router, r_1 are the users for the BE service type and r_2 are the users for the TS service type.

Equation (3) reduces to

$S_1 = Bt(r_1)/ (r_1+ r_2)$ (4)

The fair equilibrium bandwidth for BE service type will be determined by the number of BE users and those of the TS service, implying if the call arrival rate of the BE service increase, then its allocated bandwidth should also increase ceteris paribus.

Strategies that can be used by the two players can then be formulated from this postulation. The fairness here is for the services to have an equitable amount of bandwidth at equilibrium, which should be commensurate with the number of users by each service

In (4), if Bt and r_1 are constant and r_2 increases to infinity, then S_1 reduces to 0, implying S_1 is inversely proportional to r_2. Also from (4)

$Bt = S_1(r_1+ r_2)/ r_1$ (5)

Looking at (3) and working with the duopoly leader,

$S_2 = Bt – Bt(r_1)/(r_1+r_2)$

This also reduces to

$Bt = S_2(r_1+ r_2)/ r_2$ (6)

Equating (5) and (6)

$S_1 / r_1= S_2 / r_2$

This also reduces to

$S_1 = S_2(r_1/ r_2)$ (7)

From (7), if r_2 increases with r_1 being constant, this should decrease S_1 as in (4). However, from (2), if S_1 decreases, S_2 should increase so as to maintain the total bandwidth. This relationship therefore implies S_1 and S_2 are inversely proportional if and only if either r_1 or r_2 increases or decreases with all other factors held constant.

A table with five strategies each of BE player and TS player is shown in Table 5, where the row strategies are for BE player while the column strategies are for TS player. The payoffs are expressed as a ratio correct to two decimal places, so that the virtual bandwidths for the two channels can be calculated from any given wireless router bandwidth. Equations (1), (2) and (7) were used to calculate the respective payoffs of the strategies in Table 5, which are a percentage of the total bandwidth that each of the services would get at equilibrium.

Table 5: BE and TS Player Payoffs

	BE **10** TS		BE **20** TS		BE **30** TS		BE **40** TS		BE **50** TS	
10	0.48	0.52	0.41	0.59	0.38	0.62	0.36	0.64	0.35	0.65
20	0.51	0.49	0.48	0.52	0.46	0.54	0.41	0.59	0.37	0.63
30	0.57	0.43	0.51	0.49	0.48	0.52	0.42	0.58	0.39	0.61
40	0.61	0.39	0.57	0.43	0.54	0.46	0.48	0.52	0.42	0.58
50	0.63	0.37	0.61	0.39	0.59	0.41	0.53	0.47	0.48	0.52

The minimum share for the TS player in Table 5 is 37% of the available bandwidth (strategy $S_1$5 and $S_2$1) and it occurs when BE has the maximum possible users while TS has the minimum possible users. The minimum share should be enough for any TS services that need a constant guaranteed bandwidth. The players are cooperative users, choosing their strategies with the knowledge of all other players' strategies and payoffs. It is a complete information cooperative game (Fudenberg & Tirole, 1991), (Gintis, 1997), where players desire the best result albeit with limited payoffs (Zhang, Sue, Peng, & Yao, 2010).

If say the TS player has 25 requests, the third column strategy will be selected, and if the BE player has 15 requests; the second row strategy will be selected. The payoff for the players is where column three intersects row 2, resulting with 46% of the bandwidth allocated to the BE channel and 54% of the bandwidth allocated to the TS channel.

4.4 Weighted request dominance

In Table 5, each of the players cannot use a mixed strategy, as the number of users cannot be in two different strategies at the same time. The players therefore always use pure strategies (Fudenberg & Tirole, 1991), (Hargreaves-Heap & Varoufakis, 1995).

The strategies are selected by weighted request dominance instead of the strict iterated dominance. In weighted request dominance, the strategy selected by a player is the one where the number of users for that player falls at that instant, not necessarily the strategy that gives the optimum utility. The relation

$u_i(s_i^*, s_{-i}) > u_i(s_i, s_{-i}),\ s_i \Leftrightarrow r_i,\ \forall s_i \in S_i,\ \forall_i\ r_i \in R_i$ (8)

holds , where s_i^*,is the fairest strategy used, which should be fairer than any other strategy when the number of users is r_i, and S_i is the strategy set used in Table 5.

The leader selects a strategy that will enhance fairness, and the follower does the same. This is a skewed Stackelberg choice, where instead of picking a strategy that maximizes bandwidth share, the leader does not necessarily utilize his first mover advantage, but selects a strategy that maximizes fairness (Fudenberg & Tirole, 1991), (Moya & Poznyak, 2009). The Stackelberg leader – follower is thus with respect to maximising bandwidth fairness, and not bandwidth share. The equilibrium payoff will therefore always change depending upon the number of users in each service. This kind of selection would result in fair allocation of resources, and is called Weighted Request Dominance for the purpose of this research.

In weighted request dominance, the payoffs of the strategies are aligned with the number of users in that strategy. If say player BE has the highest number of users with respect to possible expected users, then referring to Table 5, he would play strategy5 and if he has the least possible users, he would play strategy1. The number of users determines which strategy to play. The same principle would apply to TS player. Once a strategy has been selected, the allocation of the virtual channels would be done according to the equilibrium payoff of the selected strategy.

4.5 Rationalisability with fairness

If BE has the highest possible users, he would not play a strategy that would not give him the highest possible payoff, as this is not what a rational player would do (Fudenberg & Tirole, 1991), (Hargreaves-Heap & Varoufakis, 1995), (Gintis, 1997). If TS on the other hand has the least possible users and knows that BE has the highest possible users, he should expect that BE would play the strategy that gives him the highest possible payoff. To be fair, TS would play the strategy that gives him the least possible payoff, knowing that if he had the highest possible users, he would play the strategy that gives him the highest possible payoff whilst if BE had the least possible users, he would play the strategy that gives him the least possible payoff. This way both the players play rationally all the time and this enhances their fairness (Zhang, Sue, Peng, & Yao, 2010).

At each instant, the bandwidth requests of each service would be different, but they are such that each and every service at that instant is aware of the bandwidth requests of the other services. A fairly rational player would therefore never play a strictly dominated strategy, nor would he always play a strictly dominating strategy (Hargreaves-Heap & Varoufakis, 1995). In Table 5, the leader can be tempted to always play the strategy with the highest number of users as from equation (7), it should give him the highest payoff. If the follower is also selfish and plays a strategy that gives him the highest possible payoff regardless of the users he has, then both the players will always have equilibrium with the 0.48 and 0.52 payoffs for BE and TS respectively. This will give an unfair advantage to BE as his few users enjoy an abundance of bandwidth compared with the 0.35 which they should have had if BE had played fairly (strategy $S_1$1 and $S_2$5, first row and fifth column in Table 5). Conversely, If TS has the minimum number of users and selfishly plays the maximum users; this will mean BE now gets a share of 0.48 if he has the maximum users instead of the 0.63 had TS played fairly (strategy $S_1$5 and $S_2$1, fifth row and first column in Table 5).

For players to be rationally fair, they play a strategy that they would want the other to play if they were in their position. A rationally fair player should thus use only those strategies that are the fairest responses to some belief they may have about strategies of their opponents, and would not play a strategy that is not a fair response to what they believe about their opponent's strategies. Since a player knows their opponent's payoff, and knows that they are rational, he should not have any doubts about their choice of strategy, nor should the opponent have a doubt about the first player's choice of strategy.

For the two player game modelled in Table 5, this becomes an infinite loop that has the form: " I am playing strategy S(i) because I think player two is using strategy S(ii), which is a reasonable belief because I would play it if I were player two and thought player one was using strategy S(`i), which is a reasonable thing for player two to expect because strategy S(`i) is a best response to strategy S(`ii), this goes on and on" (Fudenberg & Tirole, 1991)

Players make their prediction of how the other players would play by making use of introspection and deduction, using their knowledge of the opponents' number of users. The fact that each of the players is rational and all other players in the game know this knowledge implies that an infinite ingress would result out of this common knowledge, and in Table 5, each of the players would always be rationally fair (Fudenberg & Tirole, 1991).

4.6 The fairness algorithm

The payoff will be the size of the virtual channel allocated to a service at equilibrium. It should be possible that some users can be serviced quicker than others can, or some players may have very few requests although others are overburdened with requests. This can lead to a scenario where some channels may have very few users while other channels are still heavily loaded with users (Wang, Cui, Xu, Huang, & Liu, 2009).

If a service's virtual channel is full, request on that service should be allotted to the next least full virtual channel in order of priorities if the services arrive / are requested at the same time.

Figure 16 illustrates the two thresholds in each of the five virtual channels for the five services, where threshold 1 is the maximum capacity in any channel before users can be processed in other channels and threshold 2 is the maximum capacity of foreign users in a channel.

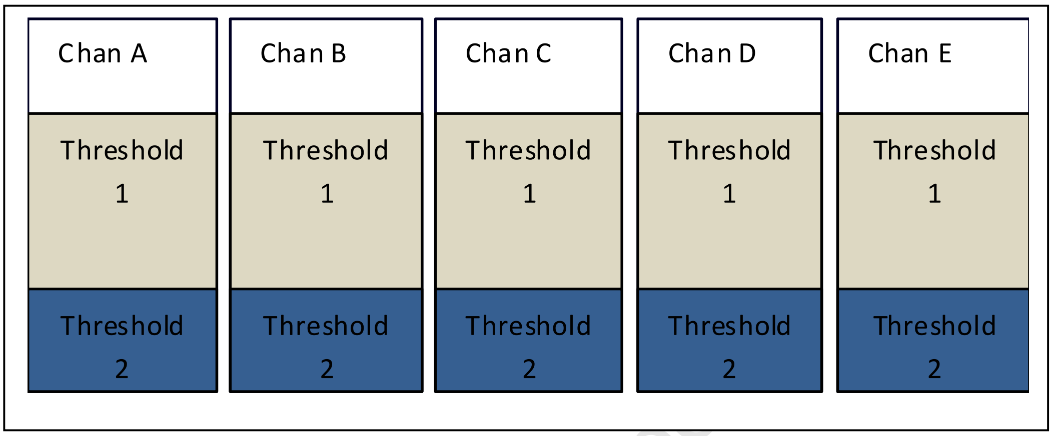

Figure 16: Virtual Channels

For example, if the threshold 1 of virtual channel A has been reached, then the next allocation for a service of channel A would perform as follows:

First, assign the channel A capacity to some variable called target channel.

If the total free capacity of channel B is greater than target channel and capacity of service A on virtual channel B is less than threshold 2, then

Target channel = virtual channel B

This logic is the same for all the other channels.

After any of the virtual channels has reached threshold 1, the proposed scheme would select the virtual channel with the largest free capacity as the channel to be used. This will enhance the fairness of bandwidth utilisation and avoid a situation where one channel is completely used up while other channels are idle.

Once a request comes through the wireless router, the first thing will be to ensure that the native channel has enough capacity and then select it as the target channel, otherwise the algorithm will select the channel with the biggest capacity as the target channel. The flowchart in Figure 17 illustrates the algorithm.

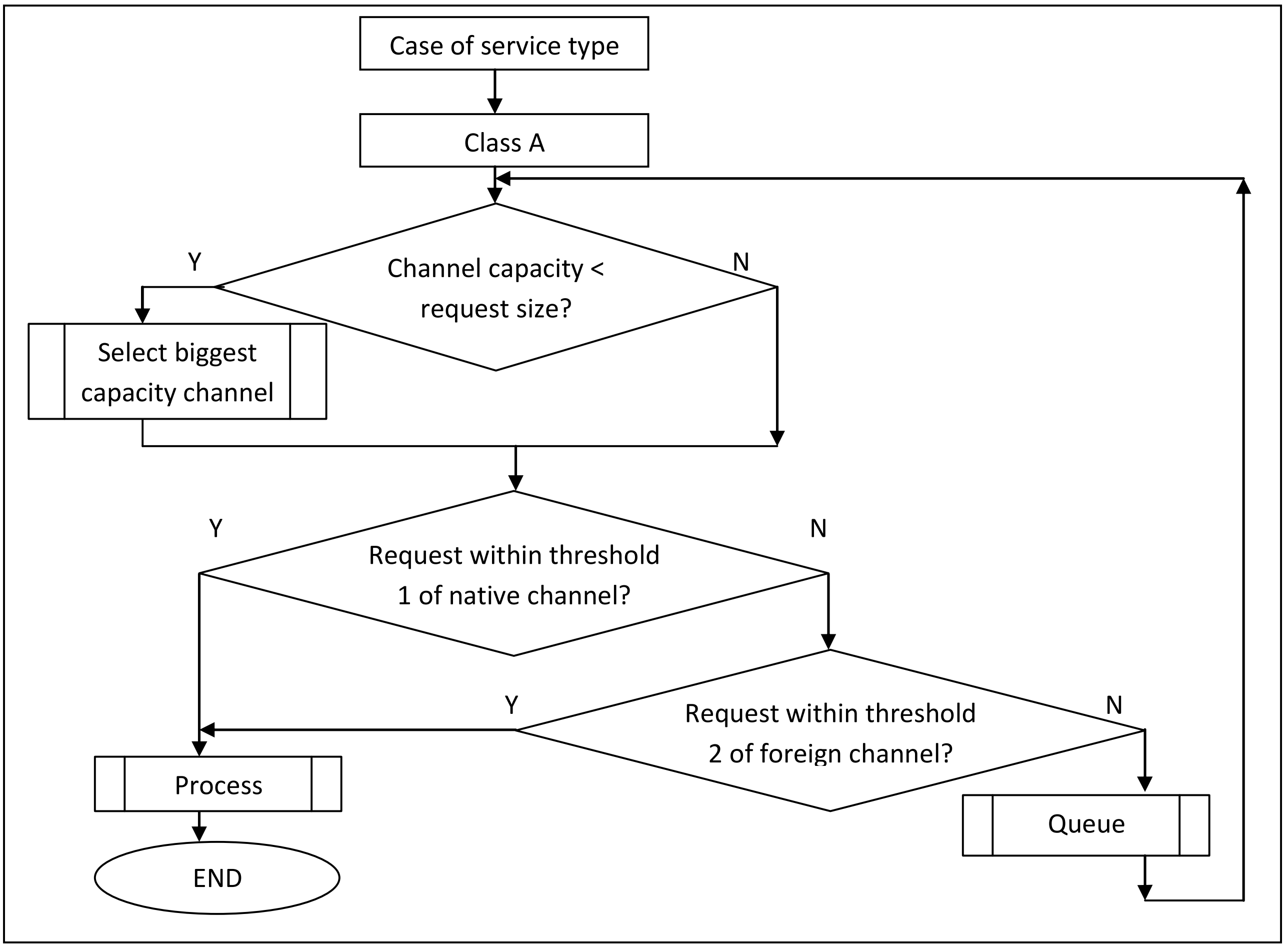

Figure 17: Flow chart for Fairness Algorithm

The sequences of events are shown in Figure 18, where a request can either be processed in its own native channel or processed in a foreign channel. Figure 18 also shows where the resources are obtained and where those resources would be returned upon completion of processing a request.

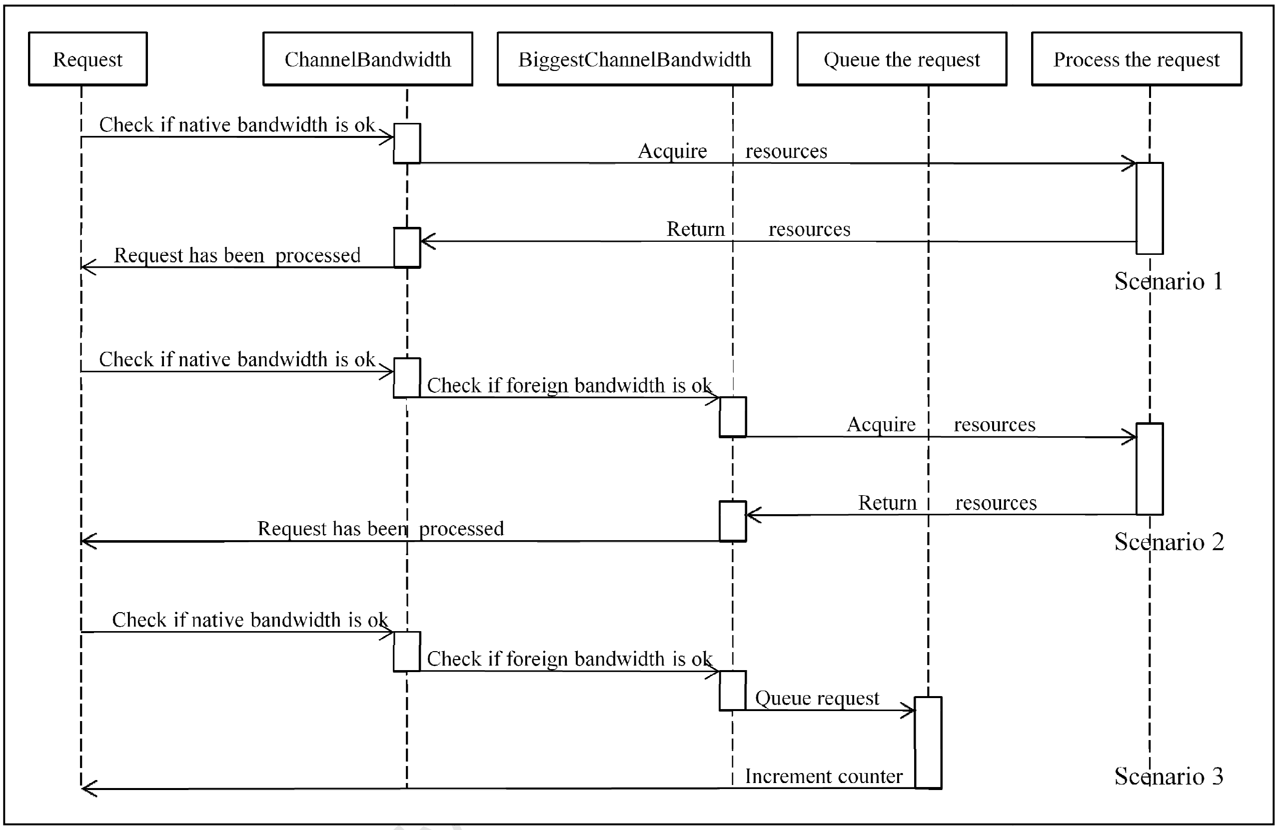

Figure 18: Sequence diagram for processing a request.

For example in scenario 1, a request finds enough capacity in its native channel and is processed by the native channel. After processing the request, the resources are returned to the native channel.

4.7 Chapter summary

In Chapter 4, the mathematical basis of the weighted request dominance algorithm was developed and followed up by implementing the logic of the algorithm. Game theory concepts were infused that resulted into a table of a strategy set from which the fairness of the inter service bandwidth sharing scheme is based.

5 Simulations and evaluation of Results

5.1 Foreword

In this chapter, the performance of the proposed scheme is evaluated. The following assumptions are made in the performance evaluation:

(i) There is always a user request on a service

(ii) The call arrivals are in a Poisson Distribution

(iii) Requests have different durations

(iv) Requests have different packet sizes

(v) Channels would vary sizes determined by the strategies that would have been played.

Analysis of the results confirms the hypothesis stated in Section 1.5, which set out to investigate a mechanism that equitably shares resources with respect to services and the number of requests on those services.

5.2 Evaluation of results

Simulation has been used to evaluate the results. The results obtained are then compared with that of other research outputs. The simulations are carried out in Java, using multithreading for the processing of different services.

Computer hardware requirements used:

300 G hard drive

Pentium 2.4G processor

2 Gigabytes RAM

32 bits

Software requirements used:

Windows XP Professional

Java Development Kit 1.7.0 standard edition

Experimental setting:

Packet size range	100 bytes to 1000 bytes
Packet duration range	100ms to 5 seconds
Channels	5

5.3 Simulation using Game Theory and Java

Game theory basics have been alluded to in Section 2.2, from where a mathematical game theory model has been developed in Section 4.3, which is the basis of an algorithm that has been implement in Java to emulate the improvement in inter service bandwidth. The results thereof have been compared with similar schemes in the research community. Java makes use of multithreading, where the various services are threaded. Each thread, representing a channel then processes a request and upon finishing, the resources of that thread and by extension the resources of the channel are released for use by other requests.

5.3.1 Overview of Evaluation framework

In Section 4.3, a two-player game and a five-player game are analysed. For the two-player game, a request from each of the two players is processed on a thread. Resources are allocated to the thread for processing the request and upon completion, resources are returned. This way, resources of requests that are processed sooner are brought back to the pool in order to be used by other requests and players. This has an effect of enhancing the fairness of the scheme.

5.3.2 Validation of results

Some of the results obtained from this research have been published as conference papers in conference proceedings (Moyo, Falowo, & Dlodlo, 2012), (Velempini, Moyo, & Dlodlo, 2012).

5.3.3 Simulation scenarios

For simulation scenarios, the first player average packet size is 200 bytes, and the average processing time 10 seconds. The second player average packet size is 500 bytes with an average processing time of 15 seconds. In this case player two has more priority than the first player according to the duopoly dictates (Gintis, 1997). The details of the simulation are elucidated in Chapter 4.

5.4 Analysis of results

In Figure 12 (Wang, Cui, Xu, Huang, & Liu, 2009), the bandwidth of service 2 remains constant while service 1 bandwidth decreases with an increase in the average call arrival rate of service 2. This is consistent with the approach as stated in equation (7). Figure 19 and Figure 20 confirm that the total bandwidth of the services at any time should be equal to the total bandwidth available in the wireless router. The data for the figures comes from Table 5.

On each of the graphs in Figure 19 through to 23, TS player would have selected a constant strategy, regardless of its requests. The bandwidth share of the TS player is observed to deteriorate as BE player changes strategies commensurate with the increasing call arrival rate.

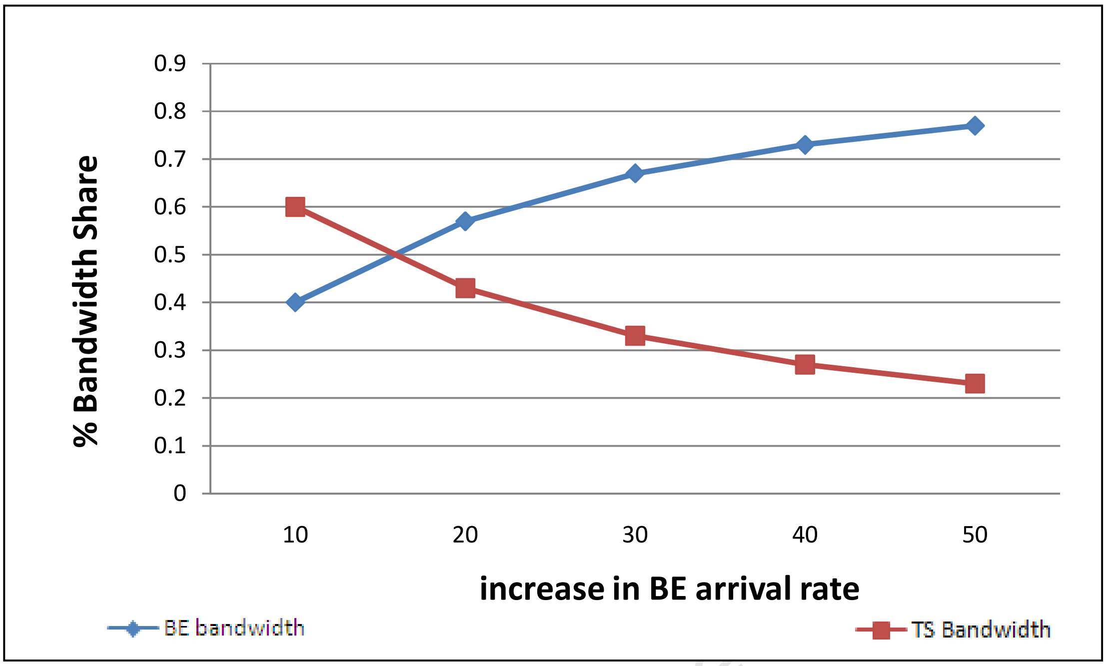

Figure 19: Distribution at TS constant (10), increasing BE arrivals

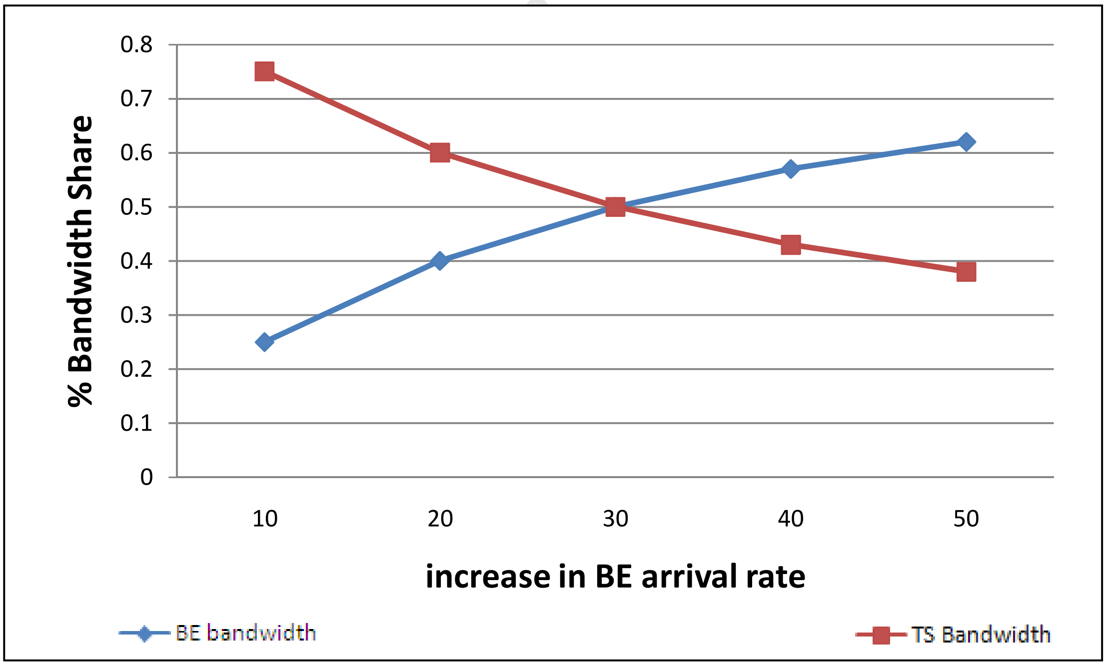

Figure 20: Distribution at TS constant (20), increasing BE arrivals

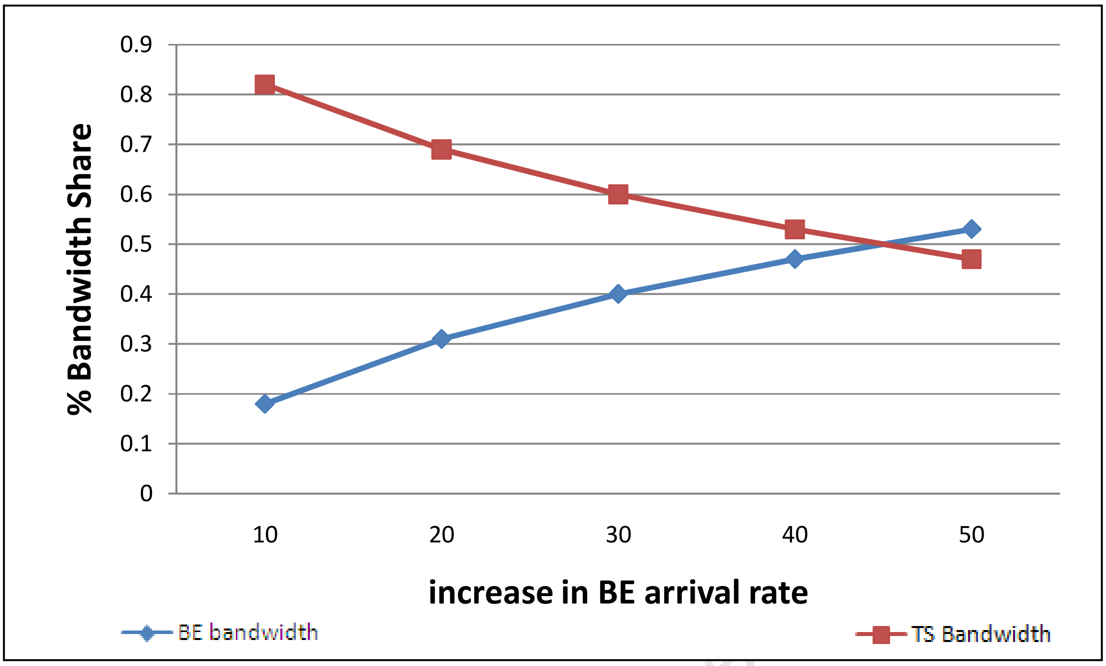

Figure 21: Distribution at TS constant (30), increasing BE arrivals

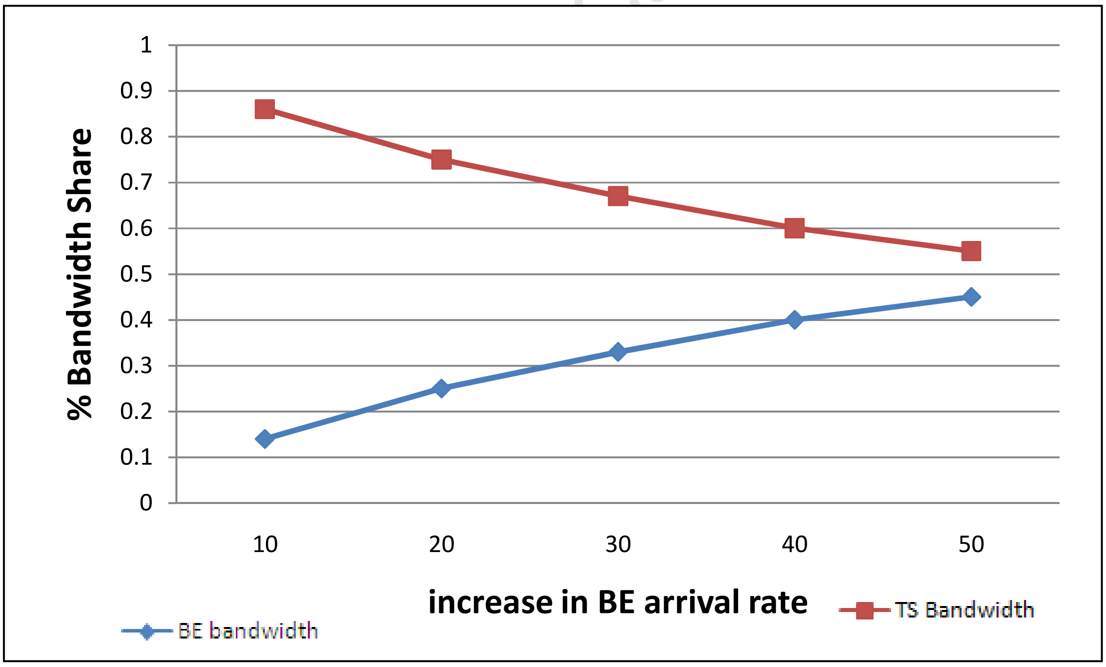

Figure 22: Distribution at TS constant (40), increasing BE arrivals

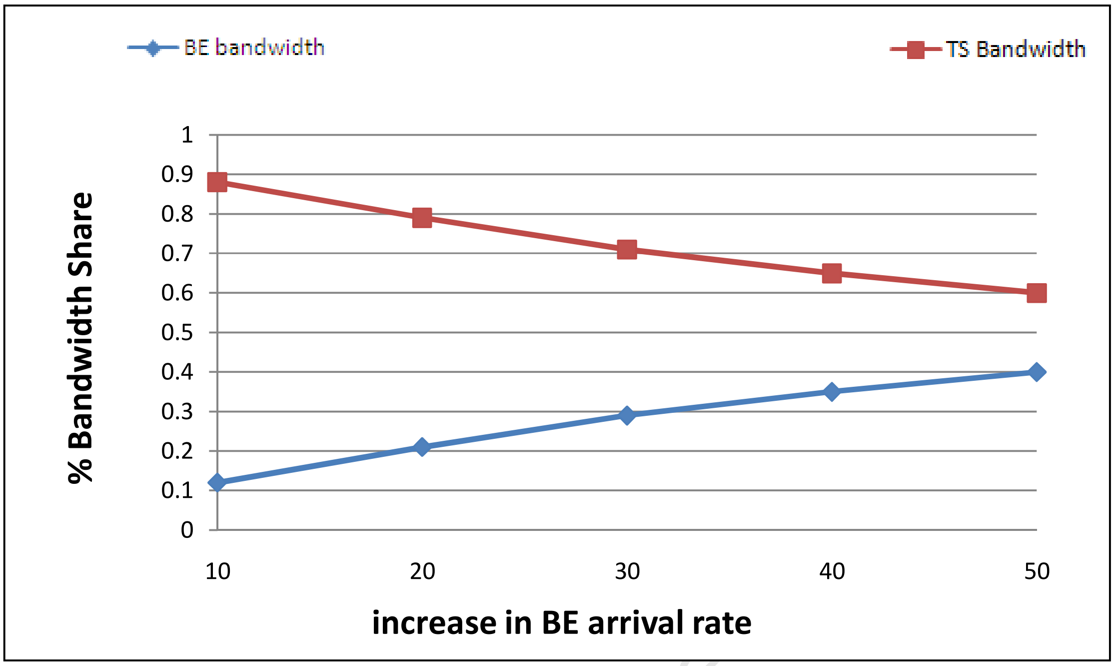

Figure 23: Distribution at TS constant (50), increasing BE arrivals

Across Figure 19 through to Figure 23, if TS player starts with a strategy that is biased towards a high call arrival rate, then the initial bandwidth share increases accordingly.

The players should thus not have static strategies, as this can always disadvantage a player or always give a player an unfair advantage.

By taking the payoff of each service from Table 5 and using it as the average for that service at the given call arrival rate, call blocking probabilities (CBP) can be calculated to show the relationship of the services, where the request are assumed to arrive at a poison distribution. The call blocking probability is calculated as:

$$CBP = (\lambda^{x}e^{-\lambda})\ (x!)^{-1} \qquad (9)$$

Where λ is the average number of requests in a given strategy and X is the instantaneous number of requests, which must fall in the requests range of that strategy.

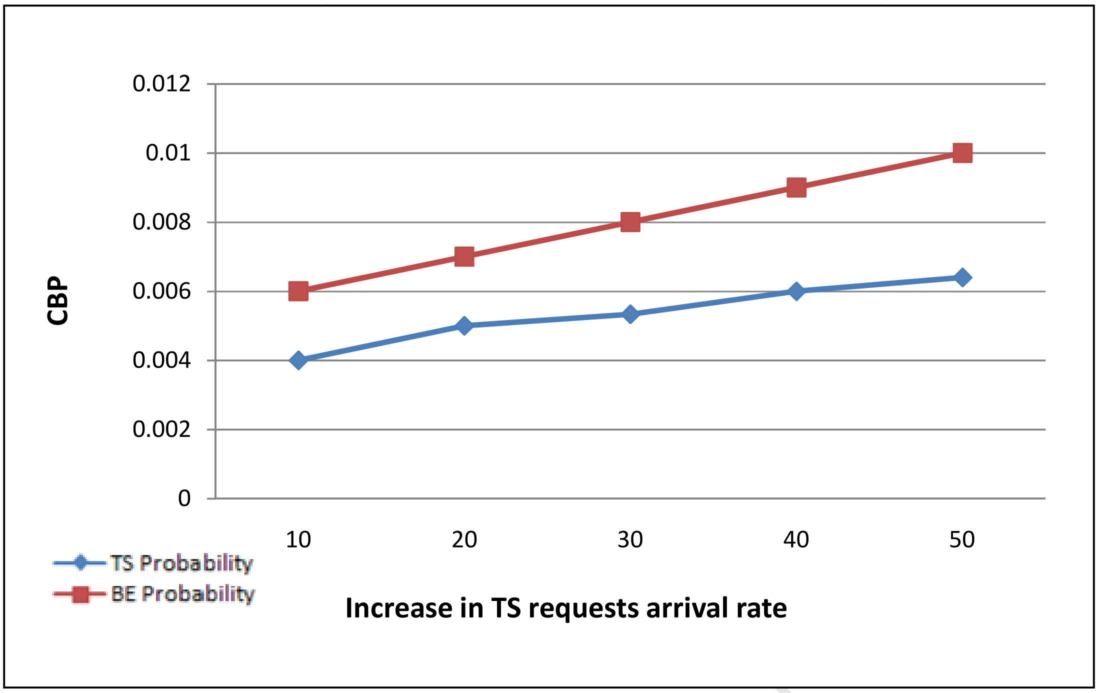

Figure 24: CBP at constant BE service (10), increasing the call arrival rate of the TS service up to 50.

In each strategy, the bandwidth share of the players is set, and as requests of any player increase, it increases the call blocking probability of that player. This is illustrated in each of the graphs in Figure 24 and Figure 25.

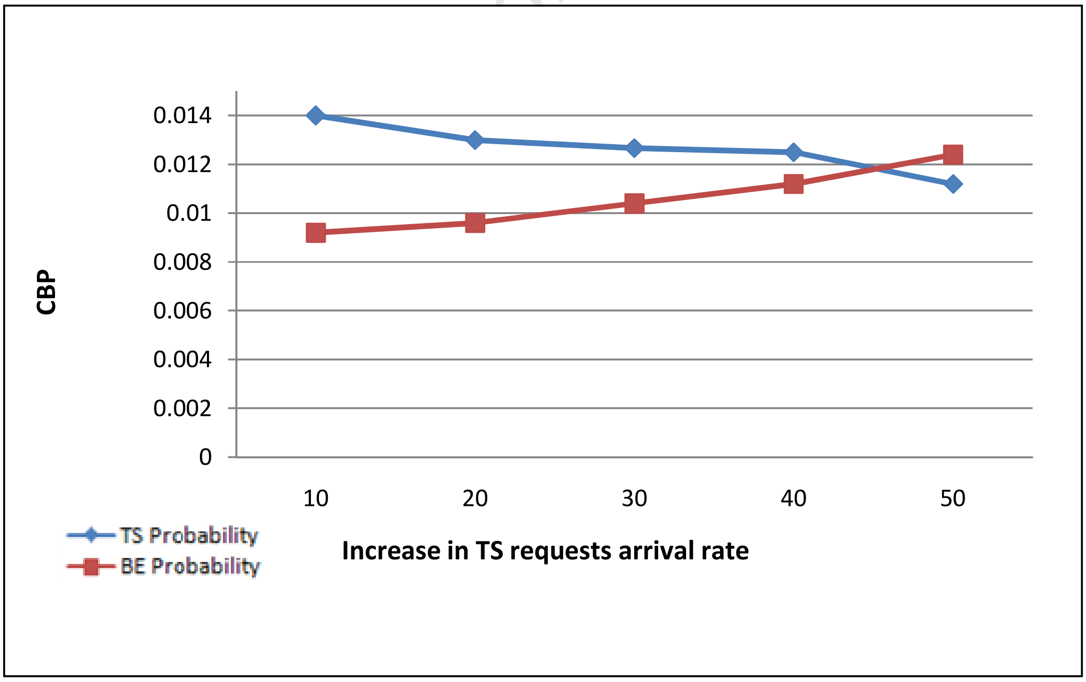

Figure 25: CBP at constant BE service (50), increasing the call arrival rate of the TS service up to 50.

If the requests of the BE player are constant, then a surge of requests of the TS player will cause the equilibrium to shift to the right in Table 5, and this improves the bandwidth share of the TS player. This is illustrated across the graphs in Figure 24 and Figure 25.

For the case of five channels, two strategies per channel were used so as to minimise on the permutations to be modelled to $2^5 = 32$. Figure 26 shows the channel capacities to be within 2.5% of each other, showing that they equitably share the available bandwidth fairly in such a way that there is no one channel that is completely used up while other channels would be idle.

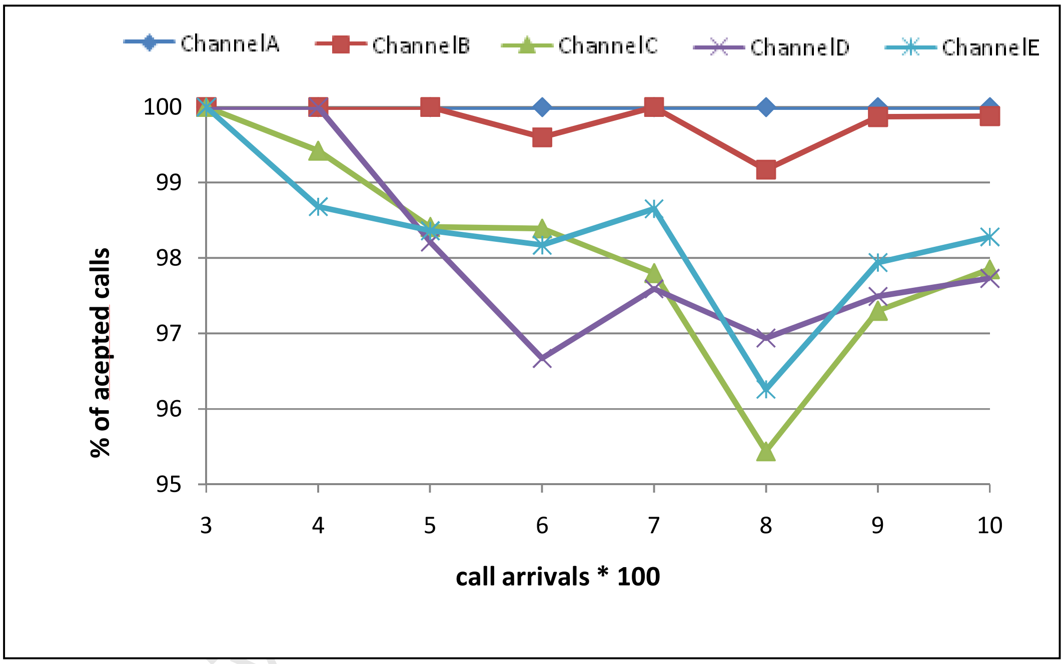

Figure 26: Comparison of five services.

5.5 Chapter summary

Improvements on the understanding of fairness with respect to inter service bandwidth fairness were introduced by incorporating the number of requests in a service to be also part of the fairness criteria. The results in Chapter 5 show the effects of these improvements.

6 Conclusion and Future work

6.1 Conclusion

From this research, it was noted that the current bandwidth sharing schemes do not consider the number of request in a service, but mainly concentrate on the number of users in order to determine fairness sharing schemes. The research therefore sought to introduce a scheme that will make use of the number of requests for the different types of requests.

Results indicate that the proposed scheme does reduce the call-blocking rate proportionate to the increase in number of requests for a player, thus enhancing the fairness among various services that compete for the same resource with respect to the number of requests in a service.

The use of more strategies for the increased number of services is likely to add more processing time, which may increase delay times. Future research would include looking into ways of minimizing delay times whilst as the same time enhancing the fairness of bandwidth sharing amongst different services.

This work therefore answers one of the leading research questions of introducing a new technique into the insights of improving fairness in bandwidth management schemes, where the number of requests in a service group and the number of service groups are included to determine a fair resource allocation scheme.

The objectives of the study have also been met in that a mathematical model was established in Chapter 4, which was used as the basis of the weighted request dominance fairness algorithm to improve inter service bandwidth sharing at the access link of the WMN.

This research has shown that it is possible for a number of services to have an equilibrium bandwidth based on the number of requests in each service that is such that each of the services has an optimum bandwidth. The weighted request dominance algorithm of Chapter 4 and the results of Chapter 5 showed this, thus proving the first hypothesis of Section 1.5

The strategy that gave the equilibrium bandwidth has been proven the most fair for services sharing the bandwidth resource as shown in Chapter 5 by the fact that all the competing service channel capacities were within 2.5 % of each other. This also confirmed the second hypothesis were the skewing of bandwidth use by the services was avoided as the channels shared their idle capacities.

6.2 Future work

With the continued shortage of spectrum (Ghasemi & Hosseini, 2010), (Stroup, 2011), (Merritt, 2012), future research will be aligned to cognitive radio networks, which are radios equipped with the ability to sense and make use of idle spectrum. The continued use of wireless broadband hinges on the availability of spectrum. Spectrum is a natural resource, which like any other natural resource can be exhausted. However spectrum can be reused repeatedly, which can thus open ways for new technologies like cognitive radios. The wireless network can thus be used to continue providing ubiquitous connectivity once spectrum is available for expansion for old telecommunications players and new telecommunications players who may mainly focus on secondary use of the spectrum.

Some spectrum licensing authorities do not move at the pace of technology developments, thus leaving spectrum unlicensed or poorly used (Vermeulen, 2012). Cognitive radios can overcome this limitation and make use of such spectrum, thereby making a provision for the improvement of capacity in wireless networks.

To this end, collaboration with other researchers (Velempini, Moyo, & Dlodlo, 2012) has been made, looking into improvements of spectrum sensing by use of cognitive collaborators to work in conjunction with cognitive radios. The idea here is to have radios that are within reach to work in such a way that one radio is mainly focused on data transmission whilst the other radio is focused on spectrum sensing. Various players compete for the sensed available unutilized radio spectrum in order to effectively utilize the available bandwidth.

The initial results indicate optimisation of spectrum sensing that results to benefits for all nodes, which will further improve the QoS for all the services at the access network. Further interesting research issues will be in improving the reliability of mobile cognitive collaborators, which should ultimately further improve the inter service bandwidth fairness in wireless mesh networks.

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Appendix A: Channel Selections

A.1: selecting the correct channel for a request

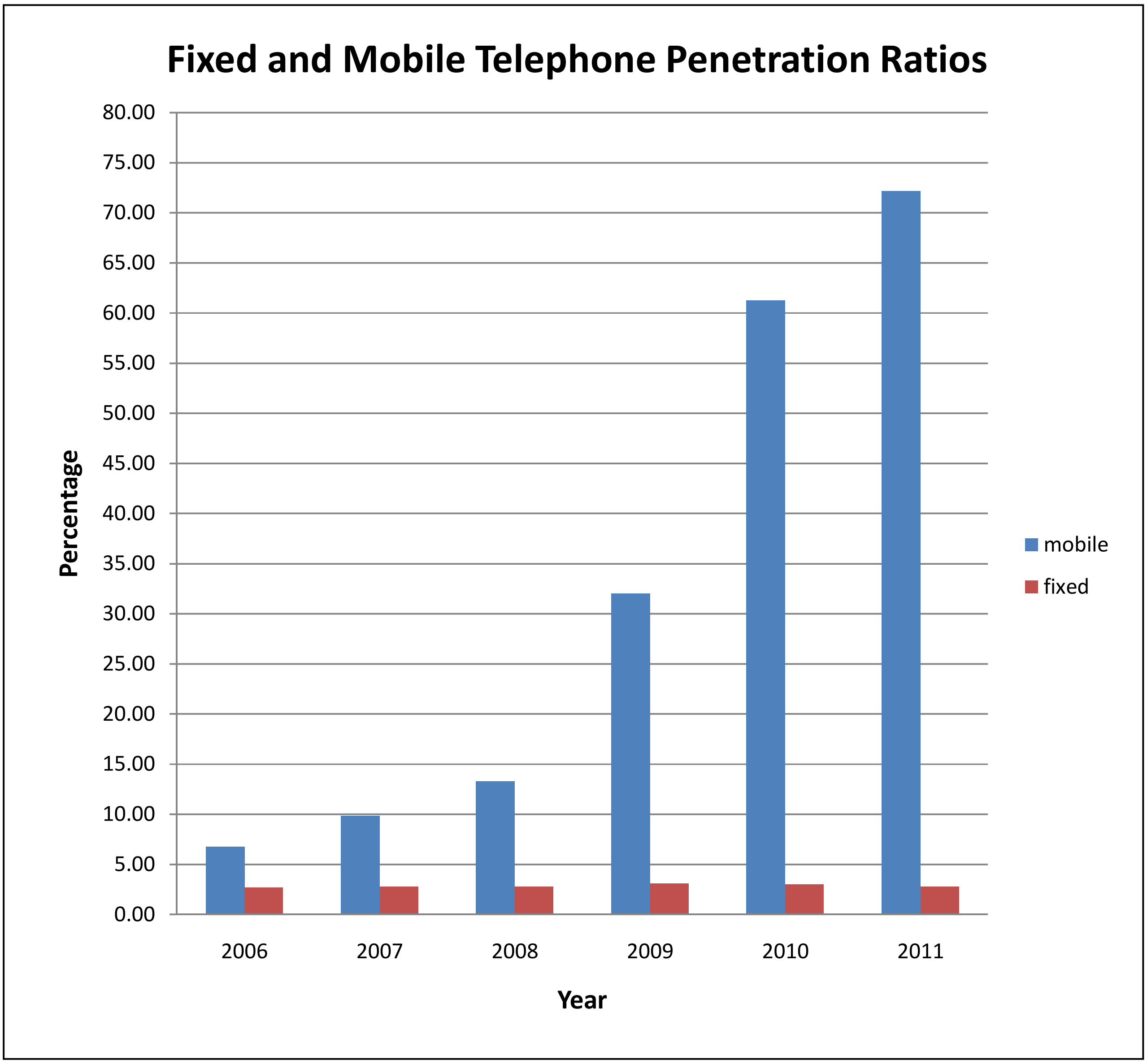
```
if (channel[chan].getChannelCapacity() < request[req].getRequestCapacity()) //to select which service to u
 {
   chan = biggest(channel, request, req);
 }//this null if statement will ensure that if the selected channel does not have enough capacity,
   //then the channel with the biggest capacity will be selected

if ((channel[chan].getChannelCapacity() >= request[req].getRequestCapacity()) &&
     ((channel[chan].getChannelType()).equals(request[req].getRequestType())))
{  //when the capacity is enough, AND the request type and channel types are the same, we process
  //else it is a foreign channel, for which we need to make sure that threshold 2 is satisfied
  process = true;
}//end of case when own channel is chosen
else
{
    if ((channel[chan].getChannelType()).equals( "TS"))
    {
        if ((channel[chan].getChannelCapacity() >= request[req].getRequestCapacity()) &&
            (channel[chan].getChannelCapacity()> threshold * channelCapacities[0]))
        {
            process = true;
        }
    }//end of if for when the channel was TIMED

    else if ((channel[chan].getChannelType()).equals( "BE"))
    {
     if ((channel[chan].getChannelCapacity() >= request[req].getRequestCapacity()) &&
        (channel[chan].getChannelCapacity()> 0.1 * channelCapacities[1]))
        {
            process = true;
        }
    }//end of if for when the channel was BE
}//end of case when foreign channel is chosen
```

A.2: Selecting the biggest available channel

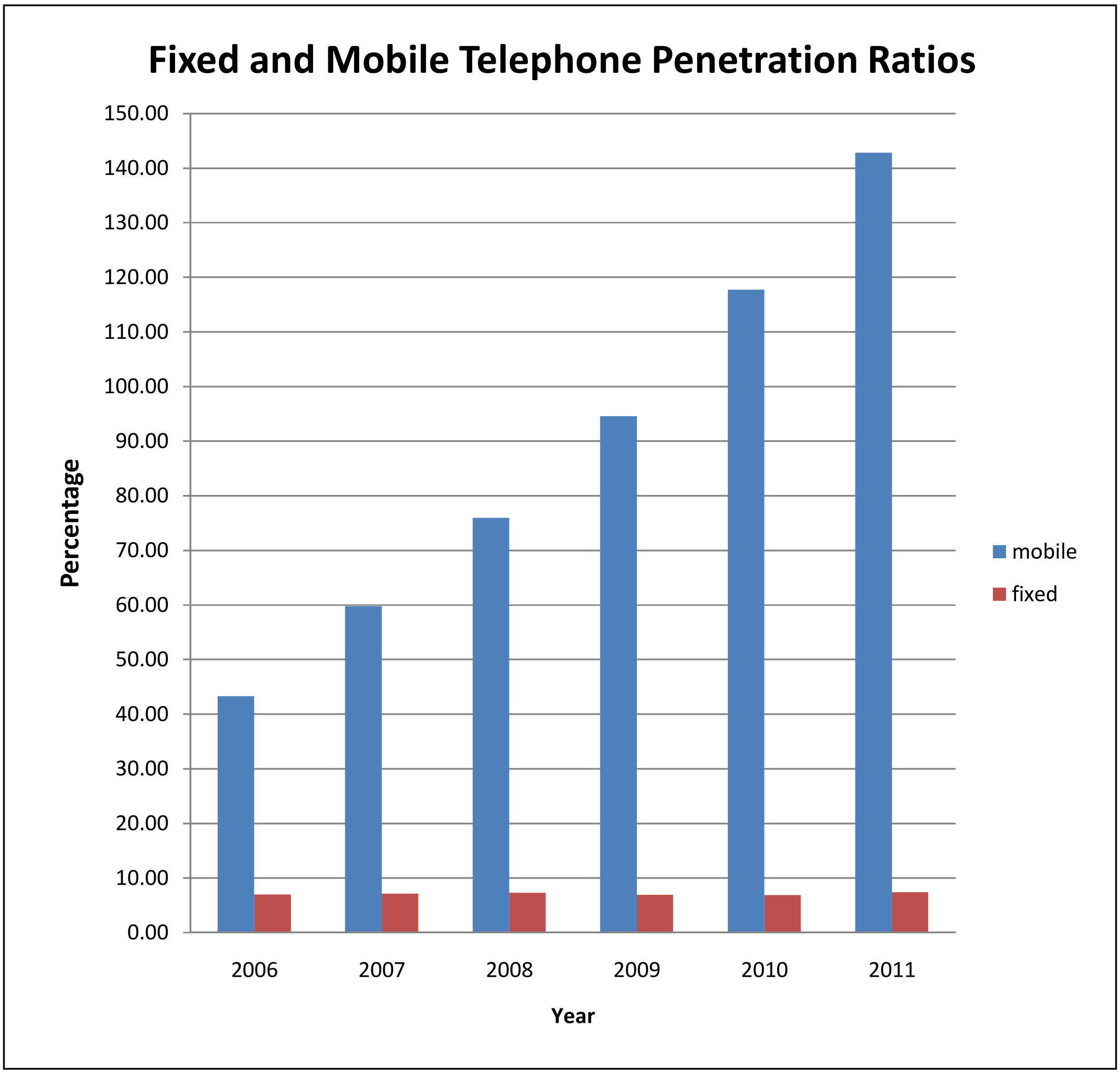
```
//function to determine the channel with the largest capacity
public int biggest(ServiceChannel[] channel, Request[] request, int req, int numOfChannels)
 {

   int targetChannel = 0;
   int biggestCapacity = 0;

   for (int channelCounter = 0; channelCounter < numOfChannels; channelCounter++)
   {
       if (channel[channelCounter].getChannelCapacity() > biggestCapacity)
       {
           biggestCapacity = (channel[channelCounter].getChannelCapacity());
           targetChannel = channelCounter;
       }
   }

   return targetChannel;
 }//end of function to determine the channel with the biggest  capacity
```

Appendix B: Penetration Ratios

B.1: Penetration Ratios in Zimbabwe, a developing country



B.2: Penetration Ratios in Botswana, a developing country



B.3: Penetration Ratios in Japan, a developed country