

Enhancing cooperation in wireless networks using different concepts of game theory

Pervaiz, Haris

For additional information about this publication click this link.

<http://qmro.qmul.ac.uk/jspui/handle/123456789/2529>

Information about this research object was correct at the time of download; we occasionally make corrections to records, please therefore check the published record when citing. For more information contact scholarlycommunications@qmul.ac.uk

Enhancing Cooperation in Wireless Networks Using different concepts of Game theory

Haris Pervaiz

A thesis submitted to University of London in partial
fulfilment of the requirements for the degree of
Master of Philosophy

School of Electronic Engineering and Computer Science
Queen Mary, University of London

2011

Abstract

Optimizing radio resource within a network and across cooperating heterogeneous networks is the focus of this thesis. Cooperation in a multi-network environment is tackled by investigating network selection mechanisms. These play an important role in ensuring quality of service for users in a multi-network environment. Churning of mobile users from one service provider to another is already common when people change contracts and in a heterogeneous communication environment, where mobile users have freedom to choose the best wireless service-real time selection is expected to become common feature. This real time selection impacts both the technical and the economic aspects of wireless network operations. Next generation wireless networks will enable a dynamic environment whereby the nodes of the same or even different network operator can interact and cooperate to improve their performance. Cooperation has emerged as a novel communication paradigm that can yield tremendous performance gains from the physical layer all the way up to the application layer. Game theory and in particular coalitional game theory is a highly suited mathematical tool for modelling cooperation between wireless networks and is investigated in this thesis.

In this thesis, the churning behaviour of wireless service users is modelled by using evolutionary game theory in the context of WLAN access points and WiMAX networks. This approach illustrates how to improve the user perceived QoS in heterogeneous networks using a two-layered optimization. The top layer views the problem of prediction of the network that would be chosen by a user where the criteria are offered bit rate, price, mobility support and reputation. At the second level, conditional on the strategies chosen by the users, the network provider hypothetically, reconfigures the network, subject to the network constraints of bandwidth and acceptable SNR and optimizes the network coverage to support users who would otherwise not be serviced adequately. This forms an iterative cycle until a solution that optimizes the user satisfaction subject to the adjustments that the network provider can make to mitigate the binding constraints, is found and applied to the real network. The evolutionary equilibrium, which is used to

compute the average number of users choosing each wireless service, is taken as the solution.

This thesis also proposes a fair and practical cooperation framework in which the base stations belonging to the same network provider cooperate, to serve each other's customers. How this cooperation can potentially increase their aggregate payoffs through efficient utilization of resources is shown for the case of dynamic frequency allocation. This cooperation framework needs to intelligently determine the cooperating partner and provide a rational basis for sharing aggregate payoff between the cooperative partners for the stability of the coalition. The optimum cooperation strategy, which involves the allocations of the channels to mobile customers, can be obtained as solutions of linear programming optimizations.

Acknowledgement

First of all, I would like to thank Allah Almighty for giving me strength to go through the hardships of life. I would like to express my deep and sincere gratitude to my parents and my supervisor, Dr. John Bigham for his helpful advice and direction throughout the entire work. His wide knowledge and logical way of thinking have been of great value for me. His understanding, encouraging and personal guidance have provided a good basis for the present thesis.

I would also like to thank all the staff of the School of Electronic Engineering and Computer Science especially Melissa Yeo for creating the welcome environment and give me so much help during my stay.

I would like to thank the colleagues and friends I met at the school, specially, Jiayi, Peng, Haibo Mei, Bushra, Sobia and Qammar Abbassi for the good times, friendship and help. Finally, with my love and gratitude, this thesis is dedicated to my family. Without their persistent support and encouragement, I cannot imagine I would be able to complete my studies.

Table of Contents

Abstract	2
Acknowledgement	4
List of Abbreviations	9
List of Figures	11
List of Tables	13
1 Introduction	15
1.1 Problem	15
1.2 Contribution	16
1.3 Research Aims.....	18
1.4 Novelty	19
1.5 Organisation of the Thesis.....	20
2 Multi-Criteria Decision Making (MCDM)	22
2.1 Features	22
2.2 Representation of MADM problem	23
2.3 Review of MADM methods	23
2.3.1 Simple Additive Weighting	24
2.3.2 Multiplicative Exponent Weighting.....	25
2.3.3 Grey Relational Analysis	25
2.3.4 Technique for Order Preference by Similarity to Ideal Solution	26
2.3.5 Elimination and Choice Translating Priority	28
2.4 Summary	30
3 The Analytic Hierarchy Process	32
3.1 Formulate the Problem	32
3.2 Determine the Relative Weights of the Comparison Attributes.....	32
3.2.1 Calculate the Eigen value and Eigen vector	34
3.3 Perform the consistency index	36
3.4 Calculate the overall level hierarchy weight to select the candidate.....	36
3.5 Worked Example.....	37
3.6 Heterogeneous wireless network model.....	39
3.6.1 Wi-Fi-/WiMAX network selection case	41
3.7 Disadvantages of AHP	47
3.8 Summary	48
4 Multi-Criteria Decision Making (MCDM) for network selection	49
4.1 Assumptions	49
4.2 Related work	50
4.3 Network Selection Modelling using MCDM method	59
4.4 Formulation of Network selection.....	61
4.4.1 Goal.....	62
4.4.2 Alternative or Candidate networks	63
4.4.3 Considered attributes	63
4.5 User Model.....	64
4.5.1 User Payment Plan.....	64
4.5.2 Assigning attribute preferences.....	64
4.5.3 Assigning application preferences	65

4.5.4	Assigning network preferences	66
4.5.5	Calculating the weight of each attribute	66
4.6	Network Model	72
4.7	Worked Example.....	75
4.8	Realistic Scenarios	78
4.8.1	Home scenario	79
4.8.2	Walking from home to the Supermarket scenario	82
4.9	Computing the payoff for each user	87
4.10	Sensitivity Analysis	88
4.11	Summary.....	89
5	Cooperating Heterogeneous Networks	91
5.1	Assumptions	91
5.2	Related Work.....	92
5.2.1	Overview of Dusit Niyato Approach	93
5.2.2	Advantages of the proposed approach	98
5.3	Internetworking Architecture	99
5.4	System Model.....	100
5.5	Heterogeneous Wireless Networks Re-configuration using Coverage Adjustment.....	101
5.5.1	Formulation of Network Selection Game	102
5.5.2	Calculating each criterion value offered by candidate network.....	103
5.5.3	User received payoff calculation	105
5.5.4	Evolutionary Network Selection using Inverse Rank	106
5.5.5	Selecting a user	109
5.6	Performance Evaluation of Inverse Rank Approach.....	111
5.6.1	Parameter Settings	112
5.6.2	Numerical Results.....	112
5.6.3	Results of Dusit Niyato's Evolutionary game theoretic approach.....	119
5.6.4	Comparison between Inverse rank and Dusit Niyato approach.....	124
5.6.5	Dynamic Behaviour of Users.....	128
5.6.6	Stability of Evolutionary equilibrium	129
5.7	Summary	130
6	Game Theory Concepts.....	133
6.1	Coalitional Game Theory	133
6.1.1	Basic Definitions.....	133
6.1.2	Types of coalition game.....	134
6.1.3	Payoff distribution methods.....	136
6.1.4	Modelling Resource Management as Standard Bankruptcy model.....	139
6.1.5	Coalition formation process	141
6.1.6	Stable partitions	147
7	Investigating the concept of Coalitions of Base stations	151
7.1	Related Work.....	152
7.2	Optimal Frequency Allocation as a coalitional game	152
7.2.1	Problem Formulation	153
7.2.2	Searching through Coalition Structures	156
7.2.3	Distribution of coalitional value among the members	165

7.2.4	Proposed Experiment	167
7.3	Inter-Provider cooperation (Dynamic Spectrum Access case)	169
7.3.1	Example of Cooperation between different providers	171
7.4	Summary	174
8	Conclusion and Discussion	177
8.1	Conclusion.....	177
8.2	Future Directions.....	178
	REFERENCES	184
	LIST OF PUBLICATIONS	193
	APPENDICES	194
	APPENDIX A. Using lpsolve from MATLAB	194
	A.1 Installation.....	194
	A.2 Solve an lp model from MATLAB via mxlpsolve	196
	APPENDIX B. Analytic Hierarchy Process related Material.....	197
	B.1 Attribute scores of different application types per payment plan	197
	B.2 Weight calculation of different application types per payment plan	197
	APPENDIX C. cnlab Speed Test Collected data sample	203
	APPENDIX D. Basics of Game Theory	204
	APPENDIX E. Multi-Network System Level Simulator	212

List of Abbreviations

3GPP	3rd Generation Partnership Projects
AHP	Analytic Hierarchy Process
AIPA	Anytime Integer Partition based Algorithm
AMC	Adaptive Modulation Coding
ANP	Analytic Network Process
AP	Access Point
AVG	Average
BPI	Banzhaf Power index
BS	Base Station
CAC	Call Admission Control
CB	Current Best
CBCN	Cooperative based Cellular Network
CI	Consistency Index
CR	Consistency Ratio
CS	Coalition Structure
CSG	Coalition Structure Generation
DCVC	Distributing Coalitional Value Calculation
DP	Dynamic Programming
Dst	Destination
ELECTRE	Elimination and Choice Expressing Reality
GRA	Grey Relational Analysis
HPI	Holler Packel Index
IEEE	Institute of Electrical and Electronics Engineer
LB	Lower Bound
LTE	Long Term Evolution
MADA	Multi Attribute Decision Analysis
MC	Marginal Contribution
MCDM	Multi Criteria Decision Making
MODM	Multi Objective Decision Making
MS	Mobile Station
NP	Non-deterministic Polynomial
NTU	Non Transferable Utility
PPI	Popularity Power Index
QoS	Quality of Service
RAT	Radio Access Technology
RF	Radio Frequency
RI	Random Index
RS	Relay Station

SAW	Simple Additive Weighting
SLA	Service Level Agreement
SNR	Signal to Noise Ratio
Src	Source
SSPI	Shapley Shaulik Power Index
TCP	Transmission Control Protocol
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TU	Transferable Utility
UB	Upper Bound
UDP	User Datagram Protocol
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WPM	Weighted Product Method
WSM	Weighted Sum Method

List of Figures

Figure 3.1 AHP model for selecting an optimal job	33
Figure 3.2 Criteria comparison matrix	33
Figure 3.3 Cnlab speed test Architecture [CNST11]	40
Figure 3.4 Heterogeneous wireless environment scenario	41
Figure 3.5 Ranking vector for alternatives with respect to each attribute	45
Figure 3.6 Network Selection based on Reward Index as user rotates clockwise	45
Figure 3.7 Network Selection with user preference on Reputation as user rotates clockwise.....	46
Figure 3.8 Network Selection with user preference on Cost as user rotates clockwise....	46
Figure 3.9 Network Selection with user preference on Bit rate as user rotates clockwise	46
Figure 4.1 Block diagram of Network selection using the MCDM method.....	61
Figure 4.2 Network Selection Hierarchy	62
Figure 4.3 Home scenario	79
Figure 4.4 Payoffs of user requesting video-interactive application	80
Figure 4.5 Payoffs of user at location 'I' requesting different applications	81
Figure 4.6 Payoffs of user at location 'A' requesting different applications.....	81
Figure 4.7 Walking from home to the shopping centre scenario	83
Figure 4.8 User perceived data rate for UMTS macro-cell [Kbps]	84
Figure 4.9 User perceived data rate of WLAN [Kbps]	84
Figure 4.10 Data rates perceived by all users in UMTS macro-cell and WLAN	85
Figure 4.11 Data rates perceived by users served by UMTS macro-cell.....	85
Figure 4.12 Data rates perceived by users served by WLAN.....	86
Figure 4.13 Network selection for User '1'	86
Figure 4.14 Network selection for User '2'	86
Figure 4.15 Network selection for User '3'	87
Figure 4.16 Network selection for User '4'	87
Figure 4.17 Ranking Index for Available networks with respect to	89
Figure 5.1 Heterogeneous wireless access environment [NH09]	94
Figure 5.2 Interworking Architecture [LB07].	100
Figure 5.3 Heterogeneous Wireless Environment	101
Figure 5.4 Network selection hierarchy of dependencies	103
Figure 5.5 The heterogeneous payoffs of five users	110
Figure 5.6 The inverse rank of the five users.....	110
Figure 5.7 Rank of five users.....	111
Figure 5.8 Payoffs of Inverse rank approach for case 1 (Minimum method).....	113
Figure 5.9 Payoffs of Inverse rank approach for case 2 (Minimum method).....	114
Figure 5.10 Payoffs of Inverse rank approach for case 3 (Minimum method).....	114
Figure 5.11 User preference partition of Inverse rank approach in different price cases (Minimum method).....	115
Figure 5.12 System blocking rate of Inverse rank approach in different price cases (Minimum method).....	116
Figure 5.13 Payoffs of Inverse rank approach for case1 (Average method)	117
Figure 5.14 Payoffs of Inverse rank approach for case 2 (Average method)	117
Figure 5.15 Payoffs of Inverse rank approach for case 3 (Average method)	118

Figure 5.16 User preference partition of Inverse rank approach in different price cases (Average method)	118
Figure 5.17 System blocking rate of Inverse rank approach in different price cases (Average method)	119
Figure 5.18 Payoffs of Dusit Niyato approach for case 1(Minimum method)	120
Figure 5.19 Payoffs of Dusit Niyato approach for case 2(Minimum method)	120
Figure 5.20 Payoffs of Dusit Niyato approach for case 3(Minimum method)	121
Figure 5.21 User preference partition of Dusit Niyato approach in different price cases (Minimum method)	121
Figure 5.22 System blocking rate of Dusit Niyato approach in different price cases (Minimum method)	122
Figure 5.23 Payoffs of Dusit Niyato approach for case 1(Average method).....	122
Figure 5.24 Payoffs of Dusit Niyato approach for case 2(Average method).....	123
Figure 5.25 Payoffs of Dusit Niyato approach of for case 3(Average method)	123
Figure 5.26 User preference partition of Dusit Niyato approach in different price cases (Average method)	124
Figure 5.27 System blocking rate of Dusit Niyato approach in different price cases (Average method)	124
Figure 5.28 Blocking rates and number of users served by Wi-Fi (Partition) of Inverse rank approach with Dusit Niyato approach for the case 1	125
Figure 5.29 Blocking rates and number of users served by Wi-Fi (Partition) of Inverse rank approach with Dusit Niyato approach for the case 3	126
Figure 5.30 Blocking rates and number of users served by Wi-Fi (Partition) of Inverse rank approach with Dusit Niyato approach for the case 2	126
Figure 5.31 Simulation Process	127
Figure 6.1 Search Space for N=3	144
Figure 6.2 Search Space for N=4	145
Figure 8.1 Evolutionary model for cognitive radio network	179
Figure C.0.1 Response time in milliseconds of Wi-Fi for scenario ‘1’ measured on 3 rd August 2011 between 12:25 pm to 13:22 pm	203
Figure D.1 Forwarder’s Dilemma game	201
Figure D.2 Joint Packet Forwarding game.....	203
Figure D.3 Repeated Prisoner’s Dilemma game.....	206
Figure E.1 Multi-network System Level Simulator.....	209

List of Tables

Table 2.1 Structure of a Decision matrix ‘D’	24
Table 3.1 Random consistency indices for different number of criteria (n)	36
Table 3.2 Different Decision points in the scenario	42
Table 3.3 Attribute Comparison	43
Table 3.4 Network Parameters.....	43
Table 3.5 Network comparisons with respect to attributes	44
Table 3.6 Ranking vector for alternatives with respect to each attribute.....	44
Table 4.1 User Payment Plan Goals	64
Table 4.2 Attribute scores per payment plan for voice application	65
Table 4.3 Application preference scores	66
Table 4.4 Network preference scores.....	66
Table 4.5 Weight of attribute for different application types per payment plan.....	72
Table 4.6 Evaluation matrix.....	73
Table 4.7 Evaluation matrix example	74
Table 4.8 Wi-Fi related data at different locations of Home scenario	80
Table 5.1 Four categories of user and their preferences	102
Table 5.2 An example of criterion quality level value offered by network	104
Table 5.3 User criterion weight value in each category in the simulation.....	105
Table 5.4 Inverse Cumulative Ranking	109
Table D.1. Forwarder’s Dilemma game in strategic form	206
Table D.2. Joint Packet forwarding game in strategic form	208
Table D.3. Two player Prisoner’s dilemma	209

1 Introduction

The role of wireless networks resource management is to provide quality of service (QoS) guarantees to traffic according to their bandwidth requirements while maintaining the high utilization of network resource. The resource management in wireless networks can be implemented in two levels [LU07]:

- Macro-level, which involves call admission control (CAC), resource allocation and resource reservation to control the connectivity and end user's perceived QoS of the applications.
- Micro-level, which deals with power control, media access control (MAC) and packet scheduling to control the QoS parameters such as delay and jitter of the applications.

This thesis works at the macro level.

In heterogeneous wireless networks, different wireless access technologies are integrated to complement each other in terms of coverage area, mobility support, bandwidth, and price. In such heterogeneous wireless networks, a dynamic network selection scheme is required not only to achieve seamless mobility, but also to support quality of service (QoS) enhancement and load balancing.

Network selection in heterogeneous wireless networks can be categorized into two concepts namely as network-driven and user-driven. In the network-driven concept, the selection decision is made from the network-side (i.e., service provider). It is typically managed in a tightly integrated environment in which a central controller distributes the traffic flows among different networks. In contrast, with a user-driven approach, users make decisions to select the network and their decisions are autonomous and distributed across the whole network.

1.1 Problem

Self organisation of a network and the option for mobile users to swap from one service provider to another in order to choose the best wireless service is expected to become a common feature. The technical and the economical aspects of wireless network design

are being affected by these latest trends in wireless communication. This thesis looks at techniques, principally based on Game Theory to support decision-making and to manage the resources of the network depending on the choices a user makes.

For reasons of self-interest, the wireless users may engage in cooperative behaviour, resulting in an improved overall network performance. Cooperation among devices can coexist with a centralized infrastructure, e.g., in a cellular network, but is also of interest in ad hoc autonomous networks. In fact, due to the advantage of cooperation, numerous aspects of cooperative communication are making their way into wireless standards such as 3GPP's long-term evolution advanced (LTE-Advanced) or the forthcoming IEEE 802.16j WiMAX standard. The implementation of cooperation among wireless network needs to address the modelling the benefit and cost tradeoffs, providing fair rules for cooperation, the modelling of users and the design of distributed approaches for cooperation among others. Therefore, an analytical framework needs to be developed which can appropriately capture these challenges of cooperation and provide guidelines for deploying cooperative nodes in next generation networks.

1.2 Contribution

Two different notions of cooperation are explored within this thesis. The first approach of cooperation uses the idea of supporting the transfer of users from one wireless network to another based on an established evolutionary equilibrium. The evolutionary equilibrium is a notion of equilibrium in which no user can increase their payoff by moving from one network to another. The second approach uses the concept of coalitional game theory to cooperatively utilize the allocation of channels between the network providers to optimize their payoffs. The coalition formation process should enable the selection of individual players that based on their own resources and availability will constitute the best group to satisfy user's QoS requirements.

The main issue in coalitional game theory is to apply heuristics on the search space to find an optimal solution as quickly as possible. The top and bottom level within the search space is searched to find current optimal solution. All the partitions within the search space having a monetary value less than the current optimal solution are pruned. The upper and lower bounds are computed for the partitions and the pruning process

considers these bounds. The notion of stability on partition is used to decide the efficiency of the selected partition. The notion of stability ensures that no user within a partition can leave or join another partition to better their gains.

Game theory is a framework consisting of set of mathematical tools to study interactions among the rational players. Game theory can be used to model the competitive and cooperative behaviour of wireless entities capable of making autonomous decisions. The self-organization, configuration and optimization of wireless networks lead to the use of game theoretic concepts.

Game theory can be classified into two areas namely as non-cooperative and cooperative game theory. The non-cooperative game theory is used to model the competitive behaviour among the players. The cooperative game theory is used to study the cooperation among the number of players. The cooperative game theory can be further subdivided into two branches, viz Nash bargaining and coalitional game theory. In this thesis, only coalitional game theory is considered.

Coalitional game theory is a potentially powerful tool to devise a fair, efficient and practical framework to model various aspects of cooperation (i.e. coalition formation model) among the players in next generation wireless networks to optimize their utilities. Hence, it is necessary to describe the basics of coalitional game theory and its application in the research area of the heterogeneous wireless communication diagnosed in a dynamically varying environment. Hence, in the next chapter, we provide an introduction to coalitional game theory, which is a suited framework for modelling cooperative behaviour to be defined fully in Chapter 7. It is impractical to assume that a grand coalition would form and it is imperative to study how cooperation among the nodes (eg. between two base stations or wireless networks) can affect the QoS perceived by the users.

This thesis only considers the cooperation among the wireless networks to provide better QoS to the mobile users. The cooperation among the mobile users is outside the scope of this thesis.

1.3 Research Aims

In recent research, dynamic radio resource management is seen as a cost effective and flexible way to optimized spectrum utilization and improve the system capacity. Dynamic radio resource management mitigates the problem by employing adaptive approaches in channel assignment, re-allocation and sharing aspects of wireless communication, and typically takes one of two approaches [ZAN97]:

1) Capacity Adaptation: An overloaded cell can try to increase its own capacity by borrowing capacity from neighbouring cells. Examples are channel borrowing [DSJ97][YW93], channel sharing [SLSX01][LSC99], dynamic channel allocation [AJK99][PMPS97][RFG95][BCH99].

Coalitional game theory uses the term coalition to refer to the collections or combinations of players with the same interests. The possible coalitions of players are dependent on the maximum number of possible combinations of players. For example, if there are four players involved in the game, the number of possible coalitions would be $2^4 - 1$. An increase in number of players exponentially increases the number of possible coalitions. A partition is a collection of one or more coalitions containing all players. For example, if there are four players involved in the game, the coalitions could be $\{2, 4\}$ or $\{1, 3\}$ whereas a partition would be $\{\{1, 3\}, \{2, 4\}\}$. As will be seen later, each partition of a game constitutes the search space. The search space can be grouped in various levels. At the top level is the partition with all players acting on their own i.e. $\{\{1\}, \{2\}, \{3\}, \{4\}\}$. The second level constitutes the partitions with collection of two coalitions i.e. $\{\{1,3\}, \{2,4\}\}$ and so on. The bottom level constitutes the partitions with all the players (also known as grand coalition) i.e. $\{1,2,3,4\}$.

The basic coalition problem can be described as: given a set of base stations or wireless networks 'N' and a resource allocation demand b_{req} they each have to satisfy, if the resource demand cannot be satisfied by a single network or when a single network handles the request inefficiently, it is necessary for the wireless networks to cooperate with each other to fulfil the resource demand. With cooperation between networks (by forming coalitions among themselves), the allocation of resources (i.e. channels) required for that application can be split over the 'N' base stations or perhaps networks. This is a

special case of Overlapping Coalition Formation. In real world, the resources (or channels) can be borrowed from the ‘N’ BS or networks to fulfil the application requirements of the coalition. Let $S = \{S_1, S_2, \dots, S_n\}$ denote a coalition structure, where $S_i \cap S_j = \emptyset \forall i \neq j$. As a result of coalition formation, individual players now act for the benefit of the coalition. Therefore the objective of each member in the coalition becomes the optimization of the coalition objectives subjected to operating constraints.

2) Load Adaptation: An overloaded cell can try to reduce its own load by forcing or directing some or all of its associated wireless devices to switch to alternative neighbouring cells. Examples are cell breathing and soft handover schemes. The load adaptation is implemented in this thesis by using a form of Evolutionary Game Theory in which the users are diverted from the congested network to the un-congested network depending on the received payoff.

1.4 Novelty

The main objective of this work is to introduce different cooperative mechanisms into wireless networks using different concepts of game theory and investigate their potential benefit as compared to non-cooperative mechanisms. The cooperative mechanisms are classified as coalitional and evolutionary.

- This thesis analyzes the cooperation between the wireless networks as an optimisation problem and solves it using the coalitional game theory. The cooperation among base stations within the same provider to share the resources is analyzed using transferable payoff coalition game model. The aim of this thesis is motivated by the need to develop efficient algorithms for solving the coalition structure generation problem. It does it by applying game theory to several problems where cooperation is required. The coalition structure generation is the formation of coalitions by the players involved such that players within each coalition coordinate their activities, but players do not coordinate between coalitions. Precisely, this means partitioning the set of players into exhaustive and disjoint coalitions. This partition is called a *coalition structure (CS)*. The characteristic function to determine the coalitional value is modelled as convex optimization and it can be solved to find an optimal cooperation.

- This thesis describes the cooperation between the heterogeneous wireless networks using population evolution algorithm. Multi-criteria mechanism such as AHP is applied to model user preferences for different criteria to get an initial partition of users (i.e. proportion of users within a network) within the heterogeneous wireless networks. Next, an evolutionary game theory is applied to re-calculate the partition by churning the users from one network to the other network depending on their received payoff. In population evolution, each user observes the payoff of other users in the same population in each period and in the next period adopts a network that offers it a higher payoff. The network is also re-configured by altering the transmission power of networks to hypothetically calculate the new partition. For example, if one network is overloaded in peak times, the neighbouring networks (might be in their off-peak time) can alter their transmission power to churn the users from the loaded network. This mechanism helps by churning the users from loaded network to the un-loaded network such that the proportion of users within the loaded network becomes within their capacity for the smooth running. The evolutionary equilibrium is considered a stable point (or partition) after which no user can move from one network to the other network.

- This thesis also investigates the order in which these cooperative mechanisms should be applied. The coalitional game based cooperative mechanism analyzes the cooperation between the base stations of the same network whereas the evolutionary game based cooperative mechanism analyzes the cooperation between different networks. In case of cooperation whether the coalitional or evolutionary based cooperation should be applied first depending on the scenario (i.e. congestion or BS failure) need to be addressed in this thesis.

1.5 Organisation of the Thesis

This thesis is divided into three main areas. Firstly, the mathematical modelling to express user preferences for the considered criteria and its potential benefit in network selection is discussed using multi-criteria decision making (MCDM) methods. In Chapter

2, different MCDM methods are discussed. In Chapter 3, the basics of Analytic Hierarchy Process (AHP) are discussed and explained with the help of simple WiMAX/Wi-Fi example. In Chapter 4, the proposed AHP network selection model to cater the user modelling is explained. This chapter also considers some realistic scenarios with realistically gathered data to explain the effectiveness of AHP. This chapter looks at network selection from user perspective.

Secondly, the concept of evolving users from congested network to uncongested network using network re-configuration and evolutionary game theory model is illustrated with the help of simulation. In Chapter 5, cooperative load balancing with the help of evolutionary game theory along with Simple Additive Weighting (SAW) method is explained using network re-configuration. This chapter considers the network selection from the network perspective.

In Chapter 6, the basic concepts of coalitional game theory, the payoff distribution methods, the coalition formation process and the stability of partitions are described in detail. Finally, the concept of cooperation in wireless communication networks is investigated in Chapter 7. Then, we introduce the analytical framework of coalitional game theory and discuss its potential application in wireless networks. Further, the basics and challenges of implementing cooperation in an integrated wireless network environment using different types of game theory (i.e. coalition based and evolutionary) are discussed.

2 Multi-Criteria Decision Making (MCDM)

In general, there exist two distinctive types of MCDM problems and these arise from different problems settings: one type has a finite number of alternative solutions and the other an infinite number of solutions. Normally in problems associated with selection and assessment, the number of alternative solutions is limited. In problems related to design, a criterion may take any value in a range. Therefore the potential alternative solutions could be infinite. If this is the case, the problem is often referred to as a multiple objective optimisation problems instead of multiple criteria decision problems.

2.1 Features

The MCDM problems can vary in context but share the following common features [XY01] as follows:

- **Multiple attributes or criteria often form a hierarchy**

The number of alternatives is evaluated on the basis of predefined attributes. The attributes are also referred to as criteria. Some attributes may be further classified into lower level of attributes called sub-attributes.

- **Conflict among criteria**

Multiple criteria usually conflict with each other. For example, in manufacturing a TV, the criteria of high quality picture may increase the product cost.

- **Hybrid nature**

1. **Different measurement units**

Each criterion might have different units of measurement. For example, in a TV selection problem the quality of picture is measured by resolution and the cost is measured in pound sterling.

2. **Mixture of qualitative and quantitative attributes**

Some attributes might be measured numerically and the other attributes can only be described subjectively. For instance, price is quantitative and customer experience is qualitative.

- **Uncertainty**

- Uncertainty can arise through subjective judgement due to lack of experience
- Uncertainty can also arise due to lack of data or incomplete information about the attributes

- **Large scale**

The real MCDM problem might consist of hundreds of attributes. The increase in the number of attributes also increases the number of comparisons between the attributes and the alternatives.

However, in most MADM methods, the general assumption is that all the criteria are independent, which may not be true in our network selection problem. In 1996, Saaty first introduced a mathematical theory named analytic network process (ANP), which manages all kinds of dependence and feedback systematically, and it can be applied in MCDM problems [LIU07]. This thesis focuses on the problems with a finite number of alternatives. For a finite number of alternatives MCDM can also be termed as Multiple Attribute Decision Making (MADM).

2.2 Representation of MADM problem

An MADM problem can be expressed in a matrix form, where each row ' i ' corresponds to the alternatives¹ and each column ' j ' corresponds to the attribute. Suppose there are m alternatives to be assessed based on n attributes, a decision matrix D (also known as evaluation or option matrix) is created. The size of decision matrix is $m \times n$ with each element a_{ij} being the value of attribute ' j ' with respect to the alternative ' i ' (i.e. action or decision). The structure of decision matrix is shown below in Table 2.1.

2.3 Review of MADM methods

Some classic methods developed in MADM are Simple Additive Weighting (SAW), Multiplicative Exponent Weighting (MEW), Grey Relational Analysis (GRA), Analytic Hierarchy Processing (AHP), Elimination and Choice Translating Priority (ELECTRE), a Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS).

¹ In this thesis, the term alternatives and candidate are interchangeably used for the available networks

Table 2.1 Structure of a Decision matrix ‘D’

Alternatives	Attributes			
	c ₁	c ₂	c ₃	c _n
A ₁	a ₁₁	a ₁₂	a ₁₃	a _{1n}
A ₂	a ₂₁	a ₂₂	a ₂₃	a _{2n}
A ₃	a ₃₁	a ₃₂	a ₃₃	a _{3n}
A _m	a _{m1}	a _{m2}	a _{m3}	a _{mn}

2.3.1 Simple Additive Weighting

Simple Additive Weighting (SAW) [NW06] method is a simple and most often used MADM scoring method. The score of each alternative A_i (typically network *i* in this thesis) is obtained by adding the normalized contributions from each metric n_{ij} multiplied by the weight w_j assigned to the attribute ‘j’. The selected alternative A_{SAW}^* is:

$$A_{SAW}^* = \operatorname{argmax}_{i \in M} \sum_{j=1}^N (w_j \times n_{ij}) \quad (2.1)$$

In Equation (2.1), n_{ij} denotes the score of the alternative ‘i’ with respect to the attribute ‘j’. w_j is the weight of the attribute ‘j’ and must satisfy $\sum_{j=1}^N w_j = 1$. In (2.1), N is the number of attributes and M is the number of candidate networks.

The attribute can be classified as positive, i.e. the larger the better or negative i.e. smaller the better and the calculation of n_{ij} are dependent on the type of attribute as shown below in (2.2) and (2.3) respectively:

$$\text{Positive attribute: } n_{ij} = \frac{a_{ij}}{a_j^+} \quad (2.2)$$

$$\text{Negative attribute: } n_{ij} = \frac{a_j^-}{a_{ij}} \quad (2.3)$$

In (2.2), a_j^+ is the maximum value of a for attribute ‘j’ (i.e. $a_j^+ = \max_{i \in M} a_{ij}$). In (2.3), a_j^- is the minimum value of a for attribute ‘j’ (i.e. $a_j^- = \min_{i \in M} a_{ij}$).

2.3.2 Multiplicative Exponent Weighting

Multiplicative Exponent Weighting (MEW) [YH95] [NW06] is another MADM scoring method. The score of alternative 'i' is determined by the weighted product of the attributes and is given as below:

$$S_i = \prod_{j=1}^n a_{ij}^{w_j} \quad (2.4)$$

where a_{ij} denotes the attribute 'j' of alternative 'i'. w_j is the weight of the attribute 'j' and must satisfy $\sum_{j=1}^n w_j = 1$. In the above equation, w_j is a positive power for positive attribute ($a_{ij}^{w_j}$) and w_j is a negative power for negative attribute ($a_{ij}^{-w_j}$).

The score of alternative obtained by MEW has no upper bound so it is convenient to compare the score of each network with the score of positive ideal alternative A^{**} . The positive ideal alternative is defined as the alternative with best values for each attribute. The definition of the best value is different for a positive attribute (i.e. the largest value) and a negative attribute (i.e. the smallest value).

The value ratio R_i between alternative i and the positive ideal is calculated by:

$$R_i = \frac{\prod_{j=1}^n a_{ij}^{w_j}}{\prod_{j=1}^n (a_j^*)^{w_j}} \quad (2.5)$$

where $0 \leq R_i \leq 1$

The selected alternative A_{MEW}^* is:

$$A_{MEW}^* = \operatorname{argmax}_{i \in M} R_i \quad (2.6)$$

2.3.3 Grey Relational Analysis

In Grey Relational Analysis (GRA) [SJA05] [NW06], grey relational co-efficient (GRC) is the score used to describe the similarity between each candidate alternative and an ideal alternative. The GRA comprises of three steps: normalization of the data, defining an ideal sequence and computing the GRC.

The normalization of the data is performed according to the three situations (larger the better, smaller the better and nominal is the best) as follows:

$$n_{ij} = \frac{a_{ij} - l_j}{u_j - l_j} \quad (2.7)$$

$$n_{ij} = \frac{u_j - a_{ij}}{u_j - l_j} \quad (2.8)$$

$$n_{ij} = 1 - \frac{|a_{ij} - m_j|}{\max\{u_j - m_j, m_j - l_j\}} \quad (2.9)$$

In (2.7), (2.8) and (2.9), $u_j = \max_{i \in M} a_{ij}$, $l_j = \min_{i \in M} a_{ij}$ and m_j is the largest value in the situation of nominal the best for $j=1, 2, \dots, n$.

The ideal sequence a_0 is defined to contain the upper bound, lower bound or moderate bound respectively in larger the better, smaller the better or nominal the better situations.

The GRC can be calculated as follow:

$$GRC_i = \frac{1}{n} \sum_{j=1}^n \frac{\Delta_{min} + \Delta_{max}}{\Delta_i + \Delta_{max}} \quad (2.10)$$

Where

$$\Delta_i = |a_{0j} - n_{ij}|$$

$$\Delta_{max} = \max_{i \in M, j \in N} \Delta_i$$

$$\Delta_{min} = \min_{i \in M, j \in N} \Delta_i$$

The larger the GRC, the more preferable the alternative will be. The selected alternative A_{GRA}^* is:

$$A_{GRA}^* = \operatorname{argmax}_{i \in M} GRC_i \quad (2.11)$$

2.3.4 Technique for Order Preference by Similarity to Ideal Solution

In Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [API10] [LFN11], two artificial alternatives are considered, i.e. an ideal alternative and a negative ideal alternative. The ideal alternative is the one having the best values for each attribute and the negative ideal alternative is the one which has the worst attribute values. TOPSIS selects the alternative which is the closest to the ideal solution and the farthest from the negative ideal solution. TOPSIS defines an index called similarity to the positive ideal solution. Considering decision matrix D (m alternatives and n attributes) as shown in Table 2.1 with each element a_{ij} being the value of attribute ' j ' with respect to the alternative ' i '. TOPSIS consists of the following six steps:

Step 1: Construct the normalized decision matrix

This step transforms different attribute dimensions into non-dimensional attributes to allow comparisons across attribute. The normalized value n_{ij} is calculated as:

$$n_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^m a_{ij}^2}}, i=1 \text{ to } m, j=1 \text{ to } n \quad (2.12)$$

This step transforms the decision matrix D into \overline{D} with each element n_{ij} being the normalized value of attribute 'j' with respect to the alternative 'i'.

Step 2: Calculation of weighted normalized decision matrix

In this step, the weight of each attribute 'j' is calculated (i.e. w_j). Each column of normalized decision matrix \overline{D} is multiplied with its associated weight w_j . The weighted normalized value v_{ij} is calculated as:

$$v_{ij} = n_{ij} \times w_j, i=1 \text{ to } m, j=1 \text{ to } n \quad (2.13)$$

Step 3: Identify ideal and negative ideal solutions

The ideal solution can be identified as:

$$A^+ = \{v_1^+, v_2^+, \dots, v_n^+\} \quad (2.14)$$

Where $v_j^+ = \{max_i(v_{ij}), j \in \text{positive attributes}; min_i(v_{ij}), j \in \text{negative attributes}\}$

The negative ideal solution can be identified as:

$$A^- = \{v_1^-, v_2^-, \dots, v_n^-\} \quad (2.15)$$

Where $v_j^- = \{min_i(v_{ij}), j \in \text{positive attributes}; max_i(v_{ij}), j \in \text{negative attributes}\}$

Step 4: Calculation the separation measures of each alternative from ideal and negative ideal solution

The separation of each alternative from the ideal solution is

$$d_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad i=1 \text{ to } m \quad (2.16)$$

The separation of each alternative from the negative ideal solution is

$$d_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad i=1 \text{ to } m \quad (2.17)$$

Step 5: Calculate relative closeness to ideal solution

$$S_i = \frac{d_i^-}{d_i^- + d_i^+}, i=1 \text{ to } m, \quad 0 < S_i < 1 \quad (2.18)$$

Step 6: Ranking the preference order

The closer the S_j is to '1' implies the highest priority of alternative 'i'.

2.3.5 Elimination and Choice Translating Priority

The ELECTRE method [HC05] consists of the following steps:

Step 1: Construct the normalized decision matrix

This step transforms different attribute dimensions into non-dimensional attributes to allow comparisons across attribute. The normalized value n_{ij} is calculated as:

$$n_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^m a_{ij}^2}}, i=1 \text{ to } m, j=1 \text{ to } n \quad (2.19)$$

This step transforms the decision matrix D into \bar{D} with each element n_{ij} being the normalized value of attribute 'j' with respect to the alternative 'i'.

Step 2: Calculation of weighted normalized decision matrix

In this step, the weight of each attribute 'j' is calculated (i.e. w_j). Each column of normalized decision matrix \bar{D} is multiplied with its associated weight w_j . The weighted normalized value v_{ij} is calculated as:

$$v_{ij} = n_{ij} \times w_j, i=1 \text{ to } m, j=1 \text{ to } n \quad (2.20)$$

Step 3: Determine concordance and discordance sets

Let's assume there are 'm' alternatives and 'n' attributes with their respective weights as w_j . With regard to two alternatives 'p' and 'q' such that ($p \neq q$), the 'n' attributes can be classified into two sets namely as concordance and discordance sets. The determination of these set is dependent on the type of attribute. In these sets, the weighted normalized value of attribute 'j' with respect to alternative 'p' (v_{pj}) and 'q' (v_{qj}) are compared under all attributes (i.e. $j=1 \text{ to } n$). The concordance set of alternatives 'p' and 'q' (C_{pq}) consist of all the attributes for which the alternative 'p' is better than 'q'. The concordance set for positive and negative attributes can be computed as follow:

$$C_{pq} = \{j | v_{pj} \geq v_{qj}\} \text{ (Positive attribute)} \quad (2.21)$$

$$C_{pq} = \{j | v_{pj} \leq v_{qj}\} \text{ (Negative attribute)} \quad (2.22)$$

The discordance set of alternatives 'p' and 'q' (D_{pq}) consist of all the attributes for which the alternative 'p' is inferior to 'q'. The discordance set for positive and negative attributes can be computed as follow:

$$D_{pq} = \{j | v_{pj} < v_{qj}\} \text{ (Positive attribute)} \quad (2.23)$$

$$D_{pq} = \{j | v_{pj} > v_{qj}\} \text{ (Negative attribute)} \quad (2.24)$$

Step 4: Determination of the concordance and discordance matrix

The size of concordance (Co) and discordance (Di) matrix are same as that of normalized decision matrix \bar{D} . The weight of each concordance set is an element in concordance matrix 'Co'. The element co_{ij} in concordance matrix 'Co' is the weight of all attributes in the concordance set C_{ij} . All the diagonal entries in concordance matrix 'Co' are kept blank because the alternatives cannot be compared with themselves. The concordance matrix Co can be created as follow:

$$Co = \begin{bmatrix} - & \cdots & co_{1m} \\ \vdots & \ddots & \vdots \\ co_{m1} & \cdots & - \end{bmatrix} \quad (2.25)$$

In (2.25), $co_{12} = \sum_{j \in C_{12}} w_j$ & $co_{m1} = \sum_{j \in C_{m1}} w_j$.

Similarly, the weight of each discordance set is an element in discordance matrix 'Di'. The element di_{ij} in concordance matrix 'Di' is the weight of all attributes in the discordance set D_{ij} . All the diagonal entries in discordance matrix 'Di' are kept blank because the alternatives cannot be compared with themselves. The discordance matrix Di can be created as follow:

$$Di = \begin{bmatrix} - & \cdots & di_{1m} \\ \vdots & \ddots & \vdots \\ di_{m1} & \cdots & - \end{bmatrix} \quad (2.26)$$

Where

$$di_{12} = \frac{\max_{j \in D_{12}} |v_{1j} - v_{2j}|}{\max_{j \in J} |v_{1j} - v_{2j}|} \quad \& \quad di_{m1} = \frac{\max_{j \in D_{m1}} |v_{1j} - v_{2j}|}{\max_{j \in J} |v_{1j} - v_{2j}|}$$

$J = \text{All attributes in discordance set 'D'}$

Step 5: Determine the concordance and discordance dominance matrix

The concordance and discordance dominance matrix are determined by their respective threshold values. The concordance dominance matrix C^+ on the basis of threshold value \bar{c} is determined as follow:

$$C^+ = \begin{bmatrix} - & c_{12}^+ & c_{1m}^+ \\ \vdots & - & \vdots \\ c_{m1}^+ & \dots & - \end{bmatrix} \quad (2.27)$$

Where

$$\bar{c} = \frac{\sum_{k=1}^m \sum_{l=1}^m c_{kl}}{m(m-1)} \quad \forall k \neq l$$

$$c_{kl}^+ = 1 \text{ if } c_{kl} \geq \bar{c}$$

$$c_{kl}^+ = 0 \text{ if } c_{kl} < \bar{c}$$

The discordance dominance matrix D^- is determined similar to the concordance dominance matrix on the basis of threshold value \bar{d} as follow:

$$D^- = \begin{bmatrix} - & d_{12}^- & d_{1m}^- \\ \vdots & - & \vdots \\ d_{m1}^- & \dots & - \end{bmatrix} \quad (2.28)$$

Where

$$\bar{d} = \frac{\sum_{k=1}^m \sum_{l=1}^m d_{kl}}{m(m-1)} \quad \forall k \neq l$$

$$d_{kl}^- = 1 \text{ if } d_{kl} \leq \bar{d}$$

$$d_{kl}^- = 0 \text{ if } d_{kl} > \bar{d}$$

Step 6: Determine the aggregate dominance matrix

The aggregate dominance matrix is determined by identifying the intersection of concordance dominance matrix C^+ and discordance dominance matrix D^- . The aggregate dominance matrix E is created as follow:

$$E = \begin{bmatrix} - & e_{12} & e_{1m} \\ \vdots & \ddots & \vdots \\ e_{m1} & e_{m2} & - \end{bmatrix} \quad (2.29)$$

Where

$$e_{kl} = c_{kl}^+ \times d_{kl}^-$$

$$e_{kl} = \begin{cases} 0 \\ 1 \end{cases} \text{ connect alternative 'k' to 'l'}$$

The final step is to eliminate the less favourable alternative. If $e_{12}=1$ it means that there is an edge from alternative '1' to '2' and the alternative with no incoming edges are eliminated.

2.4 Summary

In this chapter, some essential features of MCDM methods are briefly explained. This chapter also highlights the drawbacks (i.e. scalability and uncertainty issues) of MCDM methods. This is followed by a description of the representation of a MADM problem.

The mathematical concepts used in different MCDM methods such as SAW, MEW, GRA, TOPSIS and ELECTRE are explained in detail.

3 The Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) has been applied to a number of areas such as predicting economic outcomes and resolving conflicts when there are many attributes associated with the outcomes. Analytic Hierarchy Process (AHP) [SJ05] [SAA80], is a Multi Criteria decision making method which requires pair-wise comparison. Thomas L. Saaty developed a system called AHP that transforms the pair-wise comparison scores into weights of different attributes and priorities of all alternatives on each attribute to obtain the overall ranking of alternatives. The input can be obtained from actual measurements (price, measured quality of service attribute, etc) or from subjective opinion such as feelings of satisfaction and preference. The decision factors of the problem are identified and inserted into a hierarchy. The overall objective is placed at the topmost node of the hierarchy. The lower nodes represent the decision factors. The solution alternatives are located at the bottom nodes. The procedure of AHP can be summarized as follows:

3.1 Formulate the Problem

The first step in AHP is to formulate the problem to decide which attributes should be used to evaluate each alternative. The hierarchy for “select an optimal job” is shown in Figure 3.1. Location, salary, content and duration is considered to be the criteria (attributes) used to describe a job and denote these by C_1 , C_2 , C_3 and C_4 respectively. Each of these of four criteria is evaluated for the three jobs that are being compared.

3.2 Determine the Relative Weights of the Comparison Attributes

The second step is to determine the relative weights of the attributes i.e. Location, Salary, Content and Duration. Every attribute is compared against all attributes within the same level to decide the relative importance of each attribute. The comparisons result in a square matrix. The size of the matrix depends on the number of pair wise comparisons within the same level (e.g. for “Select an optimal job” a 4×4 square matrix is created as there are four attributes).

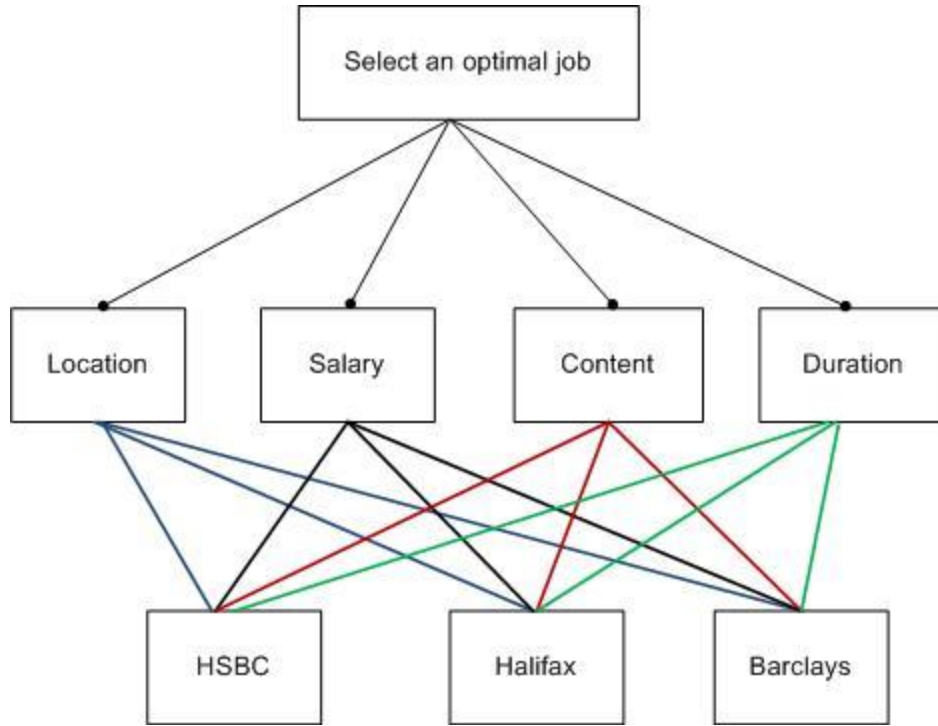


Figure 3.1 AHP model for selecting an optimal job

A 1 to 9 scale [SAA80] is used to allow the decision maker to express the strength of preference. The numbers from 1 to 9 are used to respectively represent equally, weakly moderately, moderately, moderately plus, strongly, strongly plus, very strongly, very very strongly and extremely important to the criteria with respect to the goal. Comparing criteria C_1 and C_2 gives a preference value a_{12} . If the value of $a_{12}=k$ then the value of $a_{21}=1/k$. By definition all the diagonal values in the square matrix are set to '1'. Similarly, the reciprocals of these numbers are used to show the inverted comparison results. The square matrix for the criteria comparison (for the four criteria in Figure 3.1) is shown below:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}$$

Figure 3.2 Criteria comparison matrix

3.2.1 Calculate the Eigen value and Eigen vector

Suppose the criteria comparison matrix A for ‘n’ criteria is shown as below

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \quad (3.1)$$

Let A be $n \times n$ matrix. The number λ is an eigenvalue of A if there exists a non-zero vector v such that

$$Av = \lambda v \quad (3.2)$$

In Equation (3.2), vector v is called an eigenvector of ‘A’ corresponding to Eigen value ‘ λ ’. The Equation (3.2) can be rewritten as

$$(A - \lambda I)v = 0 \quad (3.3)$$

In Equation (3.3), I is $n \times n$ identity matrix. In order for a non-zero vector v to satisfy the above equation, $A - \lambda I$ must not be invertible. The determinant of $A - \lambda I$ must be equal to 0. The characteristic polynomial of A is $p(\lambda) = \det(A - \lambda I)$. The eigenvalues of A are simply the roots of the characteristic polynomial of A.

If $A - \lambda I$ has an inverse, (3.3) can be rewritten as

$$\begin{aligned} (A - \lambda I)(A - \lambda I)^{-1}v &= (A - \lambda I)^{-1} \times 0 \\ v &= 0 \end{aligned} \quad (3.4)$$

The Eigen value or principal Eigen value of matrix A can be calculated using the following two methods that are named as the “Eigen value calculation” method and the “normalized geometric mean” method.

a. Eigen value calculation method

The easiest method [SAA90] to calculate the Eigen value is by taking the value of each criterion (say a_{11}) and dividing it by the sum of the column it appears in. In our example, the square matrix ‘A’ is a 4×4 (i.e. four columns). Let us denote the column sums by S_1, S_2, S_3, S_4 respectively.

$$S_1 = \sum_{i=1}^4 a_{i1}, S_2 = \sum_{i=1}^4 a_{i2}, S_3 = \sum_{i=1}^4 a_{i3}, S_4 = \sum_{i=1}^4 a_{i4}$$

In general terms, A is n*n matrix so the column sum S_n can be represented as

$$S_n = \sum_{i=1}^n a_{in} \quad (3.5)$$

In Equation (3.5), a_{in} are the entries in the matrix 'A' and 'n' are the number of considered criteria. After dividing every entry in the matrix by the sum of its column the matrix 'A' is now transformed to A' as shown below:

$$A' = \begin{bmatrix} a_{11}/S_1 & a_{12}/S_2 & \dots & a_{1n}/S_n \\ a_{21}/S_1 & a_{22}/S_2 & \dots & a_{2n}/S_n \\ \vdots & \vdots & \dots & \vdots \\ a_{n1}/S_1 & a_{n2}/S_2 & \dots & a_{nn}/S_n \end{bmatrix} \quad (3.6)$$

All the entries in a row are averaged to get the weight (or Eigen value) of each of the comparison criteria as shown below.

$$A'' = 1/n \times \begin{bmatrix} a_{11}/S_1 + a_{12}/S_2 + \dots + a_{1n}/S_n \\ a_{21}/S_1 + a_{22}/S_2 + \dots + a_{2n}/S_n \\ \vdots \\ a_{n1}/S_1 + a_{n2}/S_2 + \dots + a_{nn}/S_n \end{bmatrix} = \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_n \end{bmatrix} \quad (3.7)$$

The weight vector W_1, W_2, \dots, W_n represent the weight of the criteria 1 to n.

b. Normalized geometric mean calculation method

The relative importance of each criterion (aka attribute) can be computed as normalized geometric means of the rows [SAA90]. The geometric means for each criterion is computed as shown below, where 'j' indicates the criterion number:

$$m_j = \sqrt[n]{a_{j1} \times a_{j2} \times a_{j3} \times \dots \times a_{jn}} \quad (3.8)$$

In general, the geometric means can be computed for each other criterion by simply multiplying all the entries in the corresponding row and taking their n^{th} root. These groups of geometric means (m_1, m_2, m_3, m_4) divided by the sum of all geometric means are called the Relative weights for that criteria. The Relative weight for criterion j can be computed as follows:

$$W_j = m_j / x \quad (3.9)$$

$$x = \sum_{j=1}^n m_j \quad (3.10)$$

3.3 Perform the consistency index

Saaty defined the consistency index (CI) [SAA08] as deviation or degree of consistency between the pair-wise comparisons using the following equation:

$$CI = \lambda_{\max} - n / (n - 1) \quad (3.11)$$

Where λ_{\max} is the maximum Eigen value and n is the number of comparison criteria.

The λ_{\max} can be calculated by summation of products of weight of each criteria and their respective column sum as shown below:

$$\lambda_{\max} = \sum_{i=1}^n (S_i \times W_i) \quad (3.12)$$

For an optimal job selection, the λ_{\max} will be sum of the multiplication of weight of Location (W_1) with their respective column sum (S_1) and respectively for all other criterion like Salary, Content and Duration.

Accordingly Saaty defined the consistency ratio (CR) [SAA08] as a comparison between Consistency Index (CI) and Random Consistency Index (RI) using the following formula

$$CR = CI / RI \quad (3.13)$$

The RI is the random index representing the consistency of a randomly generated pair-wise comparison matrix. It is derived as average random consistency index (Table 3.1) calculated from a sample of 500 randomly generated matrices based on the AHP scale (1 to 9).

Table 3.1 Random consistency indices for different number of criteria (n)

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45

3.4 Calculate the overall level hierarchy weight to select the candidate

The next step is to evaluate all the alternatives on each criterion. In this step of AHP, the pair-wise comparison of the alternatives with respect to every criterion on scale 1 to 9 is

performed. The alternative comparison process is exactly the same as the criteria comparisons process i.e. the weights for the alternatives with respect to the criteria can be created using the same method as shown above in Section 3.2.1. For an optimal job selection, the alternatives like HSBC, Barclays and Halifax will be evaluated for the criterion Location using a pair-wise comparison. As there are three alternatives, a 3×3 matrix will be created for the criterion Location. The entries within 3×3 matrix will be on 1 to 9 scales. The Eigen value calculation or normalized geometric mean method can be applied on this 3×3 matrix to get the weights $\lambda_1^1, \lambda_1^2, \lambda_1^3$ which is the weight of HSBC, Barclays and Halifax with respect to criterion Location. Similarly the weights of HSBC, Barclays and Halifax for the criteria Salary, Content and Duration can be calculated.

Now the final evaluation metrics is produced by summation of the products of relative weights for the comparison criteria and the alternatives with respect to every criterion throughout the hierarchy. The final value of each alternative for problem goal is denoted by 'r' and for specific alternative 'i' will be of the following form:

$$r_i = W_1 \times \lambda_1^i + W_2 \times \lambda_2^i + \dots \dots + W_n \times \lambda_n^i \quad (3.14)$$

Where W_1 is the weight for criteria C_1 and λ_1^i is the weight for alternative candidate 'i' (namely as HSBC, Barclays and Halifax) with respect to criteria C_1 . The alternative with highest value of 'r' will be selected for the user.

3.5 Worked Example

The job seeker has four criteria i.e. location, salary, content and duration in mind for the selection of an optimal job. Initially all diagonal entries in a pair-wise comparison contain entries of '1' as each criterion is as important as itself.

	Location	Salary	Content	Duration
Location	1			
Salary		1		
Content			1	
Duration				1

Let us suppose that the job seeker decides that Salary is slightly more important than Location. In the next step, entry in the cell Salary-Location contains 3 and entry in the Location-Salary cell is 1/3. The job seeker also decide the Location is far important than the Content, giving 5 in the Location-Content cell and entry in the Content-Location is 1/5.

	Location	Salary	Content	Duration
Location	1	1/3	5	
Salary	3	1		
Content	1/5		1	
Duration				1

The job seeker decides that Salary is much more important than the Content giving 5 in the Salary-Content cell and respectively 1/5 in Content-Salary cell. The job seeker decides that Duration is much more important than the Content giving 5 in the Duration-Content cell and respectively 1/5 in Content-Duration cell.

	Location	Salary	Content	Duration
Location	1	1/3	5	1
Salary	3	1	5	1
Content	1/5	1/5	1	1/5
Duration	1	1	5	1

Method 1: Eigen value calculation method

$$S_1 = 1 + 3 + \frac{1}{5} + 1 = 5.2$$

$$S_2 = \frac{1}{3} + 1 + \frac{1}{5} + 1 = 2.533$$

$$S_3 = 5 + 5 + 1 + 5 = 16$$

$$S_4 = 1 + 1 + \frac{1}{5} + 1 = 3.2$$

	Location	Salary	Content	Duration
Location	$1/5.2=0.193$	$0.333/2.533=0.132$	$5/16=0.313$	$1/3.2=0.313$
Salary	$3/5.2=0.577$	$1/2.533=0.395$	$5/16=0.313$	$1/3.2=0.313$
Content	$0.2/5.2=0.038$	$0.2/2.533=0.079$	$1/16=0.063$	$0.2/3.2=0.065$
Duration	$1/5.2=0.193$	$1/2.533=0.395$	$5/16=0.313$	$1/3.2=0.313$

$$w_{location} = \frac{1}{4} [0.193 + 0.132 + 0.313 + 0.313] = 0.194$$

$$\begin{aligned}
w_{salary} &= \frac{1}{4} [0.577 + 0.395 + 0.313 + 0.313] = 0.495 \\
w_{content} &= \frac{1}{4} [0.038 + 0.079 + 0.063 + 0.065] = 0.052 \\
w_{duration} &= \frac{1}{4} [0.193 + 0.395 + 0.313 + 0.313] = 0.26
\end{aligned}$$

Method 2: Normalized geometric method

$$\begin{aligned}
m_1 &= \sqrt[4]{1 \times \frac{1}{3} \times 5 \times 1} = \sqrt[4]{\frac{5}{3}} = 1.136 \\
m_2 &= \sqrt[4]{3 \times 1 \times 5 \times 1} = \sqrt[4]{15} = 1.968 \\
m_3 &= \sqrt[4]{\frac{1}{5} \times \frac{1}{5} \times 1 \times \frac{1}{5}} = \sqrt[4]{\frac{1}{125}} = 0.299 \\
m_4 &= \sqrt[4]{1 \times 1 \times 5 \times 1} = \sqrt[4]{5} = 1.495 \\
x &= m_1 + m_2 + m_3 + m_4 = 4.898 \\
w_{location} &= \frac{1}{4.898} [1.136] = 0.232 \\
w_{salary} &= \frac{1}{4.898} [1.968] = 0.402 \\
w_{content} &= \frac{1}{4.898} [0.299] = 0.061 \\
w_{duration} &= \frac{1}{4.898} [1.495] = 0.305
\end{aligned}$$

3.6 Heterogeneous wireless network model

A competitive heterogeneous wireless access network model is considered in which multiple wireless networks operated by the same service provider coexist and offer their services to users. The integrated heterogeneous wireless access system model consists of cellular networks and Wi-Fi hotspots operated by the same or different providers. The cellular network has greater coverage area as compared to Wi-Fi, so it is imperative for a set of users to stay within Wi-Fi coverage for a sensible time frame to be considered for selection in order to avoid frequent vertical handoffs and because Wi-Fi is not suited to fast moving traffic. The user decision could be either maintain the actual connection as it has a favourable price or move to an alternative network which offers a better access

service. In this work, we assume the latter case. When the user selects a provider, a contract is established with the provider. It is also assumed that the network selection is reconsidered periodically after a predefined time interval.

In the following section, the simple network selection between Wi-Fi and WiMAX network is explained with an example to evaluate the AHP simulator. In this network selection, it is assumed that all the users request the same application type and belong to the “pay as you go” payment plan. In the next chapter, the concrete case of network selection with the download data rate offered by different networks measured using “Cnlab speed test” [CNST11] application. The “Cnlab speed test” allows selecting a Test server and measures the download and upload data rate along with the response time. The response time is measured by using a SYN packet (port 80). In order to validate the results, it is better to complete at least 20 measurements over a period of several days and if possible at different times of day so that your results will not be distorted due to possible short-time malfunctions. The architecture for “Cnlab speed test” is shown below in Figure 3.3.

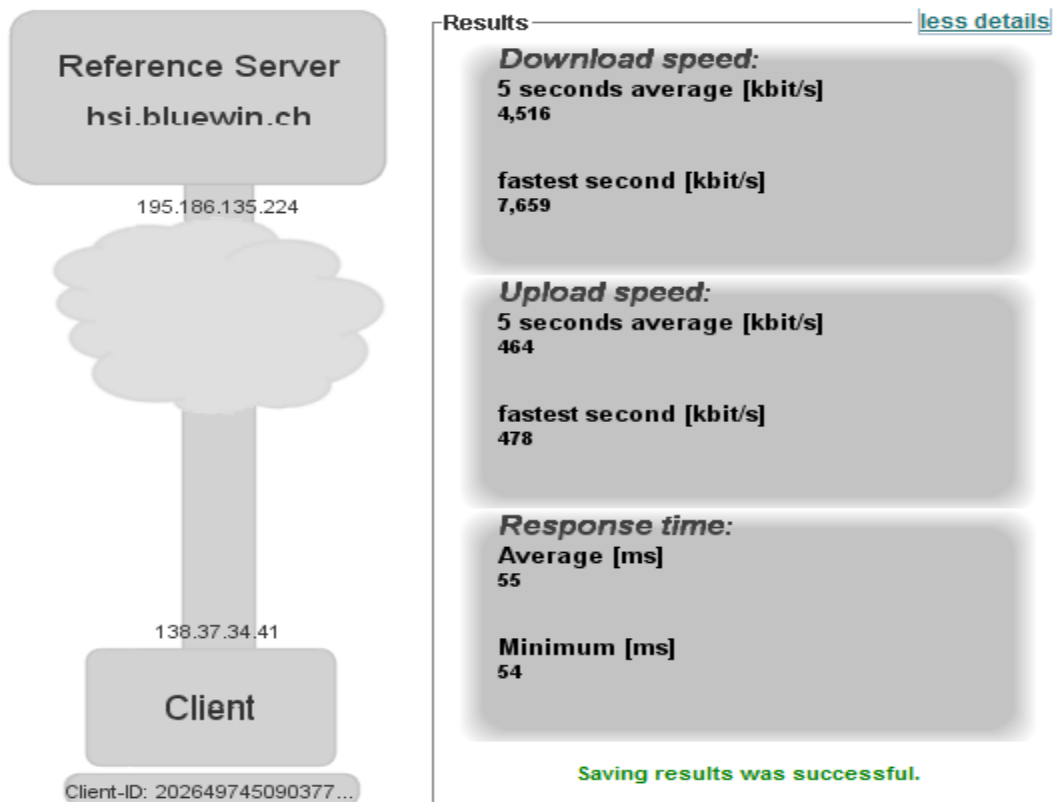


Figure 3.3 Cnlab speed test Architecture [CNST11]

3.6.1 Wi-Fi-/WiMAX network selection case

In this scenario, the heterogeneous wireless environment consisting of IEEE 802.16 WiMAX network provider and two IEEE 802.11 based WLAN providers ('A' and 'B') are assumed. All BSs and AP's are in the centre of the considered cell. The network which satisfies the user requirements and the requested QoS is selected. Simulations are based on three AP's of each WLAN provider lie within one cellular WiMAX network. The coverage of each AP of WLAN provider '1' (A) and WLAN provider '2' (B) are assumed as 200m and 400m respectively. The coverage of WiMAX BS's is assumed as 1000m respectively. In the simulation scenario, a mobile user is moving clockwise at a constant speed of 10 meters per second throughout the simulation scenario shown in Figure 3.4.

The network selection decisions for this scenario can be divided into three cases:

- 1) When there is only one network (WiMAX) that can be chosen. This case is considered because WLAN provider '1' (A) and WLAN provider '2' (B) has less coverage area as compared to WiMAX. The WLAN providers also lie within coverage area of WiMAX.
- 2) Within the overlapping coverage area of WiMAX and WLAN provider '1' (A).
- 3) Within the overlapping coverage area of WiMAX, WLAN provider '1' (A) and WLAN provider '2' (B).

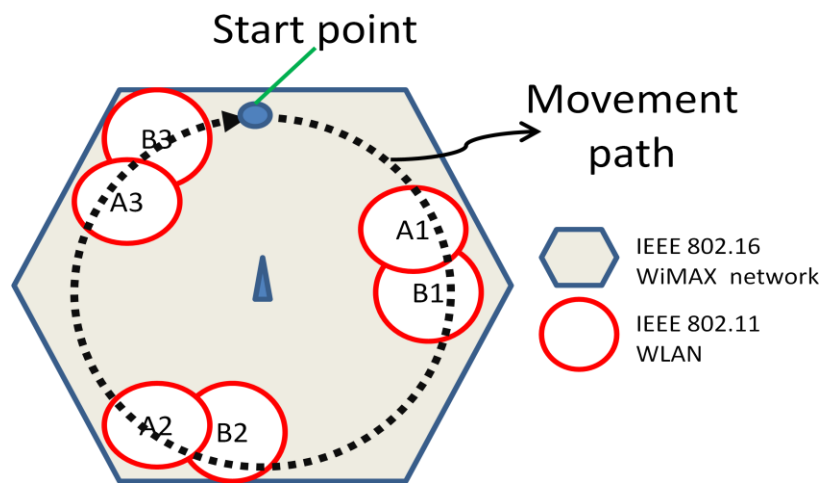


Figure 3.4 Heterogeneous wireless environment scenario

The network selection for the Wi-Fi and WiMAX model can be divided into different decision points as shown below in Table 3.2.

Table 3.2 Different Decision points in the scenario

Decision Points	Available Networks
D ₁	WiMAX
D ₂	WiMAX and WLAN '1' (A ₁)
D ₃	WiMAX , WLAN '1' (A ₁) and WLAN '2' (B ₁)
D ₄	WiMAX and WLAN '2' (B ₁)
D ₅	WiMAX
D ₆	WiMAX and WLAN '2' (B ₂)
D ₇	WiMAX , WLAN '1' (A ₂) and WLAN '2' (B ₂)
D ₈	WiMAX and WLAN '1' (A ₂)
D ₉	WiMAX
D ₁₀	WiMAX and WLAN '1' (A ₃)
D ₁₁	WiMAX , WLAN '1' (A ₃) and WLAN '2' (B ₃)
D ₁₂	WiMAX and WLAN '2' (B ₃)
D ₁₃	WiMAX

Based on Table 3.2, the network selection decisions for this scenario can be divided into four cases:

- 1) When there is only one network (WiMAX) that can be chosen. This case is considered because WLAN provider '1' (A) and WLAN provider '2' (B) has less coverage area as compared to WiMAX. The WLAN providers also lie within coverage area of WiMAX.
- 2) Within the overlapping coverage area of WiMAX and WLAN provider '1' (A).
- 3) Within the overlapping coverage area of WiMAX, WLAN provider '1' (A) and WLAN provider '2' (B).
- 4) Within the overlapping coverage area of WiMAX and WLAN provider '2' (B).

The pair-wise comparison values between the network attributes are assumed and the equation (3.8) is applied to the network attribute values mentioned in Table 3.3 to calculate the weight of network attributes. Similarly, the equation (3.8) can also be applied to the respective network attribute values offered by different networks mentioned in Table 3.5 to calculate the relative network scores for network attributes. The ranking of networks are determined through the sum of the products of weight of each network attribute with the relative network scores for that network attribute.

3.6.1.1 Network Selection

User's preferences on network attribute are defined in Table 3.3. The pair wise comparison of available networks for each attribute i.e. Reputation (R), Cost (C), Bit rate (B) and Mobility support (M) are done based on original network parameters shown in Table 3.4 which decide the preferred network and intensity of importance. In Table 3.4, the cellular WiMAX network, WLAN provider '1', WLAN provider '2' are represented as 'NW1', 'NW2' and 'NW3' respectively.

Table 3.3 Attribute Comparison

	R	C	B	M	w_i
R	1	1/3	5	1	0.232
C	3	1	5	1	0.402
N	1/5	1/5	1	1/5	0.061
M	1	1	5	1	0.305

Table 3.4 Network Parameters

	NW1	NW2	NW3
R	0.3	0.4	0.5
B	2	3	5
C	\$1.2	\$0.8	\$0.9
M	0.6	0.35	0.25

For every pair wise comparison between alternative networks, the respective cost being charged is considered. When both the cost being offered is well above (or well below) the user expected value, they are equally preferred. When both costs being offered are less than the user expected value, a \$1 difference in cost does not matter, but a \$2 difference is considered strongly important, and a \$4 difference is extreme. Whenever a network with a cost that is less than user expected value is compared with another network having cost well above user expected value, the former is extremely preferred. The network costs being offered above or below the user expected value determine the preferred network whereas their difference decides the relative importance. The network's parameters for each attribute can vary for different users.

The relative importance of each network for every attribute (Bit rate, Cost, Reputation

and Mobility Support) is defined in Table 3.5 (a),(b),(c) and (d) respectively. The Relative value vector of alternative networks for each attribute is shown below in Table 3.6.

**Table 3.5 Network comparisons with respect to attributes
(Network preferences for attribute derived from Table 3.4)**

B	NW1	NW2	NW3
NW1	1	1	5
NW2	1	1	3
NW3	1/5	1/3	1

(a) Bit rate

C	NW1	NW2	NW3
NW1	1	1/9	1/5
NW2	9	1	2
NW3	5	1/2	1

(b) Cost

R	NW1	NW2	NW3
NW1	1	1/3	1/9
NW2	3	1	1/3
NW3	9	3	1

(c) Reputation

M	NW1	NW2	NW3
NW1	1	5	9
NW2	1/5	1	3
NW3	1/9	1/3	1

(d) Mobility Support

Table 3.6 Ranking vector for alternatives with respect to each attribute

	R	B	C	M	r_i
NW1	0.077	0.480	0.066	0.751	0.392
NW2	0.231	0.406	0.615	0.178	0.406
NW3	0.692	0.114	0.319	0.071	0.204

The graphical representation of Table 3.6 is shown below in Figure 3.5. The network selection results based on reward index for each competing networks are shown below in Figure 3.6. The results show that network 3 never gets selected because its reward index is less than the other two competing networks. The network selection results with user preference based on attribute Reputation is shown below in Figure 3.7. In Figure 3.8, the network selection is shown with user preference on cost while Figure 3.9 and 3.10 show network selection with user preferences on Bit rate and Mobility Support respectively.

It is also noted that mobile user selects high reliable WLAN 'B' (NW3), when WiMAX (NW1), WLAN 'A' (NW2) and WLAN 'B' (NW3) are simultaneously available. Similarly the mobile user selects low price WLAN 'A', when WiMAX (NW1), WLAN 'A' (NW2) and WLAN 'B' (NW3) are simultaneously available.

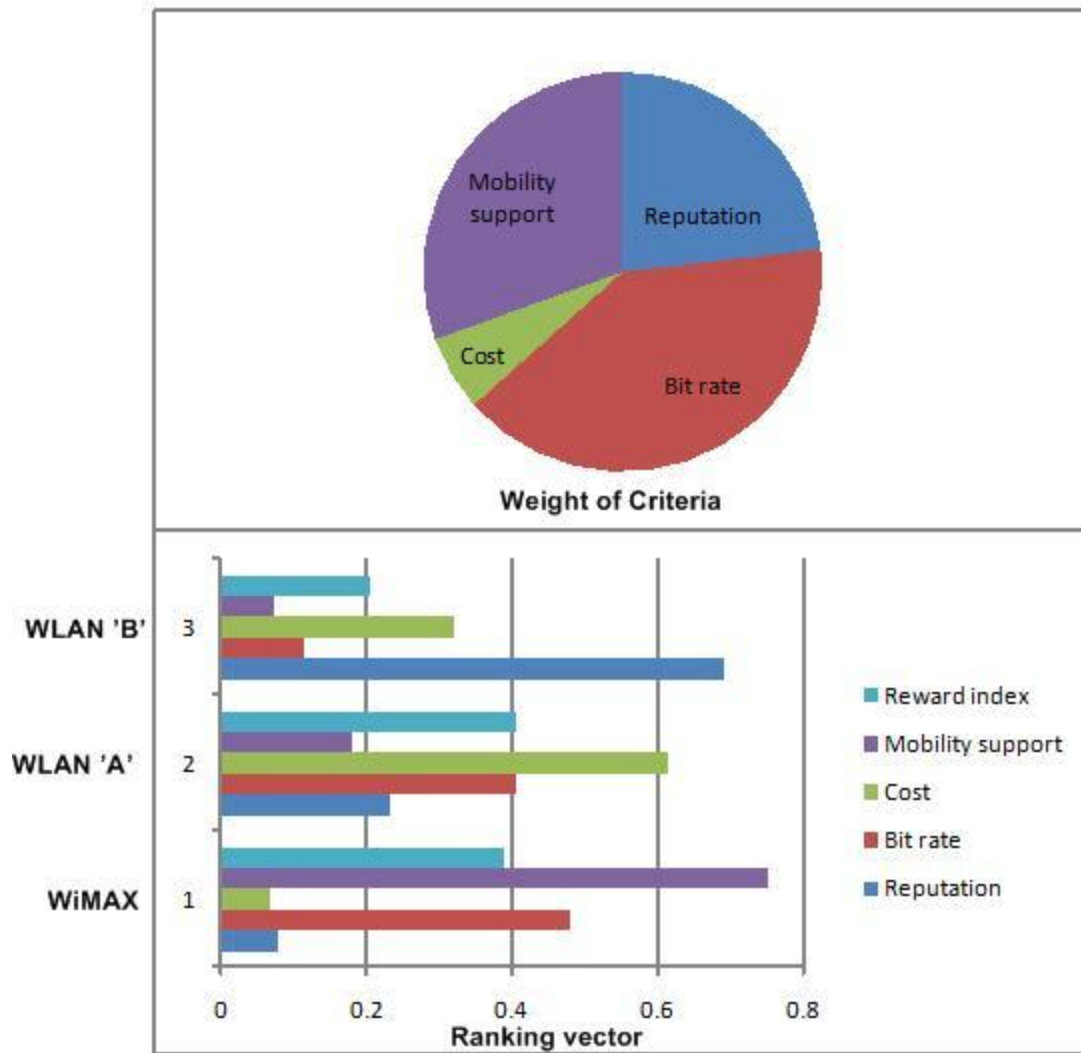


Figure 3.5 Ranking vector for alternatives with respect to each attribute

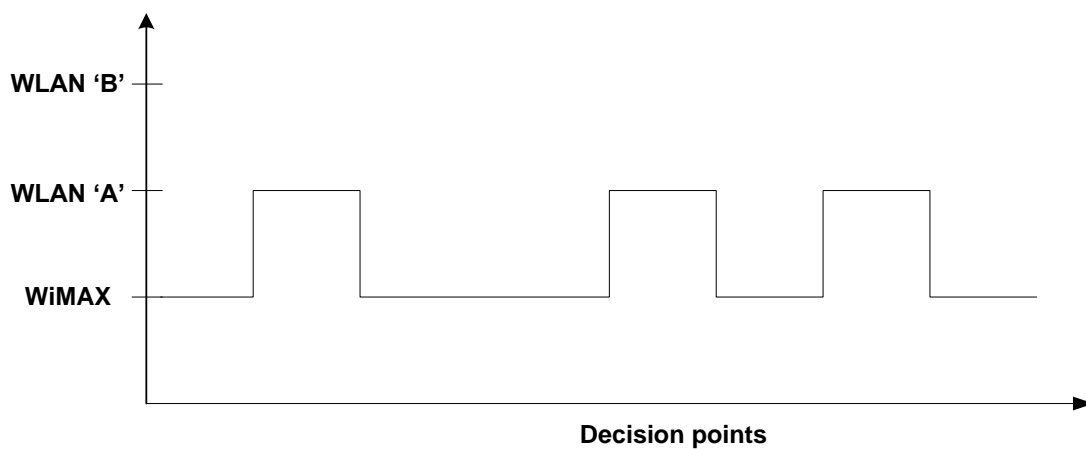


Figure 3.6 Network Selection based on Reward Index as user rotates clockwise

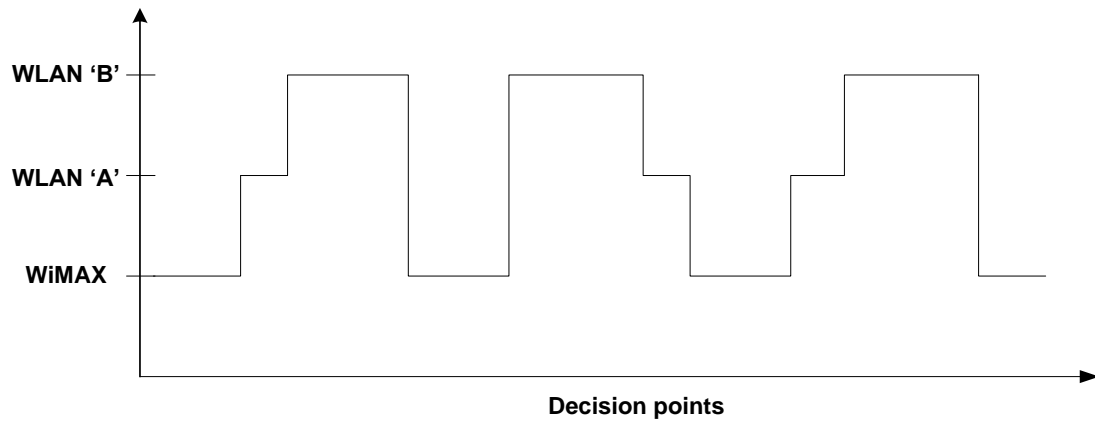


Figure 3.7 Network Selection with user preference on Reputation as user rotates clockwise

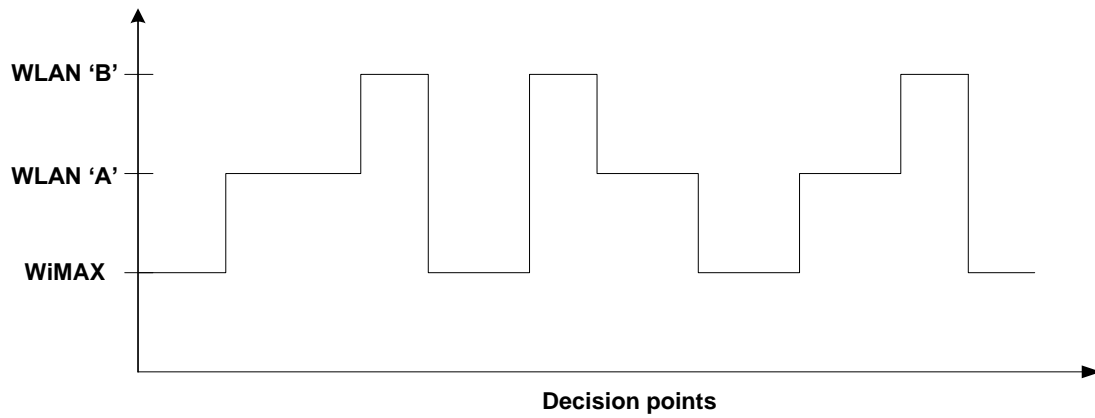


Figure 3.8 Network Selection with user preference on Cost as user rotates clockwise

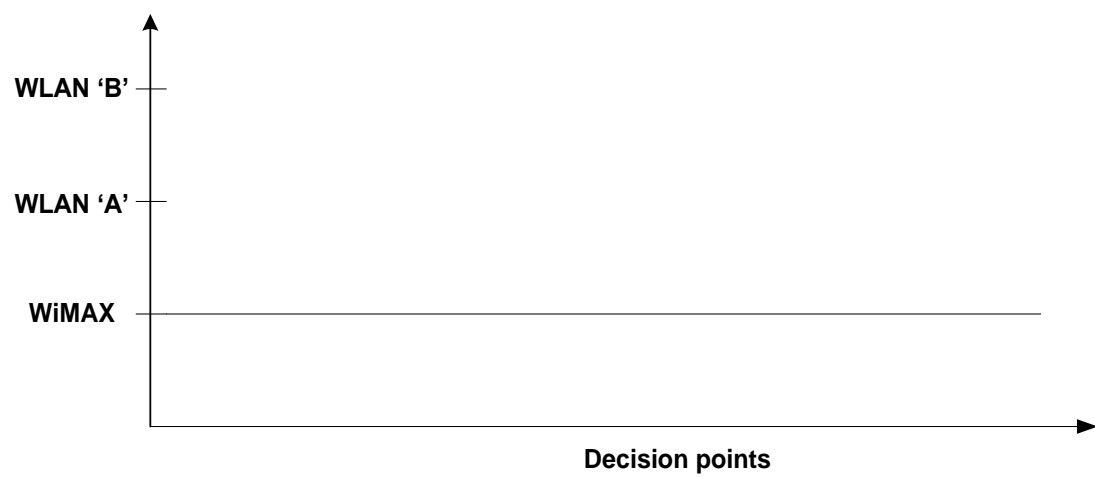


Figure 3.9 Network Selection with user preference on Bit rate as user rotates clockwise

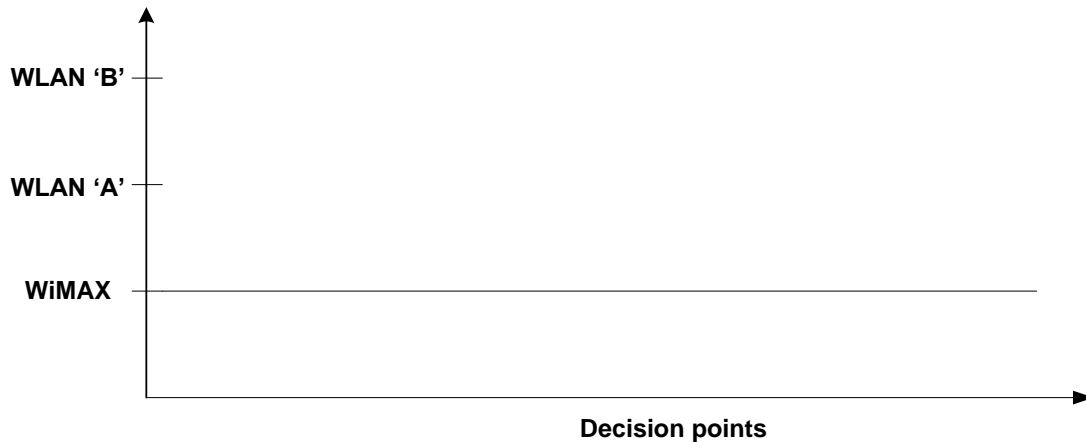


Figure 3.10 Network Selection with user preference on Mobility Support as user rotates clockwise

3.7 Disadvantages of AHP

The drawbacks of AHP are explained as follow:

- The first problem is that the hierarchy used to build additive value function for calculation actually requires independence among all those criteria that are in the same hierarchy level. In many cases, the AHP [DYE90] is misused by not maintaining the independence among elements of a hierarchy.
- The second disadvantage is the scalability issue of AHP in the real world as the number of pair-wise comparisons increases exponentially with the number of considered attributes.
- The third disadvantage of AHP is called rank reversal. The meaning of rank reversal can be explained in two cases:
 - 1) Assume after calculated by AHP, the order of preference is, for example, A, B, C then D, but if C is eliminated for other reasons, the order of A and B could be reversed so that the resulting priority is B, A, then D [SV06].
 - 2) A, B, C and D are ranked according to the criteria, say, W, X, Y, adding another criterion about which A, B, C, and D are equal, should have no bearing on the ranks. Yet, Perez et al proved in [DYE90] that ranking change is possible in this case by using AHP.

Rank reversal [HY81] is a typical problem of many MADM methods like AHP, ANP, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and ELECTRE.

The rank reversal issue can be resolved using Analytic Network Process (ANP) for the calculation of weights of criteria [LK00]. ANP allows the interaction and dependence of higher-level elements on lower-level elements as well as elements in the same level.

3.8 Summary

In this chapter, the key features of the Analytic Hierarchy Process model used in this thesis are given. The complete AHP procedure is illustrated using two different methods (the Eigen-value calculation and normalized geometric mean) to compute the weights from the comparison matrix. A simple example to “select a job” considering different attributes is demonstrated to give an insight into the AHP. This chapter also describes network selection in a WiMAX and Wi-Fi simulation model considering four attributes namely as reputation, offered bit rate, cost and mobility support. The last section explains the disadvantages of AHP.

4 Multi-Criteria Decision Making (MCDM) for network selection

This chapter looks at Multi-Criteria Decision Making (MCDM) techniques like Analytic Hierarchy Process (AHP) and Simple Additive Weighting (SAW) methods for selection between networks, possibly of different types and analyzes how they can be incorporated to improve the quality of the network selection by incorporating the different factors affecting the choice. AHP is used as it allows the strengths and weaknesses of the different technologies to be accommodated into the user preferences, thus supporting rational decision making. The trust in the relationship between the user and network also plays an important part in network selection. If the network is committed to provide users the specified Quality of Service (QoS) but fails to deliver, then the service will be penalised for a certain amount of time depending on the strategies being applied at the network and user level. The approach discussed in this section considers the suitability of a network offering a particular Radio Access Network (RAN) for a particular service (like voice, video-streaming, video-interactive and data) from a user perspective. It is to be noted that this approach does not focus on applying a service dependent Call Admission Control (CAC) later on as part of network selection scheme. This section presents a generic framework for network selection that can easily be extended in future for a range of wireless technologies.

4.1 Assumptions

In this chapter, the following assumptions are considered:

- i. All considered attributes are assumed independent of each other (i.e. no rank reversal problem).
- ii. The scalability issues of AHP are not considered.
- iii. The users give their preferences for mobility support but no mobility model is considered.
- iv. A vertical handover scheme from one network to another network is assumed.
- v. The reputation for each network is assumed identical.
- vi. Each network charges a constant price.

- vii. All users requesting the same service type with identical payment plan give similar preferences for the considered attributes.
- viii. The weights of each attribute could be estimated. To do this a survey was carried out that asked users belonging to different payment plans to give pair-wise comparison between the considered attributes on a 1 to 9 scale and these user inputs were used to compute the weights of each considered attribute for different service types per payment plan.

4.2 Related work

Several multi-criteria decision making based algorithms have been proposed, e.g. [BL07][BLC07][AGAPL05][PGALPA03]. These conventional multi-criteria based algorithms do not take into account the complexities and uncertainties that arise from the different characteristics and natures of the different Radio Access Technologies (RATs). For example, these algorithms do not have a proper method to address the importance of the different criteria to the access network selection. Several multi-criteria based algorithms that employ tools such as fuzzy logic, neural networks, and genetic algorithms [GAPS05][WLM05] suffer from scalability and modularity problems. These algorithms, for example, take all inputs from the different RATs at once into one fuzzy logic block, so suffer from scalability and complexity problems when more RATs or membership functions are added due to the exponential increase on the number of inference rules.

In [ZSWD98] different types of models are used for multiple criteria decision making such as Simple Additive Weighting (SAW), Multiplicative Exponential Weighting (MEW), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Analytical Hierarchy Process (AHP).

In [ZM06], Zhu and McNair proposed a cost function based on *Multiservice Vertical Handoff Decision Algorithm* (MUSE-VDA). The cost function is evaluated for each network 'n' covering the service area of a user and the network with the lowest cost is selected for handover. The cost function for 'n' network (i.e. C_n) is computed as follow [ZM06]:

$$C^n = \sum_s C_s^n \quad (4.1)$$

In Equation (4.1), s is the user requested service and C_s^n is the QoS experienced by choosing network 'n' for service type s . The C_s^n can be calculated as follow [ZM06]:

$$C_s^n = \sum_j W_{s,j}^n \times Q_{s,j}^n \quad (4.2)$$

In Equation (4.2), $Q_{s,j}^n$ is the normalized QoS provided by network 'n' for parameter 'j' and service 's'. $W_{s,j}^n$ is the weight of QoS parameter on the user or network. The objective of this work is to divert the users towards the less congested network. By combining Equations (4.1) and (4.2), the general form of cost function is as follow:

$$C_s^n = \sum_s \sum_j W_{s,j}^n \times Q_{s,j}^n \quad s.t. E_{s,j}^n \neq 0 \quad \forall s, j \quad (4.3)$$

In Equation (4.3), $E_{s,j}^n$ is the network elimination factor indicating whether QoS parameter 'j' can be satisfied by network 'n'. The $E_{s,j}^n$ can be computed as follow:

$$E_{s,j}^n = \begin{cases} 0 & \text{if QoS parameter } j \text{ is unsatisfied} \\ 1 & \text{if QoS parameter } j \text{ is satisfied} \end{cases} \quad (4.4)$$

Zhu and McNair considered a cost function example with three networks (UMTS, WLAN or satellite network), the services (voice, video and images) and QoS parameters (battery power consumption, bandwidth and delay). The two different vertical handoff policies namely as collective session handoff and prioritized session handoff are illustrated. The C^{UMTS} , C^{WLAN} and $C^{Satellite}$ for collective session handoff policy using Equation (4.3) can be computed and one with the lowest cost is selected. For prioritized session handoff policy with video having the highest priority i.e. C_{video}^{UMTS} , C_{video}^{WLAN} and $C_{video}^{Satellite}$ can be computed using Equation (4.3) and one with lowest cost is selected.

In [NW06], the performance of different MCDM methods like SAW, TOPSIS, GRA and MEW are discussed for vertical handoffs decisions. It also explains the basics of each MCDM method and their procedures. This study assumes to have four collocated networks namely as UMTS, GPRS and two WLANs. The conversational, streaming, interactive and background traffic classes are considered. The available bandwidth, end-to-end delay, jitters and bit error rate are the considered attributes for the network selection. The eigenvector method using AHP is used to determine the weights of attributes for each traffic class. The Markov chain with state transition matrix is used to vary the value of metrics. The paper also studied the allocation of bandwidth to different traffic classes by four MCDM based handoff decision algorithms. The simulation

demonstrates that the same amount of bandwidth is allocated to both the conversational and streaming traffic classes by four MCDM based handoff decision algorithms. The interactive and background traffic classes are allocated slightly more bandwidth when GRA based handoff decision algorithm is used. Similarly for average delay, the four MCDM performs similarly for both conversational and streaming traffic classes. The GRA have a slightly smaller delay for both interactive and background classes. The sensitivity analysis of attribute 'jitter' shows that by increasing its weight, all four algorithms select the network with the lowest jitter. The sensitivity analysis of attribute 'bit error rate' shows that by increasing its weight, all four algorithms select the network with the lowest bit error rate. This paper also studies the percentage of time all four algorithms select the same network.

In [MRN10], the performance of MCDM methods like SAW, MEW, TOPSIS, ELECTRE, VIKOR, GRA and WMC is illustrated for voice and data applications with the help of numerical example. In this work, the six attributes (available bandwidth, total bandwidth, packet delay, packet jitter, packet loss and cost per byte) are evaluated for vertical handoff in an integrated 4G environment with three network types namely as WLAN, UMTS and WiMAX. This study also considered three different cases of assigning weights to the considered attributes: case 1, all the attributes are assigned same weight; case 2: packet delay and jitter are assigned 70% of importance and the rest is equally distributed among the remaining attributes; and case 3: available and total bandwidth are assigned 70% of importance and the rest is equally distributed among the remaining attributes. The simulations study shows that SAW, VIKOR and TOPSIS methods perform better by providing lower values of delay and jitter for case 2 (voice connections) whereas GRA and MEW algorithms perform better by providing highest available bandwidth for case 3 (data connections).

In [AKL06], an AHP based context aware decision algorithm is proposed. This algorithm considered six primary objectives namely as interface priority, minimum cost, maximum mean throughput, minimum delay, minimum jitter and minimum Bit Error Rate (BER) based on the QoS parameters defined in 3GPP. This algorithm constitutes of five stages. In stage 1, the user gives their preferences for the primary objectives, available interface preferences and application type preferences. Based on user preferences and number of

possibilities, the scores are assigned equally spaced integers on 1 to 9 scale (the most preferred choice is assigned a score of '1' and the least preferred choice is assigned a score of '9') using the space gap [TAKL06] as defined below:

$$I = \frac{S_h - S_l}{N_c} \quad (4.5)$$

In Equation (4.5), N_c is the number of attributes, S_h and S_l are the highest and the lowest possible scores (i.e. 9 and 1) respectively. I is the numeric space gap between two subsequent scores which is rounded to the next integer.

In stage 2, the network QoS parameters such as maximize mean throughput, minimize delay, minimize jitter and minimize Bit Error Rate (BER) are assigned upper and lower limit values for three different types of applications [AKL06]. These network QoS parameters can be classified as positive parameters (larger the better) or negative parameters (smaller the better). The mean throughput is classified as positive parameter whereas the remaining three parameters are classified as negative parameters. The lower limit values of positive parameters for each application types are fixed (i.e. mean throughput is 4 kbps for conversational class) and the upper limit varies according to the score assigned to the parameters. If the positive parameter such as mean throughput for conversational class is assigned a score '1', the upper limit is set to 25 kbps whereas for a score of '7', the upper limit is set to 8 kbps. In case of negative parameters, the upper limit value is fixed and the lower limit value varies according to the scores assigned to the parameters.

In stage 3, the scores are assigned based on the six primary objectives to each available network. Static primary objectives (e.g. interface priority and cost) are assigned score in a straight forward way by using Equation (4.5) as mentioned in step 1. For interface priority, the scores already defined by users in stage '1' are assigned to the available networks depending on their type. For cost, the network with cheapest cost is assigned a score of '1' and the most expensive network is assigned a score of '9' using Equation (4.5). For dynamic primary objectives (delay, jitter, mean throughput and BER), all available networks are compared with the individual upper and lower limit values of a primary objective defined in stage '2'. The network score S_i [AKL06] for a particular dynamic parameter depending on whether larger the better (mean throughput) or smaller

the better (delay, jitter and BER) are calculated using Equations (4.6) and (4.7) respectively.

$$S_i = \left(1 - \frac{n_i - l_i}{u_i - l_i}\right) \times 10 \quad l_i < n_i < u_i$$

$$S_i = 1 \quad n_i \geq u_i \quad (4.6)$$

$$S_i = 9 \quad n_i \leq l_i$$

$$S_i = \left(\frac{n_i - l_i}{u_i - l_i}\right) \times 10 \quad l_i < n_i < u_i$$

$$S_i = 1 \quad n_i \leq l_i \quad (4.7)$$

$$S_i = 9 \quad n_i \geq u_i$$

Where u_i and l_i denotes the upper and lower limits of a particular parameter and n_i denotes the value offered by a network for particular parameter.

In stage 4, the relative scores between two particular scores assigned to primary objectives in stage ‘1’ and the network scores assigned in stage ‘3’ are calculated as shown below in [AKL06]:

$$c_{ab} = \left(1 - \frac{s_a}{s_b}\right) \times 10, s_a < s_b \quad (4.8)$$

$$\frac{1}{c_{ab}} = \left(1 - \frac{s_b}{s_a}\right) \times 10, s_a > s_b \quad (4.9)$$

$$c_{ab} = 1, s_a = s_b \quad (4.10)$$

In Equations (4.8), (4.9) and (4.10), c_{ab} is relative score between primary objectives ‘a’ and ‘b’, and s_a and s_b are their respective scores. The pair-wise comparison method [SAA90] is applied to the relative scores of primary objectives to calculate their respective priorities. Similarly, the network weights of each available network for the considered primary objectives are calculated. The overall ranking of each available network is computed by multiplying the sum of products of network weights for each individual primary objective with their respective objective priorities as shown below [AKL06]:

$$R_i = \sum_1^{ij} c_{ij} \times (p_j) \quad (4.11)$$

In Equation (4.11), R_i is an overall ranking and is always in the range of 0 to 1, c_{ij} is the network weight of network 'i' for primary objective 'j' and p_j is the priority for primary objective 'j'.

In [MAPP09], the authors explain a new architecture Y-Comm proposed jointly by researchers at the Networking Research Group at Middlesex University, Computer Laboratory at Cambridge University, Samsung Research and Deutsche Telekom to support heterogeneous networking by addressing the new challenges faced at the network, device and application level. It adopts a layered approach and acts as a reference model similar to OSI reference model. Y-Comm consists of two frameworks namely as Peripheral Framework (deals with operations and functions on the mobile node) and Core framework (functionality required in the core network to support the Peripheral Framework). The key requirement of Y-Comm infrastructure is to support efficient vertical handover. More detail about the architecture and functionalities of Y-Comm architecture can be found in [MAPP06][MAPP07]. The author investigates the design of imperative handover mechanisms using the Y-Comm Framework and also claims that Y-Comm Framework can be easily mapped onto the GSM/GPRS architecture. Y-Comm architecture supports both reactive and proactive handovers. The main contributions of Y-Comm architecture are at Policy Management Layer and QoS Plane. The Policy Management Layer resides the circumstances under which vertical handovers occur and determining the time before vertical handovers using the proposed Time Before Vertical Handover (TBVH) models. The TBVH is derived to pass it to other layers such as the QoS Plane and Vertical Handover layer to start preparing for the vertical handover by proactively negotiating for resources with the core network. The proposed Stream Bundle Management layer for handling downward QoS resides in the QoS Plane of the MN. This layer collects context information from the network, client and application domains to make intelligent choices in network selection and QoS management. This is one layer that actively applies information on Time before Vertical Handover (TBVH) to choose a stable network interface for a requesting application by avoiding unnecessary vertical handovers.

In [SHAIKH08], the authors present the proactive modelling-based approach for policy management which allows the Mobile Node (MN) to calculate Time before Vertical

Handover (TBVH) for open and closed environments. The network boundaries can be determined by proposing additional specifications to the boundary BS (BBS) to inform imminent network boundaries to the mobile node in outdoor scenarios and the dimensions of enclosed environment and the position of various exits for indoor environment. The parameters used to calculate TBVH are location co-ordinates of MN and BBS (using GPS or network based positioning techniques). The location coordinates of MN and BBS can be used to calculate the MN-BBS distance, angle of direction and MN velocity [SHAIKH07]. The TBVH for outdoor environment with outward movement of MN in BBS towards boundary can be estimated as follow [SHAIKH08]:

$$TBVH = \frac{(d\cos x) + \sqrt{r^2 - d^2\sin^2 x}}{v}$$

Similarly, the TBVH for outdoor environment with MN in normal BS moving towards the boundary BS (BBS) can be estimated as follow [SHAIKH07]:

$$TBVH = \frac{(b\cos \beta) + \sqrt{r^2 - b^2\sin^2 \beta}}{v}$$

The TBVH in indoor scenarios needs to cater the false handover triggers caused by MN moving closer to the threshold circle but in the direction of wall as compared to the exit. In order to cater this false handover triggers, the cosine of the direction of MN (W1) is calculated with respect to a particular exit point as shown below and is assigned to TBVH [SHAIKH10].

$$W1 = \cos \alpha = \frac{(mid_distance)^2 + (old_distance)^2 - (new_distance)^2}{2 \times (mid_distance) \times (old_distance)}$$

Where

- mid_distance is the distance between the previous MN position and current MN position
- old_distance is the previous distance between the MN position and the point of exit
- new_distance is the current distance between the MN position and the point of exit

This mechanism will accommodate for indoor environments with multiple exits but the TBVH and W1 will be calculated separately with respect to each point of exit.

Stream Bundle Management (SBM) layer (above Transport layer in OSI reference model) residing in the multi-interfaced heterogeneous network client is presented to tackle the

issues of traffic management in heterogeneous environment [SHAIKH06]. These decision making mechanisms rely on the feedback received from lower layers about prevailing network conditions. The SBM layer updates these values based on the periodic updates it receives normally. It also maintains a prioritized list of compatible networks for each traffic type. In the event of sudden dramatic changes in the parameter values, the layer receives triggers which prompt it to take immediate notice of the changed values. The network context information for available network is stored in two dimensional matrix called Network Descriptor Matrix (NDM). The NDM consist of network id, network status, available network bandwidth, received signal strength (RSS), TBVH and round trip time (RTT). In [SHAIKH06], four types of traffic namely as audio, video-interactive, one way video streaming and data are considered. The application's parameter values (AP) are sent down to the decision making mechanism through the stream priority mechanism where they are assigned a priority, or are sent directly if the priorities are predefined. The Traffic Management sub-layer first checks the resources available in the available networks to the application's parameter values. If the application's parameter values are satisfied, the mechanism maps the traffic stream onto the most appropriate channel. If the application's parameter values are not satisfied, it is then added to a waiting queue (urgency value is incremented) and will be activated when required resources become available. The amount of bandwidth allocated to each stream is decided with the help of Weighted Resource Allocation (WRA) [SHAIKH06] as follow:

$$(TBVH \times w_1) + (UV \times w_2) + (V \times w_3)$$

Where UV is the urgency value of a stream, V is the velocity of MN and $(w_1 + w_2 + w_3 = 1)$. In [SHAIKH10], main functions of six modules within the SBM layer are summarized as follow:

- i. Application QoS specification module
Stores QoS requirements and the priorities of the application streams
- ii. Priority score repository
Stores the scores for application, interface and objective priority sets
- iii. TBVH filtration module
Stores the TBVH values
- iv. Network descriptor module

Stores the latest values of network parameters obtained from lower layers

v. Call admission control module

It is responsible for negotiating resources based on application requirements and TBVH values

vi. Network selection module

Analytic Hierarchy Process based network selection algorithm to select an optimal network.

In [SHAIKH10], the proposed Stream Bundle Management (SBM) based network selection module is compared with the T-NS mechanism presented in [AKL06]. The deficiencies of T-NS are highlighted such as allocation of scores to the primary objectives by users, same relative score allocation to the primary objectives for all profiles, lack of network coverage prediction mechanism (TBVH) and lack of resource negotiation mechanism to avoid vertical handoffs. The deficiencies of T-NS are catered in the SBM based network selection mechanism.

The SBM based network selection is similar to the T-NS approach mentioned in [AKL06] except that it has an extra primary objective i.e. TBVH. The effectiveness of SBM based network selection in comparison with T-NS for two different types of traffic namely as voice and data of student profile are evaluated. The calculations of TBVH values for WLAN are considered and the calculation of TBVH values for WiMAX and UMTS is out of scope. The TBVH score changes dynamically as MN moves towards or away from the boundary and its performance to avoid unnecessary vertical handovers are highlighted. It also evaluates the efficient handling of FTP request by SBM based network selection utilizing the TBVH concept to find an optimal network considering the following constraints: 1) available bandwidth sufficient to complete the FTP request within the TBVH values; 2) available bandwidth is not sufficient to complete the FTP request within the TBVH values; 3) AP grants request for additional bandwidth; 4) AP rejects request for additional bandwidth and 5) AP rejects bandwidth request and TBVH is very low.

In this thesis, the proposed network selection is based on the concepts mentioned in the literature [SHAIKH10][AKL06] mainly on their concrete contribution to model the user preferences and selecting an optimal network. In this thesis, the primary objective is to

model the user preferences considering the application type on per payment plan basis and the avoidance of vertical handovers are out of scope. The TBVH concept is quite useful in predicting the future network availability to avoid unnecessary vertical handovers. In the future, this concept can be extended in the proposed user modelling.

4.3 Network Selection Modelling using MCDM method

In this section, the selection of an optimal network for the users is modelled as a Multi-Criteria Decision Making (MCDM) problem. The MCDM problem consists of three types of elements namely the Goal, the Criteria² (or attributes) and the Alternatives. In the network selection context, these three elements are defined as below:

Goal: select an optimal network

Attributes: Reputation, Bit rate, Cost and Mobility Support

Alternatives: WiMAX and Wi-Fi

The complete proposed network selection mechanism using MCDM method can be classified into the following steps:

- i. Establish the decision context, the decision goals and identify the decision maker.
- ii. Identify the candidate (or alternative) networks
- iii. Identify the attributes that are relevant to the decision problem
- iv. Identify the user preferences for considered attributes to generate a user decision matrix
- v. Calculate the weight of each attribute in order to calculate their importance to the overall goal
- vi. For each attribute, assign scores to measure the performance of alternatives with respect to these attributes and construct an evaluation table. The number of columns and rows in an evaluation table are 'n' and 'm' respectively.
- vii. Calculate the priority score of each alternative for every considered attribute.
- viii. The relative score of each alternative is determined by multiplying their priority score for each attribute (in step vii) with their respective assigned weight (in step v).

² The term attribute will be used from now onwards instead of criterion

- ix. Perform a sensitivity analysis to assess the robustness of the preference ranking to changes in the attribute scores and/or the assigned weights.

Based on the above steps, the process of selection between available networks can be divided into three main stages namely as formulation of network selection, user model and network model.

In the formulation of network selection, the problem of network selection is represented as a hierarchical structure. In the hierarchical structure, the goal is the top most node followed by the considered attributes as the second node and the set of alternatives as the bottom node. This stage defines the attributes considered by users and the number of available networks for the user request. This comprises of the above mentioned steps i-iii.

In the user model, each user expresses their preferences for the considered attributes. In the approach, there are four types of application and three types of user payment types so in total there are 12 categories of user. These categories of user need to be created only once. All the users belonging to the same category have similar preferences for the considered attributes. For each user or category of user, the square matrix (also known as user decision matrix) of size $n \times n$ is created where 'n' is the number of considered attributes. There are different types of methods mentioned in the literature namely the ranking method, rating method and pair-wise comparison for comparing attribute to create a user decision matrix. The rating method can be further classified into point allocation and ratio estimation. Each element in the user decision matrix is a comparison between two attributes. The attributes cannot be compared against themselves so all the diagonal elements in the user decision matrix are set to '1'. A square matrix can be created that assign weights to each attribute for each category of user. This stage constitutes mentioned steps iv-v above.

In the network model (different from the user group model), all the candidate or alternative networks are compared among themselves for each attribute and each network is assigned a priority score for the corresponding attribute. The relative score of each alternative network is the summation of priority score of each alternative (computed in step vii) multiplied with their respective assigned weights (computed in step iv) to rank

the alternatives in descending order. This stage constitutes of the above mentioned steps vi-vii.

The top most ranked candidate or alternative network is selected. The block diagram of selecting the most suitable candidate network using MCDM method is shown below in Figure 4.1. The procedures involved in the network selection mechanism using MCDM are represented by a step number within a circle.

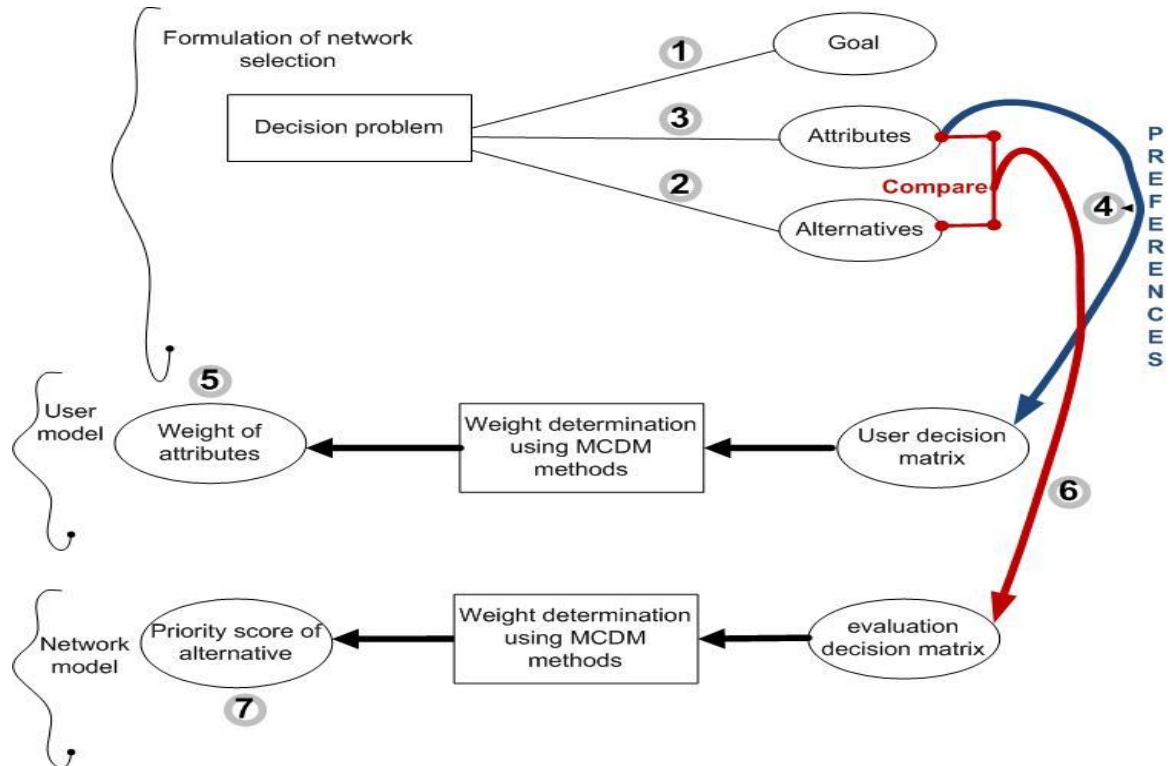


Figure 4.1 Block diagram of Network selection using the MCDM method

4.4 Formulation of Network selection

The hierarchy corresponding to “choosing a network” is shown in Figure. 4.2.

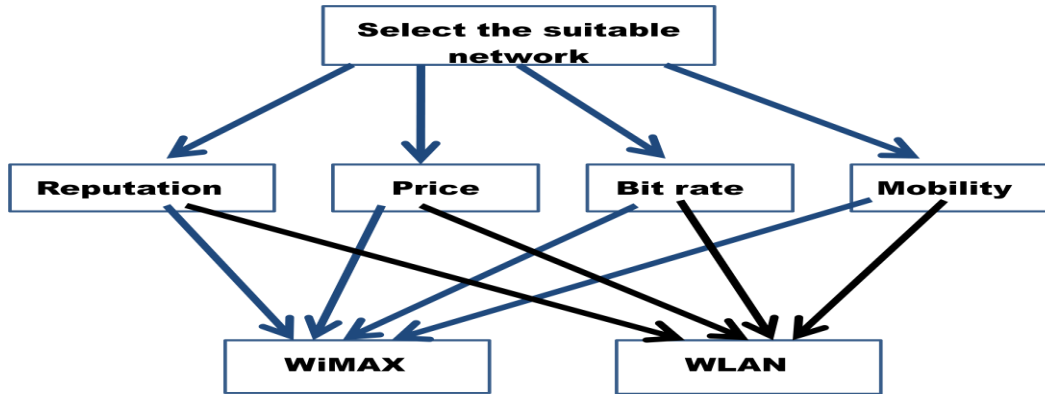


Figure 4.2 Network Selection Hierarchy

In this model multiple wireless networks operated by the same service provider offering its services to users. Pair-wise comparisons and the determination of the weights to be assigned to each attribute are performed following the AHP. For simplicity here, all users are assumed to be of same importance. We assume the providers offer their prices for the different networks simultaneously. The provider makes the first move by deciding to accept or reject the new connection request. After that the user decides whether to activate the subscription or not.

4.4.1 Goal

Each network controller is aware of the competitive nature but is not aware of other controllers' actions, and bases its actions on its own network's condition. Each time a user wishes to receive a service, they can express their preferences for different attributes according to their requirements e.g. by type of call. When the user selects a network, a contract is established with the network. The pilot signal strength, (modelled as a function of distance in the simulations, though in general this is observable) is used as a measure of power consumed to serve a user. The distance is a guide to how much it costs the provider to provide the service as the achieved bit rate for a unit of resource decreases. The network would prefer its users to be near the BS as then it can meet the bit-rate requirements, e.g. using different coding, without allocation lots of channels. It can then provide more bit rate in a single channel (a channel is not a constant bit rate). The QoS depends on how many channels the network is prepared to allocate given the rate it can transmit data (or receive data) to the user. The objective is to select an optimal network in accordance to the preferences of users for the considered attributes.

4.4.2 Alternative or Candidate networks

In the proposed model, there are two alternative networks considered namely the Wi-Fi hotspots within the coverage area of a WiMAX network.

4.4.3 Considered attributes

The following are the attributes used in our proposed network selection model:

Reputation: A measure of the user perceived satisfaction for a particular access network based on their delay and jitter parameters. In this chapter, reputation is assumed same as interface priority defined in [SHAIKH10]. The users prefer a network which provides the lowest delay and jitter according to the QoS limits defined for the requested application type. In Chapter 5, the reputation is the same for all the networks.

Cost: The price being offered by the access network for the service request. In the simulation, the price can be modelled as linear pricing or constant pricing. In the linear pricing, the networks charged price increases with the number of served users. For example, the loaded network will charge high price as compared to the un-loaded network for the same user. In this chapter constant pricing is assumed.

Offered Bit rate: The bit rate is the rate at which the user can transmit or receive their data. A user closer to the base station can transmit at a faster rate compared to a user farther away from the base station. The bit rate is dependent on the Signal to Noise Ratio (SNR). Depending on the SNR the network can provide different modulation schemes and based on this the bit rate can be calculated. In the simulation, the bit rate is computed depending on the user location and the modulation coding being applied by the base station.

Mobility support: The user can be of static, pedestrian or vehicle based and so requires different degrees of mobility support. User mobility support requirement plays an important role in the selection of the appropriate network. The mobility support offered by WiMAX to a user is greater as compared to the WLAN because the WiMAX has greater coverage area as compared to WLAN and the protocol has been designed to support mobility chosen attribute.

4.5 User Model

In the proposed network selection approach, the procedure can be divided into four steps as shown below:

4.5.1 User Payment Plan

Different users can have different priorities even though they may use the same application type. The user model contains a set of pre-defined payment plans to meet the specific needs of different types of users.

Table 4.1 User Payment Plan Goals

User Profile	Defining Objective
Pay as You Go	Low cost, acceptable QoS
Pay Monthly	Good QoS, fixed cost
Business	Excellent QoS, cost within budget

4.5.2 Assigning attribute preferences

The four network attributes namely as Cost, Bit rate, Mobility support and Reputation are considered in the network selection mechanism. The attribute preferences are assigned scores separately for each application type on a per user payment plan basis. For example, the video application has three sets of attribute priorities, one for each user profile.

Each attribute is ordered based on its relative importance for the goals of each user payment plan. For example, the order of the network attributes for voice application for pay as you go plan is shown below:

Pay as You Go [Cost, Reputation, Bit rate, Mobility support]

The order of attributes for a voice application for the pay monthly plan is shown below:

Pay Monthly [Reputation, Bit rate, Mobility support, Cost]

The order of network attributes for voice application for the business plan is shown below:

Business [Bit rate, Cost, Reputation, Mobility support]

The users for their payment plan and chosen application types give its preferences for the network selection attributes are mapped into the scores 1 to 9. The next step is to assign a set of scores in between 1-9 scale to network attribute in the descending priority order. The scores are equally spaced integers with a space gap dependent on the number of attribute [25] defined by Equation (4.5). Therefore, applying Equation (4.5) for the situation where $N_c = 4, S_h = 9$ and $S_l = 1$ give $I = \frac{9-1}{4} = 2$. Since the value of I is 2, the next important attribute for each user payment plan of a specific application type is assigned a score of ‘3’. Similarly, the remaining attributes are assigned scores of ‘5’ and ‘7’ respectively. The scores of attribute of each user payment plan for voice application are shown below in Table 4.2. The scores of attribute of each user payment plan for other application types are mentioned in Appendix B.1.

Table 4.2 Attribute scores per payment plan for voice application

Score	Pay as you go	Pay Monthly	Business
1	Cost	Reputation	Bit rate
3	Reputation	Bit rate	Cost
5	Bit rate	Mobility support	Reputation
7	Mobility support	Cost	Mobility support

4.5.3 Assigning application preferences

In this MCDM based network selection framework, four different types of application are considered namely as voice, video streaming, video interactive and data transfer. Therefore, applying (4.5) for the situation where $N_c = 4, S_h = 9$ and $S_l = 1$ give $I = \frac{9-1}{4} = 2$. The application preference scores are shown below in Table 4.3. Table 4.3 shows that independent of payment plan the model prefers the voice, video interactive, video streaming and data transfer in descending order. In [ZCKN11], the large amount of collected data is statistically analyzed to make the following observations:

- HTTP is the most popular application type. Its usage is more during the business hours and also a peak at 8 pm. Its usage starts to decrease after midnight.
- SIP based VOIP and push to talk services are more used in the business hours.

Based on the above observations, different preference scores can be defined for application types dependent on the time of day (i.e. business hours, off peak and night).

Table 4.3 Application preference scores

Score	Application
1	Voice
3	Video interactive
5	Video streaming
7	Data transfer

4.5.4 Assigning network preferences

Let WiMAX and WLAN be the two candidate networks available for selection. Network preference scores are assigned on a per application basis in a similar manner by applying Equation (4.5). With $I=4$ in this case, the network preference scores for each four type of application are shown below in Table 4.4. Table 4.4 shows the importance of WiMAX and WLAN networks for different application types independent of payment plan. This order can be varied based on the payment plan but it is not considered here.

Table 4.4 Network preference scores

Scores	Voice	Video interactive	Video streaming	Data transfer
1	WiMAX	WLAN	WLAN	WLAN
5	WLAN	WiMAX	WiMAX	WiMAX

4.5.5 Calculating the weight of each attribute

Every new user connection request has some parameters associated with it. Some users prefer the quality of service whereas some prefer low cost. The network should be able to provide the services requested by users. There are two comparison groups: a group of 'n=4' attributes and a group of 'm=2' alternatives.

In the first step we use AHP to calculate the weights of the chosen attributes based on the pair-wise comparisons. The pair-wise comparison describes the relative importance of one attribute over another attribute. Every attribute is compared against all other attributes to decide the relative importance of each attribute. Each user performs pair wise

comparisons between attributes using a 1 to 9 scale. The relative importance of network attribute ‘a’ as compared to the network attribute ‘b’ is computed using Equations (4.6), (4.7) and (4.8).

The pair-wise comparisons between the attributes result in a square matrix namely as C. The matrix C is created on per plan basis for each application type. This imply that user with similar payment plan with same application type would have similar matrix ‘C’. In this proposed MCDM based network selection model, the total number of matrix ‘C’ need to be created are given below:

$$n_C = n_{application} \times n_{profile} \quad (4.12)$$

Where n_c is the number of matrices ‘C’, $n_{application}$ is the number of application types considered and n_{plan} is the number of user payment plans. In this situation, $n_c = 4 \times 3 = 12$ (i.e. $C_{voice, pay as you go}$, $C_{voice, pay monthly}$, $C_{voice, business}$, $C_{video-int, pay as you go}$, $C_{video-int, pay monthly}$, $C_{video-int, business}$, $C_{video-str, pay as you go}$, $C_{video-str, pay monthly}$, $C_{video-str, business}$, $C_{data, pay as you go}$, $C_{data, pay monthly}$, $C_{data, business}$). The size of matrix ‘C’ is dependent on the number of considered network attributes and for the problem of choosing a network a matrix ‘C’ (square matrix of size ‘4’ is created) is shown below in Equation (4.13).

$$C = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \\ c_{41} & c_{42} & c_{43} & c_{44} \end{bmatrix} \quad (4.13)$$

Let’s consider the example of creating a comparison matrix ‘C’ for pay as you go payment plan with the voice application namely as ” $C_{voice, pay as you go}$ ” with the scores for the attributes defined as below:

$$S_{cost}=1, S_{reputation}=3, S_{bit rate}=5 \text{ and } S_{Mobility support}=7$$

The attributes cannot be compared against themselves so all the diagonal elements of matrix ‘C’ $c_{voice, pay as you go}$ i.e. $c_{11}=1$, $c_{22}=1$, $c_{33}=1$ and $c_{44}=1$. The attribute ‘cost’ can be compared with the attribute ‘reputation’ using Equation (4.6) as shown below:

$$c_{12} = \left(1 - \frac{1}{3}\right) \times 10 = \frac{20}{3} \approx 7$$

Similarly,

$$c_{21} = \frac{1}{c_{12}} = \frac{1}{7}$$

The attribute ‘cost’ can be compared with the attribute ‘bit rate’ using Equation (4.6) as shown below:

$$c_{13} = \left(1 - \frac{1}{5}\right) \times 10 = 8$$

Similarly,

$$c_{31} = \frac{1}{c_{13}} = \frac{1}{8}$$

The attribute ‘cost’ can be compared with the attribute ‘mobility support’ using Equation (4.6) as shown below:

$$c_{14} = \left(1 - \frac{1}{7}\right) \times 10 = \frac{60}{7} \approx 9$$

Similarly,

$$c_{41} = \frac{1}{c_{14}} = \frac{1}{9}$$

The attribute ‘reputation’ can be compared with the attribute ‘bit rate’ using Equation (4.6) as shown below:

$$c_{23} = \left(1 - \frac{3}{5}\right) \times 10 = 4$$

Similarly,

$$c_{32} = \frac{1}{c_{23}} = \frac{1}{4}$$

The attribute ‘reputation’ can be compared with the attribute ‘mobility support’ using Equation (4.6) as shown below:

$$c_{24} = \left(1 - \frac{3}{7}\right) \times 10 = \frac{40}{7} \approx 6$$

Similarly,

$$c_{42} = \frac{1}{c_{24}} = \frac{1}{6}$$

The attribute ‘bit rate’ can be compared with the attribute ‘mobility support’ using Equation (4.6) as shown below:

$$c_{34} = \left(1 - \frac{5}{7}\right) \times 10 = \frac{20}{7} \approx 3$$

Similarly,

$$c_{43} = \frac{1}{c_{34}} = \frac{1}{3}$$

The comparison matrix 'C' for pay as you go payment plan with the voice application namely as " $C_{voice, pay as you go}$ " is shown below:

$$C_{voice, pay as you go} = \begin{bmatrix} 1 & 7 & 8 & 9 \\ \frac{1}{7} & 1 & 4 & 6 \\ \frac{1}{8} & \frac{1}{4} & 1 & 3 \\ \frac{1}{9} & \frac{1}{6} & \frac{1}{3} & 1 \end{bmatrix}$$

Similarly, the comparison matrixes 'C' for voice application with pay monthly and business payment plans are shown below:

$$C_{voice, pay monthly} = \begin{bmatrix} 1 & \frac{1}{9} & \frac{1}{6} & \frac{1}{3} \\ 9 & 1 & 7 & 8 \\ 6 & \frac{1}{7} & 1 & 4 \\ 3 & \frac{1}{8} & \frac{1}{4} & 1 \end{bmatrix}$$

$$C_{voice, business} = \begin{bmatrix} 1 & 4 & \frac{1}{7} & 6 \\ \frac{1}{4} & 1 & \frac{1}{8} & 3 \\ 7 & 8 & 1 & 9 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{9} & 1 \end{bmatrix}$$

Similarly, the comparison matrixes 'C' for video interactive application with pay as you go, pay monthly and business payment plans are shown below:

$$C_{videoint, pay as you go} = \begin{bmatrix} 1 & \frac{1}{4} & \frac{1}{8} & 3 \\ \frac{1}{7} & 1 & 4 & 6 \\ 8 & 7 & 1 & 9 \\ \frac{1}{9} & \frac{1}{6} & \frac{1}{3} & 1 \end{bmatrix}$$

$$C_{\text{videoint,pay monthly}} = \begin{bmatrix} 1 & \frac{1}{6} & \frac{1}{3} & \frac{1}{9} \\ \frac{1}{7} & 1 & 4 & 6 \\ 8 & 7 & 1 & 9 \\ 3 & \frac{1}{4} & \frac{1}{8} & 1 \end{bmatrix}$$

$$C_{\text{videoint,business}} = \begin{bmatrix} 1 & 4 & \frac{1}{7} & 6 \\ \frac{1}{4} & 1 & \frac{1}{8} & 3 \\ 7 & 8 & 1 & 9 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{9} & 1 \end{bmatrix}$$

Similarly, the comparison matrixes ‘C’ for video streaming application with pay as you go, pay monthly and business payment plans are shown below:

$$C_{\text{videostr,pay monthly}} = \begin{bmatrix} 1 & \frac{1}{6} & \frac{1}{9} & \frac{1}{3} \\ 6 & 1 & \frac{1}{7} & 4 \\ 9 & 7 & 1 & 8 \\ 3 & \frac{1}{4} & \frac{1}{8} & 1 \end{bmatrix}$$

$$C_{\text{videostr,pay as you go}} = \begin{bmatrix} 1 & 4 & \frac{1}{7} & 6 \\ \frac{1}{4} & 1 & \frac{1}{8} & 3 \\ 7 & 8 & 1 & 9 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{9} & 1 \end{bmatrix}$$

$$C_{\text{videostr,business}} = \begin{bmatrix} 1 & 6 & \frac{1}{7} & 4 \\ \frac{1}{6} & 1 & \frac{1}{9} & \frac{1}{3} \\ 7 & 9 & 1 & 8 \\ \frac{1}{4} & 3 & \frac{1}{8} & 1 \end{bmatrix}$$

Similarly, the comparison matrixes ‘C’ for data application with pay as you go, pay monthly and business payment plans are shown below:

$$C_{\text{data,pay as you go}} = \begin{bmatrix} 1 & 4 & \frac{1}{7} & 6 \\ \frac{1}{4} & 1 & \frac{1}{8} & 3 \\ 7 & 8 & 1 & 9 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{9} & 1 \end{bmatrix}$$

$$C_{\text{data,pay monthly}} = \begin{bmatrix} 1 & 4 & \frac{1}{7} & 6 \\ \frac{1}{4} & 1 & \frac{1}{8} & 3 \\ 7 & 8 & 1 & 9 \\ \frac{1}{6} & \frac{1}{3} & \frac{1}{9} & 1 \end{bmatrix}$$

$$C_{\text{data,business}} = \begin{bmatrix} 1 & \frac{1}{3} & \frac{1}{9} & \frac{1}{6} \\ 3 & 1 & \frac{1}{8} & \frac{1}{4} \\ 9 & 8 & 1 & 7 \\ 6 & 4 & \frac{1}{7} & 1 \end{bmatrix}$$

For each comparison matrix C, the “eigenvector” for the network attributes [HY81] can be calculated using geometric mean method. Specifically the element \bar{w}_i is derived as shown below in Equation (4.14).

$$\bar{w}_i = \sqrt[n]{c_{i1} \times c_{i2} \times c_{i3} \times c_{in}} \quad (i = 1, 2, \dots, n) \quad (4.14)$$

These \bar{w}_i (*in our case* $\bar{w}_1, \bar{w}_2, \bar{w}_3, \bar{w}_4$) for each of the network attributes are normalized to get their respective weight w_i . The weight value w_i is determined using Equation (4.15)

$$w_i = \frac{\bar{w}_i}{\sum_{i=1}^4 \bar{w}_i} \quad (i = 1, 2, \dots, 4) \quad (4.15)$$

Hence each payment plan and application type combination will have a weight for each network attribute. The four weights $W = [w_1 \ w_2 \ w_3 \ w_4]$ corresponds to the Reputation (R), Cost (C), Bit rate (B) and Mobility support (M) respectively. The weight of attribute for different application types per payment plan calculations are mentioned in Appendix B.2. In total, there will be twelve sets of ‘W’ as there are three types of payment plan and four types of application.

Table 4.5 Weight of attribute for different application types per payment plan

Application Type /Payment plan	Pay as you go	Pay Monthly	Business
Voice	$w_C = 0.683$ $w_R = 0.196$ $w_B = 0.080$ $w_M = 0.041$	$w_C = 0.040$ $w_R = 0.692$ $w_B = 0.193$ $w_M = 0.076$	$w_C = 0.193$ $w_R = 0.076$ $w_B = 0.692$ $w_M = 0.040$
Video-streaming	$w_C = 0.193$ $w_R = 0.076$ $w_B = 0.692$ $w_M = 0.040$	$w_C = 0.040$ $w_R = 0.193$ $w_B = 0.692$ $w_M = 0.076$	$w_C = 0.193$ $w_R = 0.040$ $w_B = 0.692$ $w_M = 0.076$
Video-interactive	$w_C = 0.084$ $w_R = 0.538$ $w_B = 0.334$ $w_M = 0.043$	$w_C = 0.047$ $w_R = 0.517$ $w_B = 0.313$ $w_M = 0.123$	$w_C = 0.193$ $w_R = 0.076$ $w_B = 0.692$ $w_M = 0.040$
Data	$w_C = 0.193$ $w_R = 0.076$ $w_B = 0.692$ $w_M = 0.040$	$w_C = 0.193$ $w_R = 0.076$ $w_B = 0.692$ $w_M = 0.040$	$w_C = 0.040$ $w_R = 0.076$ $w_B = 0.692$ $w_M = 0.193$

4.6 Network Model

A network model consisting of a two-dimensional matrix called an evaluation matrix is created. In the evaluation matrix, each column corresponds to a value for the considered network attribute and each row corresponds to the candidate networks. In user model, the users are categorised on payment plan and application type combination whereas in network model each user request is a separate entity irrespective of payment plan and application type combination. The users with same payment plan and application type combination can be closer or further away from the base station thus can be offered different bit rates and modulation scheme by the base station. In order to cater this concept, an evaluation matrix is generated for each user request irrespective of payment plan and application type. This implies that users having identical payment plan and

application type combination can have different evaluation matrix. An evaluation matrix representing 1-n networks is given below in Table 4.6:

Table 4.6 Evaluation matrix

Candidate Network/Attribute	Reputation	Bit rate	Mobility support	Cost
Network 1	R_1	B_1	M_1	C_1
Network 2	R_2	B_2	M_2	C_2
Network n	R_n	B_n	M_n	C_n

The *Bit rate* column stores the value of the current bit rate offered by a certain network. *Reputation*, *Mobility support* and *Cost* indicate the historical interaction of a particular user (irrespective of payment plan and application type combination) with a certain network, mobility support offered by a certain network and the cost charged for transmission by certain network respectively.

Assigning scores to static attributes such as reputation, mobility support and cost is simple. For cost, the available networks are compared with each other and assigned scores between 1 to 9 based on Equation (4.5) where the cheapest network has a score '1'. The network with unknown cost is assigned a score '9'. Dynamically changing attributes such as offered bit rate for available networks are compared with the individual network attribute limit values. The network score S_i is calculated using Equations (4.6) and (4.7). The Equation (4.6) is applied for the positive attributes (i.e. larger the better) whereas Equation (4.7) is applied for negative attributes (i.e. smaller the better).

For every user request, the available network ($j = 1, 2$) offers different values for each network attribute ($i = 1, 2, \dots, 4$). These values of each attribute offered by each available network represent how well each available network performs in terms of each network attribute. A pair-wise comparison is carried out on the basis of offered quality levels by available networks for each attribute.

In this step the network scores (calculated using Equations 4.6 or 4.7) among available networks for certain network attribute are compared using Equations (4.8), (4.9) and

(4.10) to constitute a comparison matrix of available networks for each network attribute. For example, let's consider a user with pay as you go payment plan requesting a voice application with the respective evaluation matrix as shown below in Table 4.7:

Table 4.7 Evaluation matrix example

	Reputation	Bit rate	Mobility support	Cost
Wi-Fi	2	36kbps	Low	25p/min
WiMAX	3	42kbps	High	22p/min

Using Equation (4.6) to calculate the score of network attribute 'reputation' for Wi-Fi and WiMAX network with the following condition $l_i < n_i < u_i$ where $l_i = 1$ & $u_i = 5$ and $n_{WiFi} = 2$ & $n_{WiMAX} = 3$.

$$S_{WiFi} = \left(1 - \frac{2-1}{5-1}\right) \times 10 = 30/4$$

$$S_{WiMAX} = \left(1 - \frac{3-1}{5-1}\right) \times 10 = 5$$

By applying Equation (4.9) to get a comparison matrix where subscript '1' is used for Wi-Fi and subscript '2' is used for WiMAX

$$\frac{1}{c_{12}} = \left(1 - \frac{S_{WiMAX}}{S_{WiFi}}\right) \times 10 = 3.333$$

$$c_{21} = \frac{1}{c_{12}} = 3.333$$

$$c_{12} = \frac{1}{c_{21}} = 0.3$$

$$C_{\text{voice, pay as you go}}^{\text{reputation}} = \begin{bmatrix} 1 & 0.3 \\ 3.333 & 1 \end{bmatrix}$$

The size of comparison matrix of available networks for each network attribute would be 2×2 . There are four network attributes so we would have four 2×2 available network comparison matrixes i.e. one for each network attribute. The Equations (4.14) and (4.15) mentioned in step 4.4.5 can be applied to the comparison matrix to find the

relative network scores of available networks for each of the network attributes Cost, Reputation, Bit rate and Mobility support.

The final overall ranking of each network is determined through the sum of the products of weight of each attribute (obtained from section 4.4.5) with the relative network scores for that attribute. For ‘i’ number of attributes and ‘j’ number of networks, the network ranking is given as

$$r_j = \sum_1^{ij} (w_i \times p_j^i) \quad (4.16)$$

In Equation (4.16), w_i is the weight of attribute ‘i’ and p_j^i is the network score of network ‘j’ for attribute ‘i’. In our model, there are four attributes and two available networks so the network ranking for available networks WiMAX and Wi-Fi is given as below:

$$r_{WiMAX} = w_R \times p_{WiMAX}^R + w_B \times p_{WiMAX}^B + w_M \times p_{WiMAX}^M + w_C \times p_{WiMAX}^C \quad (4.17)$$

$$r_{Wi-Fi} = w_R \times p_{Wi-Fi}^R + w_B \times p_{Wi-Fi}^B + w_M \times p_{Wi-Fi}^M + w_C \times p_{Wi-Fi}^C \quad (4.18)$$

The network with the highest ranking is chosen.

4.7 Worked Example

The comparison matrix ‘C’ for pay as you go payment plan with the voice application namely as “ $C_{voice, pay as you go}$ ” based on Table 4.2 (containing network attributes scores for pay as you go payment plan) is shown below:

$$C_{voice, pay as you go} = \begin{bmatrix} 1 & 7 & 8 & 9 \\ \frac{1}{7} & 1 & 4 & 6 \\ \frac{1}{8} & \frac{1}{4} & 1 & 3 \\ \frac{1}{9} & \frac{1}{6} & \frac{1}{3} & 1 \end{bmatrix}$$

$$\overline{w_C} = \sqrt[4]{1 \times 7 \times 8 \times 9} = \sqrt[4]{504} = 4.738$$

$$\overline{w_R} = \sqrt[4]{1/7 \times 1 \times 4 \times 6} = \sqrt[4]{\frac{24}{7}} = 1.361$$

$$\overline{w_B} = \sqrt[4]{1/8 \times 1/4 \times 1 \times 3} = \sqrt[4]{\frac{3}{32}} = 0.554$$

$$\overline{w_M} = \sqrt[4]{1/9 \times 1/6 \times 1/3 \times 1} = \sqrt[4]{\frac{1}{162}} = 0.281$$

$$w_C = \frac{4.738}{6.934} = 0.683$$

$$w_R = \frac{1.361}{6.934} = 0.196$$

$$w_B = \frac{0.554}{6.934} = 0.080$$

$$w_M = \frac{0.281}{6.934} = 0.041$$

An evaluation matrix as mentioned before in Table 4.7 is reconsidered,

i. Reputation

$$C_{\text{voice, pay as you go}}^R = \begin{bmatrix} 1 & 0.300 \\ 3.333 & 1 \end{bmatrix}$$

$$\bar{p}_{WiMAX}^R = \sqrt[2]{1 \times 3.333} = 1.826$$

$$\bar{p}_{WiFi}^R = \sqrt[2]{0.300 \times 1} = 0.548$$

$$p_{WiMAX}^R = \frac{1.826}{2.374} = 0.769$$

$$p_{WiFi}^R = \frac{0.548}{2.374} = 0.231$$

ii. Bit rate

$$S_{WiFi} = \left(1 - \frac{36 - 4}{64 - 4}\right) \times 10 \approx 5$$

$$S_{WiMAX} = \left(1 - \frac{42 - 4}{64 - 4}\right) \times 10 \approx 4$$

$$\frac{1}{c_{12}} = \left(1 - \frac{4}{5}\right) \times 10 = 2$$

$$c_{21} = \frac{1}{c_{12}} = 2$$

$$c_{12} = \frac{1}{c_{21}} = \frac{1}{2}$$

$$C_{\text{voice, pay as you go}}^B = \begin{bmatrix} 1 & 0.5 \\ 2 & 1 \end{bmatrix}$$

$$\bar{p}_{WiFi}^B = \sqrt[2]{1 \times 0.5} = 0.707$$

$$\bar{p}_{WiMAX}^B = \sqrt[2]{2 \times 1} = 1.414$$

$$p_{WiFi}^B = \frac{0.707}{2.121} = 0.333$$

$$p_{WiMAX}^B = \frac{1.414}{2.121} = 0.667$$

iii. Cost

$$S_{WiFi} = \left(\frac{25 - 3}{30 - 3} \right) \times 10 \approx 8$$

$$S_{WiMAX} = \left(\frac{22 - 3}{30 - 3} \right) \times 10 \approx 7$$

$$\frac{1}{c_{12}} = \left(1 - \frac{7}{8} \right) \times 10 = 1.25$$

$$c_{21} = \frac{1}{c_{12}} = 1.25$$

$$c_{12} = \frac{1}{c_{21}} = \frac{1}{1.25} = 0.8$$

$$C_{\text{voice, pay as you go}}^C = \begin{bmatrix} 1 & 0.8 \\ 1.25 & 1 \end{bmatrix}$$

$$\bar{p}_{WiFi}^C = \sqrt[2]{1 \times 0.8} = 0.895$$

$$\bar{p}_{WiMAX}^C = \sqrt[2]{1.25 \times 1} = 1.118$$

$$p_{WiFi}^C = \frac{0.895}{2.013} = 0.445$$

$$p_{WiMAX}^C = \frac{1.118}{2.013} = 0.555$$

iv. Mobility support

$$S_{WiFi} = 7$$

$$S_{WiMAX} = 1$$

$$\frac{1}{c_{12}} = \left(1 - \frac{1}{7}\right) \times 10 \approx 8$$

$$c_{21} = \frac{1}{c_{12}} \approx 8$$

$$c_{12} = \frac{1}{c_{21}} = \frac{1}{8} \approx 0.125$$

$$C_{\text{voice, pay as you go}}^M = \begin{bmatrix} 1 & 0.125 \\ 8 & 1 \end{bmatrix}$$

$$\bar{p}_{WiFi}^M = \sqrt[2]{1 \times 0.125} = 0.356$$

$$\bar{p}_{WiMAX}^M = \sqrt[2]{8 \times 1} = 2.828$$

$$p_{WiFi}^M = \frac{0.356}{3.184} = 0.112$$

$$p_{WiMAX}^M = \frac{2.828}{3.184} = 0.888$$

$$r_{WiMAX} = w_R \times p_{WiMAX}^R + w_B \times p_{WiMAX}^B + w_C \times p_{WiMAX}^C + w_M \times p_{WiMAX}^M$$

$$r_{WiMAX} = 0.196 \times 0.769 + 0.080 \times 0.667 + 0.683 \times 0.555 + 0.041 \times 0.888$$

$$r_{WiMAX} = 0.151 + 0.053 + 0.379 + 0.037 = 0.62$$

$$r_{Wi-Fi} = w_R \times p_{Wi-Fi}^R + w_B \times p_{Wi-Fi}^B + w_C \times p_{Wi-Fi}^C + w_M \times p_{Wi-Fi}^M$$

$$r_{Wi-Fi} = 0.196 \times 0.231 + 0.080 \times 0.333 + 0.683 \times 0.445 + 0.041 \times 0.112$$

$$r_{Wi-Fi} = 0.045 + 0.026 + 0.304 + 0.005 = 0.38$$

Decision: WiMAX is selected

4.8 Realistic Scenarios

The scenarios consider two types of Radio Access Networks (RANs), a UTRAN based macro-cell and an IEEE 802.11b based WLAN. All the users are covered by both the UTRAN cell and the WLAN with acceptable radio channel conditions. The simulations implement the four types of applications namely as voice, video interactive, video

streaming and data. For the UDP based real time applications, the data rate values are fixed. For TCP based non-real time applications, the data rate values are the minimum requirements for each service.

The number of users already being served by UMTS macro-cell and WLAN hotspot at any location on the shown path is unknown. In order to cater this situation, it is assumed that the data rates are measured multiple times (i.e. 20 times for Home scenario in this thesis) for both UMTS macro-cell and WLAN hotspots at each location. The mean and variance of measured data rate for both UMTS macro-cell and WLAN hotspots are calculated at each location.

The users start the services gradually and each user can start one service at a time. When a service request is received, the MCDM based network selection algorithm assigns the service request to an appropriate network. The measurements can be taken at multiple times during different times of day (as peak, off-peak and night).

4.8.1 Home scenario

To evaluate the behaviour of our proposed network selection algorithm, a scenario is assumed with two users at Locations 'A' and 'I' (as shown in Figure 4.3) belonging to same or different payment plans making request for same or different type of applications. In this scenario, the measurements are taken during the peak times for Wi-Fi and UMTS as shown below in Table 4.8 and 4.9 respectively. All the users at a particular location in Home are assumed to have mean bit rate. All the users are equipped with multi-mode terminal and uses same type of handset.

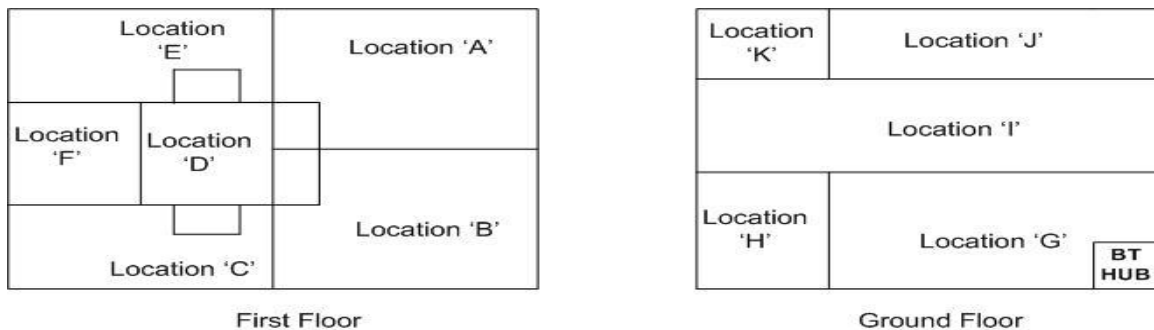


Figure 4.3 Home scenario

Table 4.8 Wi-Fi related data at different locations of Home scenario

Wi-Fi	Location 'A'	Location 'E'	Location 'I'	Location 'J'
Min	252.75	489.125	40.875	603.75
Max	634.625	578.375	607.5	679.875
Mean	595.68125	564.45625	383.0125	665.3375
Std Deviation	113.516193	26.2449373	172.27895	25.24096

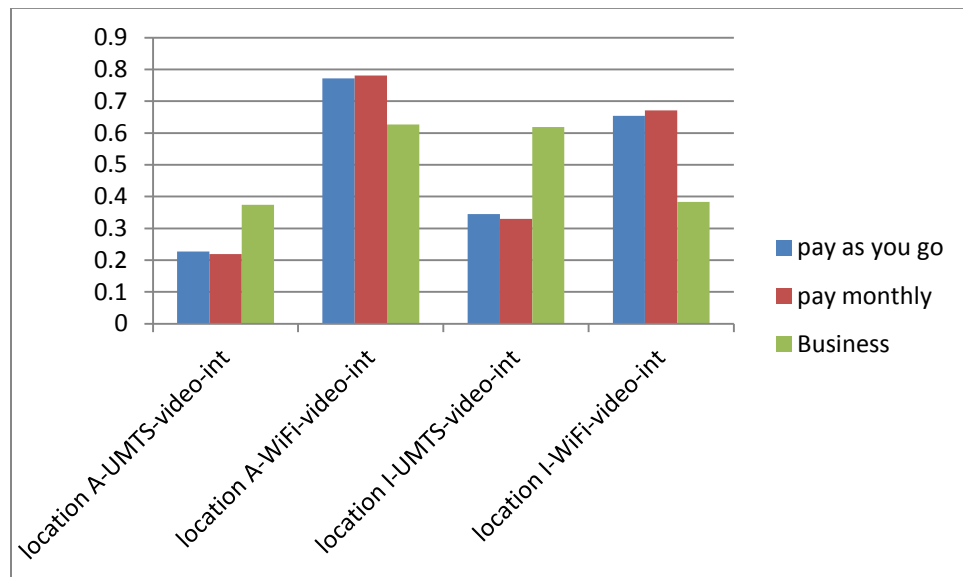
Table 4.9 UMTS related data at different locations of Home scenario

UMTS	Location 'A'	Location 'E'	Location 'I'	Location 'J'
Min	17.25	15.25	24.375	24.25
Max	73.25	45	40.875	79.375
Mean	43.2875	27.50625	30.68125	48.9
Standard Deviation	17.7167244	9.10928067	5.132097524	17.5852846

In this scenario, the network selection is evaluated for the following cases:

Case 1: The users at locations 'A' and 'I' within the Home requesting same type of application with same payment plan or different payment plans are shown below in Figure 4.4.

Case 2: The users at locations 'A' and 'I' within the Home requesting different type of applications with same or different payment plans are shown below in Figure 4.5 and 4.6.

**Figure 4.4 Payoffs of user requesting video-interactive application at locations 'A' and 'I'**

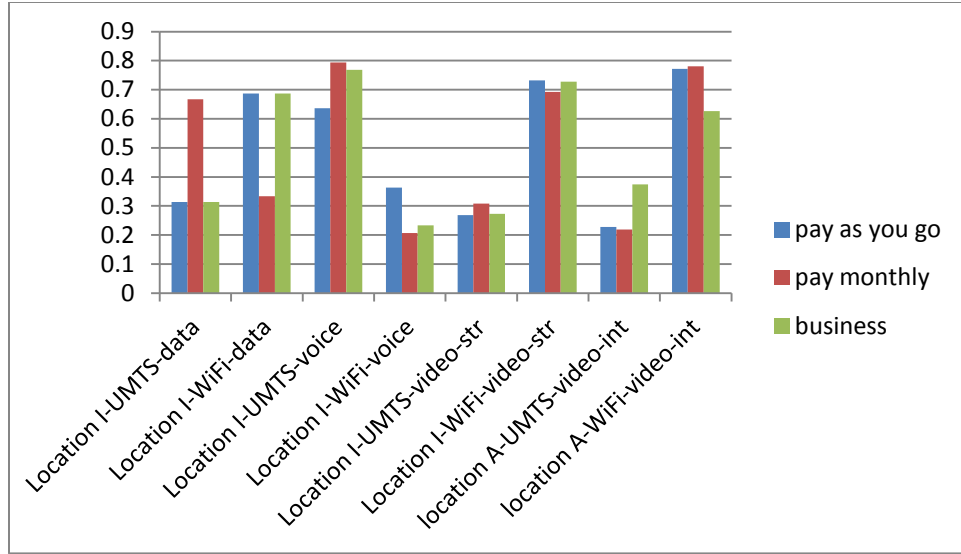


Figure 4.5 Payoffs of user at location 'I' requesting different applications whereas the user at location 'A' request video-interactive application

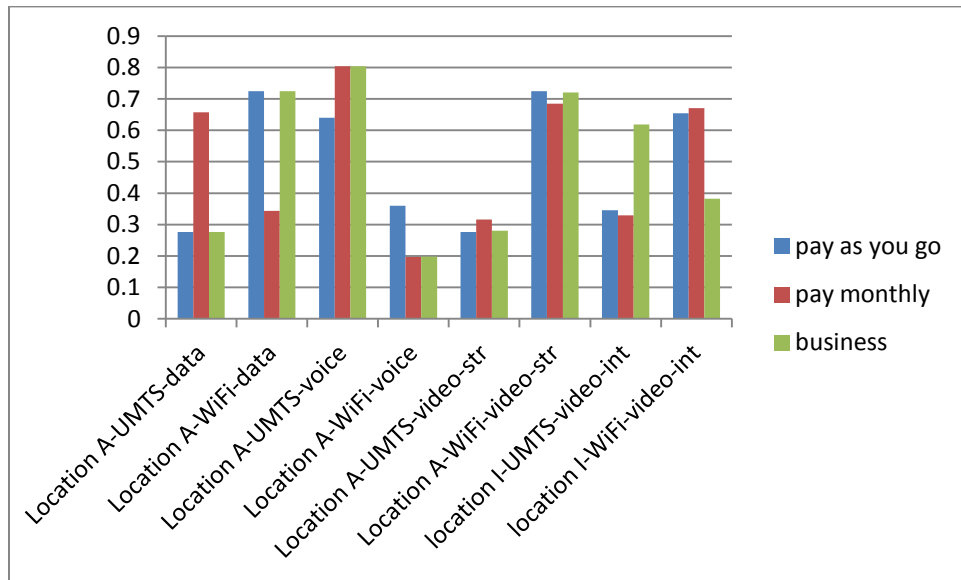


Figure 4.6 Payoffs of user at location 'A' requesting different applications whereas the user at location 'I' request video-interactive application

In case 1 (as shown in Figure 4.4), the user at location 'A' requesting video-interactive application always select Wi-Fi network irrespective of the payment plan whereas the user at location 'I' requesting video-interactive application always select Wi-Fi network except in case of business payment plan (UMTS is selected). At location 'I' (as shown in Figure 4.5), the UMTS network is selected for voice applications request irrespective of payment plan and data application request for pay monthly plan. Similarly for all other

application request at location ‘A’ and ‘I’, the Wi-Fi network is selected. In Figure 4.6, the UMTS network is selected for voice applications request irrespective of payment plan and data application request for pay monthly plan at location ‘A’. At location ‘I’, the UMTS network is selected only for video-interactive application request. The Wi-Fi network is selected for all other application requests at location ‘A’ and ‘I’.

4.8.2 Walking from home to the Supermarket scenario

To evaluate the behaviour of our proposed network selection algorithm, a scenario with four users belonging to pay as you go payment plan is assumed moving from Region ‘A’ to ‘B’ through the same path (marked by blue line on the map shown in Figure 4.7) at pedestrian speed.

In the scenario, user ‘1’ started File transfer service from start of the journey (location ‘1’) to the location ‘8’ (i.e. 0 to 480 seconds) followed by voice service from location ‘8’ to ‘15’ (i.e. 480 to 900 seconds). The user ‘2’ uses video streaming application throughout the considered scenario. The user ‘3’ only uses voice services throughout the considered scenario whereas user ‘4’ only initiates video-interactive. All the users are equipped with multi-mode terminal and uses same type of handset. In this scenario, the measurements are taken during the peak times for the shown path. The weights of attributes of different application types for pay as you go payment plan are mentioned in Table 4.5. The considered networks are UMTS and WLAN. The users while walking through the locations ‘1’ to ‘15’ have an access to different WLAN hotspots operated by different network providers.

In this scenario, the data rates offered by UTRAN based macro-cell operated by “Three network” are measured using “cnlab speed test” application installed on “Iphone 4” at every minute interval as shown below in Figure 4.8. Similarly, the data rates offered by BT Open-zone hotspots and BTFON hotspots at different locations of the considered scenario are assumed as shown below in Figure 4.9.

The data rate is measured at each location using Iphone ‘4’ handsets and can be allocated to each individual user. For example, at location ‘A’ in the above mentioned scenario, the data rates are measured four times at each location for both UMTS macro-cell (e.g. u_1 , u_2 ,

u_3, u_4) and WLAN hotspot (e.g. wl_1, wl_2, wl_3, wl_4). There are four users so each user is assigned a (u, wl) pair at each location.

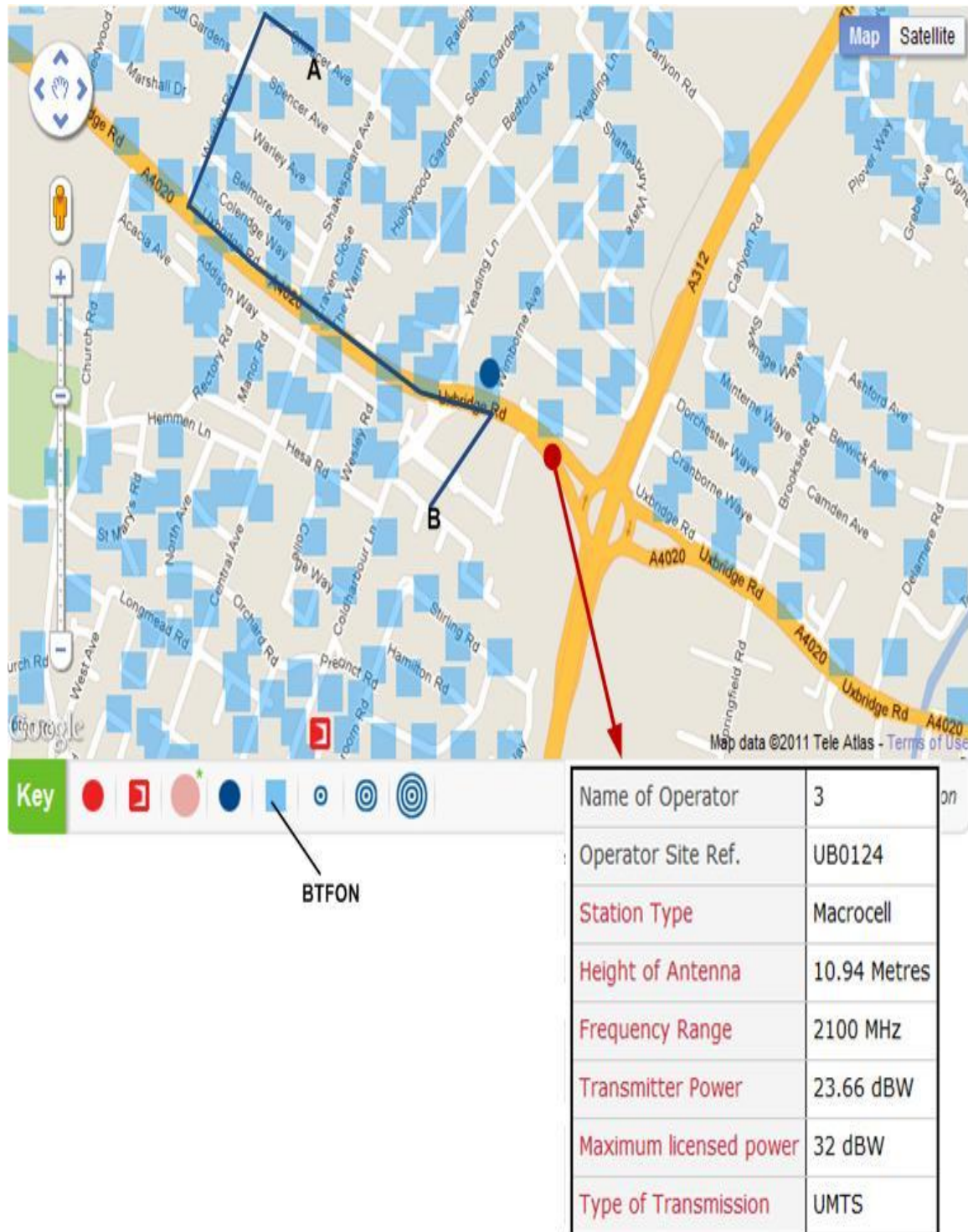


Figure 4.7 Walking from home to the shopping centre scenario

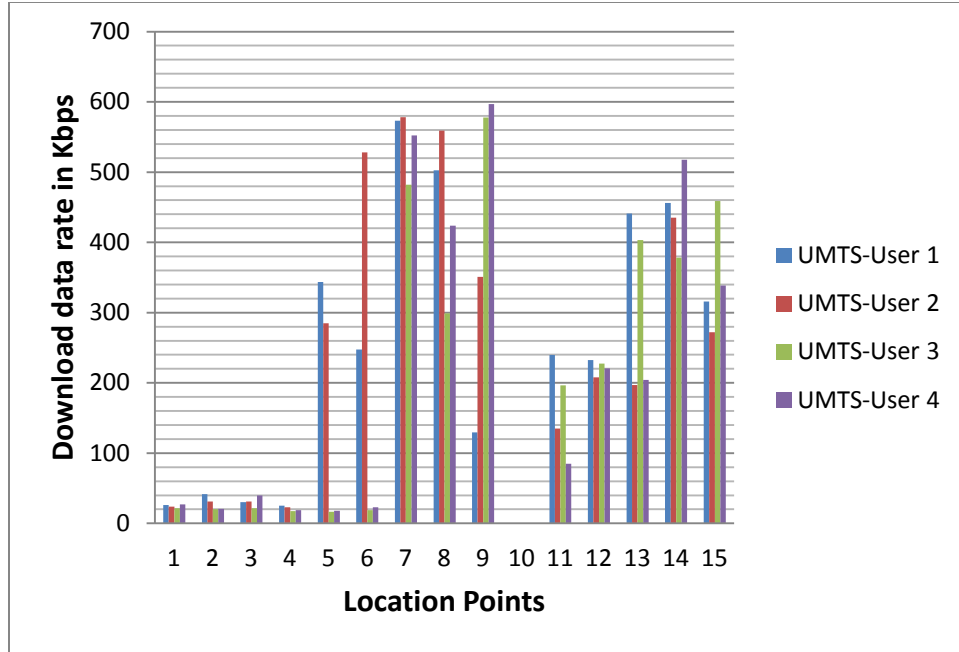


Figure 4.8 User perceived data rate for UMTS macro-cell [Kbps]

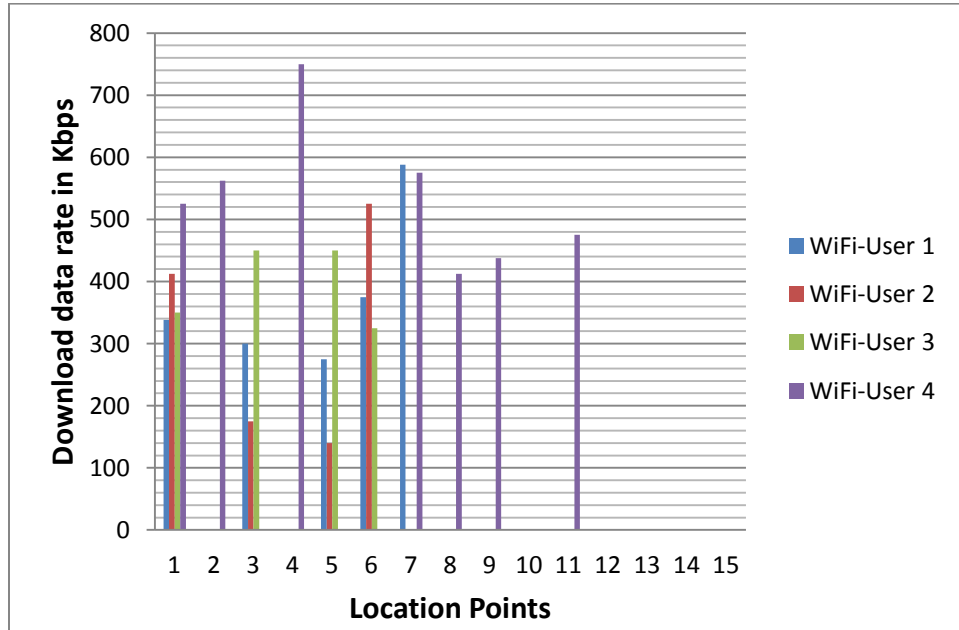


Figure 4.9 User perceived data rate of WLAN [Kbps]

4.8.2.1 Performance Evaluation

The performance are evaluated and compared in terms of the data rates perceived by the users and the selection of an optimal network. The results are presented in Figure 4.10, 4.11, 4.12 and 4.13 respectively. Figure 4.10 compares the data rate perceived by all users in UMTS macro-cell and the WLAN hotspot. Figure 4.11 shows the data rate

perceived by the users served by UMTS macro-cell and Figure 4.12 shows the data rate perceived by the users served by WLAN hotspot. Figure 4.13, 4.14, 4.15 and 4.16 shows the selection of an optimal network for all users at the different locations of the path.

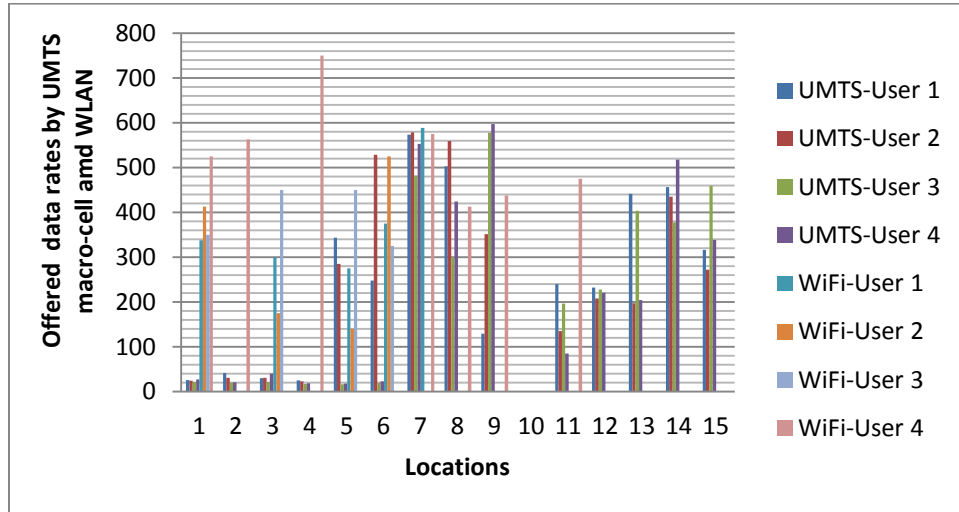


Figure 4.10 Data rates perceived by all users in UMTS macro-cell and WLAN

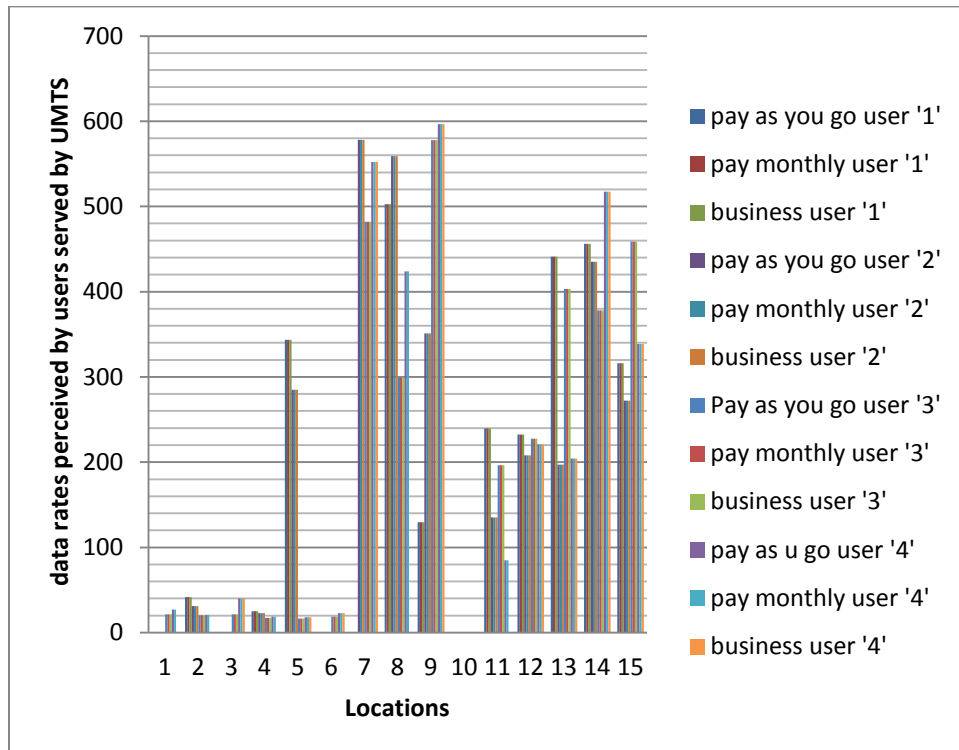


Figure 4.11 Data rates perceived by users served by UMTS macro-cell

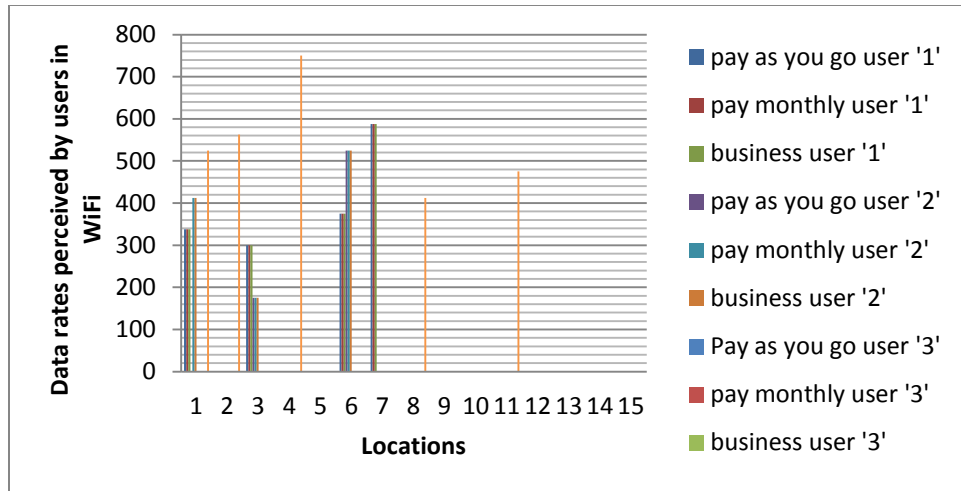


Figure 4.12 Data rates perceived by users served by WLAN

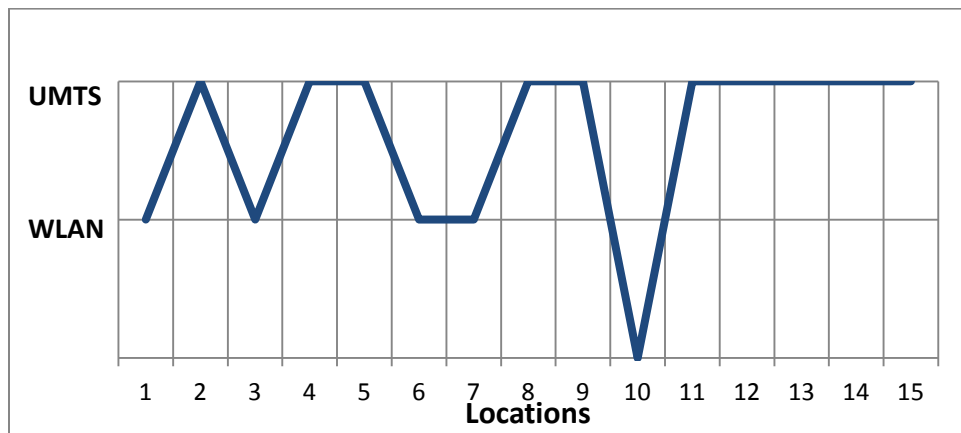


Figure 4.13 Network selection for User '1'

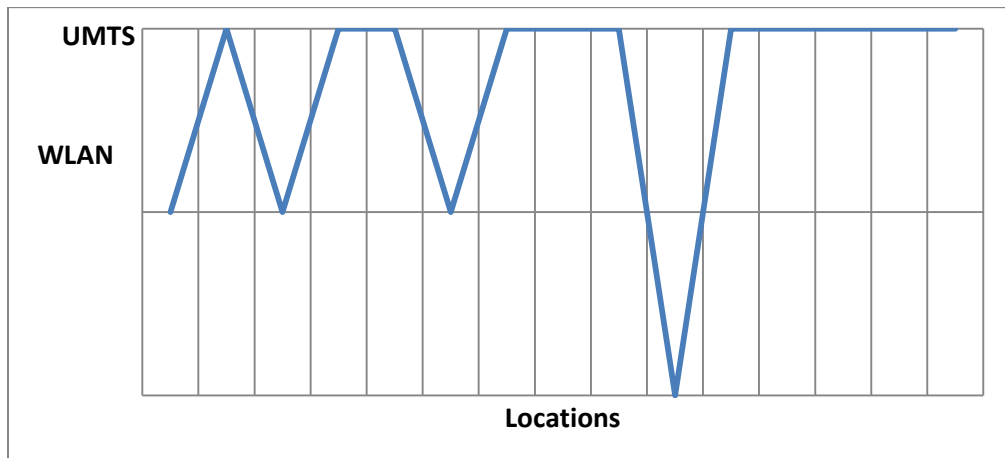


Figure 4.14 Network selection for User '2'

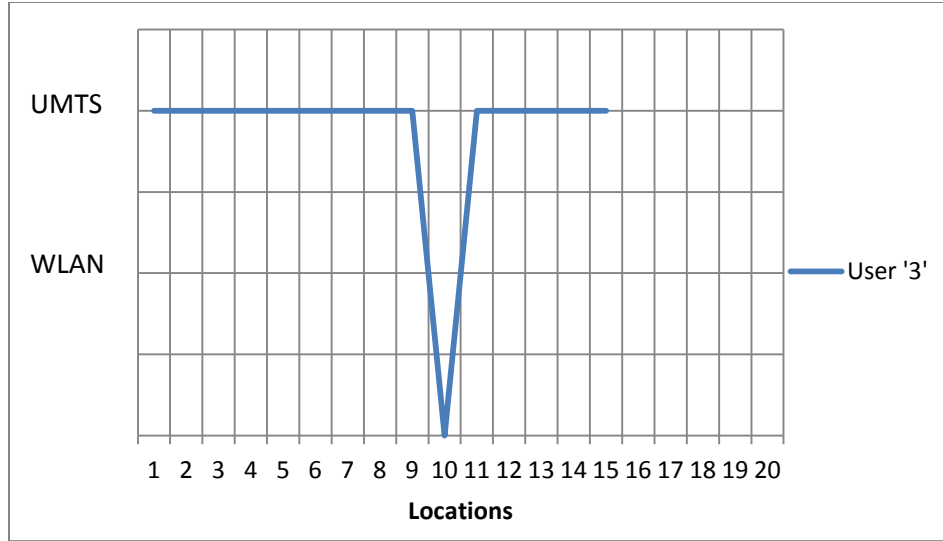


Figure 4.15 Network selection for User '3'

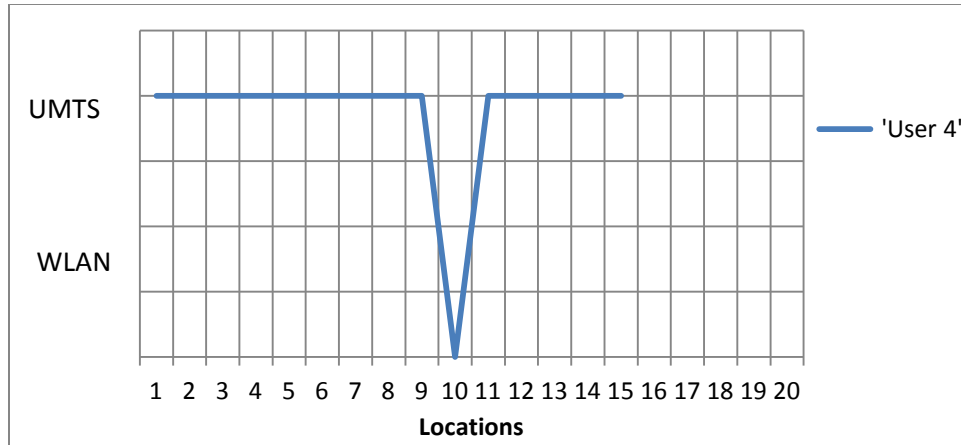


Figure 4.16 Network selection for User '4'

4.9 Computing the payoff for each user

The previous sections consider the selection from the user perspective whereas in this section network perspective is considered. The payoff for each network compromises two parts namely the network reward index and the utility ' U_i ' to be gained by network ' i ' if the user selects the network ' i '. The pilot signal strength, (modelled as a function of distance in the simulations) is used as a measure of power consumed to serve a user. The distance is a guide to how much it costs the provider to provide the service. The provider would prefer its users to be near the BS as then it can meet the bit-rate requirements e.g. using different coding, without allocation lots of channels. It can provide more bit rate in

a single channel. The QoS depends on how many channels the provider is prepared to allocate given the rate it can transmit data (or receive data) to the user.

In this case, the utility of providing the bit rate ‘ U_i ’ in fact depends on the location of the mobile unit as the resources required depend on the location. U is defined as a number between 0 and 1 such that it is ‘1’ when the user is close to the base station (or AP) and ‘0’ when the user is far from the base station (or AP). From the network perspective, the less transmitting power will be needed to serve a user at a minimum distance to the network as compared to user at the border of coverage area. The payoff for each network in a particular cell is shown below in Equation (4.19):

$$R_i = r_i \times U_i \quad (4.19)$$

In (4.19), r_i is the utility value from the user perspective and U_i is the utility value from the network perspective. In the simulation the modified utility value decreases with the perceived distance from the particular base station (or AP) as shown below in Equation (4.20).

$$U_i = 1 - \gamma(d - d_{min}) \quad (4.20)$$

The value of α , d_{min} and d_{max} is chosen so that U ranges from ‘1’ to ‘0’ according to the wireless network being used. However there are situations where it is possible to configure the antenna so that the network provider can change the value of U . The details of how this can be done are not described here, but are described in [JBW08]. The Equation (4.19) can be rewritten as shown below in Equation (4.21).

$$R_i = r_i \times (1 - \gamma(d - d_{min})) \quad (4.21)$$

The payoff of all candidate networks is determined in accordance with the user’s attribute and the network with highest payoff is selected as the candidate solution. The AHP is used to calculate the reward index for each candidate network considering the user’s preferences whereas the concept of wireless environment (i.e. every network can cover a mobile user within a particular coverage area) is employed in the form of utility function for the calculation of payoff.

4.10 Sensitivity Analysis

There are issues relating to the determination of the preferences and the sensitivity of the decisions to the values. The network selection would change if the user changes his

preference on cost (the weight of cost w_c is varied from 0.1 to 0.7 for the example mentioned in Chapter 3) as shown in Figure 4.12. Initially at $w_c=0.1$, the network '3' is the most preferred network whereas at $w_c=0.5$ the network '2' becomes the most preferred network. Increase in the weight of cost enhances the selection of network '2'. The network '3' is the least preferred network throughout the variations of weight of cost. Similarly increase in the weight of Mobility support and Bit rate enhances the selection of Network '1'. Network selection mechanism is a process of balancing user preferences and network condition.

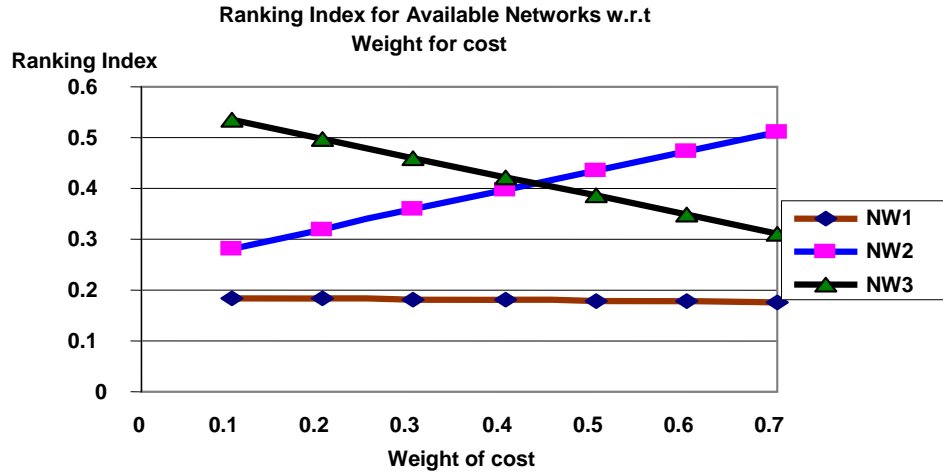


Figure 4.17 Ranking Index for Available networks with respect to Weight for Cost

4.11 Summary

This chapter describes the MCDM techniques that can be applied to find an appropriate network dependent on the user requirements. The proposed MCDM scheme considers multiple decision factors and multiple optimization objectives. The modelling approach for network selection in heterogeneous wireless environment considering four user preferences in the form of reputation, cost, offered bit rate and mobility support is modelled and evaluated for the three payment plans. The plans were Pay as you Go, Pay Monthly and Business. A wireless environment where user commitment to a particular network depends on attributes each of which contributes to the provider's utility is considered. The proposed network selection mechanism shows the variations in policy as a user changes preferences.

The network selection based on user preferences along with real-time collected data using the NetSpeed application) of UMTS macro-cell and WLAN for two realistic scenarios are modelled and illustrated using an AHP.

However, there are still some issues related to the mobility model that needs further consideration. This proposed work can be further enhanced, e.g. by using a mathematically derived mobility model [MAPP09] capable of depicting Time before Vertical Handoff (TBVH) and the approximate time the user would be in a particular network. An improvement on the approach in this chapter would be to define a threshold value for each considered attribute requiring that the selected network needs to satisfy these threshold values.

5 Cooperating Heterogeneous Networks

In this chapter the focus moves from mere network selection by the user to the use of game theory to manage the cooperation between networks so as to satisfy more users. It is assumed that the networks are either managed by the same provider or there is an appropriate collaboration agreement. However, as the network providers need to have a model of how the users' will select the offered networks, the work of the previous chapter will be used to model the users.

5.1 Assumptions

The following assumptions are made in this chapter

- i. Each user has no influence on the decision of other users.
- ii. The users give their preference for mobility support but no mobility model is used to predict future trajectories.
- iii. Linear and constant pricing scheme is used.
- iv. The initial partition is computed using either random allocation or based on the Analytic Hierarchy Process (AHP).
- v. The rational behaviour of a user is to choose the wireless network with the highest payoff.
- vi. Irrational behaviour of a user is to choose a wireless network with lower payoff.
- vii. Churning of users from Wi-Fi to WiMAX is only considered in this chapter.
- viii. The optimal partition is considered to be the proportion of users selecting Wi-Fi and WiMAX at the end of simulation.
- ix. The heterogeneous payoff of each user is the utility value based on the four attributes whereas the homogeneous payoff is the population payoff where all users are treated identical.
- x. Two methods labelled as *average* and *minimum* are assumed to compute the population payoff (i.e. homogeneous payoff).
- xi. An evolutionary equilibrium is considered as a solution.

5.2 Related Work

The network selection problem has been mainly addressed in WLAN/cellular integrated environments [SJ04], [SJ05], [SJA05]. In [SJ04],[SJA05] the proposed methodology combines two methods, called AHP (Analytical Hierarchy Process) and GRA (Grey Relational Analysis) so as to compare networks based on the level of end-to-end QoS provided. In [BL07], compensatory and non-compensatory multi-attribute decision making algorithms were proposed to assist mobile users in selecting the most suitable network. A cost function based network selection strategy from the system perspective was proposed in [SZ08]. A similar approach, which also constitutes a fine example of how these methods can be applied and combined, can be found in the work of Ourania Markaki at [MCN07]. In [KKGGM05], a hierarchical radio resource management framework supporting seamless handoff between WLAN and a cellular network is proposed. In [SJZ07], a performance analysis model for an integrated cellular network and a WLAN is proposed. However, this does not consider the competition among users to access different wireless networks so the dynamics of network selection is not considered.

Some algorithms already exist to carry out cooperative network control for user QoS in traditional cellular network. In [BD03], agent based cooperative negotiation implementing geography load balance is discussed. In [DBC04], the bubble oscillation algorithm is introduced. The analogy is that cells are bubbles and demand is related to the pressure. The bubbles oscillate to cell shape leading to reasonable cellular radio coverage for user QoS. In [DBC03], particular utility function is introduced for utility-based network entity control to realize networks optimization. In [MJB10] and [JBW08] cooperative pilot power control algorithm for user QoS, network capacity throughput improving is provided.

An evolutionary game is used to model the network routing problem in [FV]. The users were modeled as a population and the route of data flow to the destination was the choices available to the user in a single wireless network.

In [NH08], the churning behaviour of wireless service users using the theory of evolutionary game was modelled. A system model consisting of WLAN hotspots where a wireless user can choose among different WLAN access points based on the

performances or price. A continuous-time Markov chain model was established to capture the connection arrival and departure processes, as well as the rational and irrational churning behaviours of wireless service users. The evolutionary equilibrium, which is used to compute the average number of users choosing each wireless service, is considered as the solution. Based on this evolutionary game framework, two different possible pricing schemes, namely, non-cooperative and cooperative pricing schemes, for the wireless service providers were investigated. These schemes maximize individual revenue and total revenue, respectively, of the service providers. Performance analysis results are presented for the proposed modelling framework.

In [ZNW10] the network selection problem in heterogeneous wireless networks with incomplete information is formulated as a Bayesian game. In general, the preference (i.e., utility) of a mobile user is private information. Therefore, each user has to make the decision of network selection optimally given only partial information of the preferences of other users. The dynamics of network selection are applied using the Bayesian best response dynamics and aggregate best response dynamics. The Bayesian Nash equilibrium is considered to be the solution of this game, and there is a one-to-one mapping between the Bayesian Nash equilibrium and the equilibrium distribution of the aggregate dynamics. The numerical results show the convergence of the aggregate best response dynamics for this Bayesian network selection game. This result ensures that even with incomplete information, the equilibrium of network selection decisions of mobile users can be reached. In [MFS05], an evolutionary game was used to model and solve the problem of congestion control in wired networks. A Markov chain was used to model the evolution of users. However, in the efforts, the network dynamics due to the arrival and the departure processes of the connections were ignored. Also, the pricing issues were not considered.

5.2.1 Overview of Dusit Niyato Approach

In Dusit Niyato approach [NH09], the authors use evolutionary game theory to model a heterogeneous wireless access environment consisting of IEEE 802.16 based WMAN, CDMA cellular network and IEEE 802.11based WLAN as shown in Figure 5.1. The considered geographic area is entirely covered by a WMAN base station (area '1') and

partly covered by the CDMA cellular base station (area '2') and WLAN access point (area '3'). The users in different areas have an access to different type of wireless networks and users are assumed to be static.

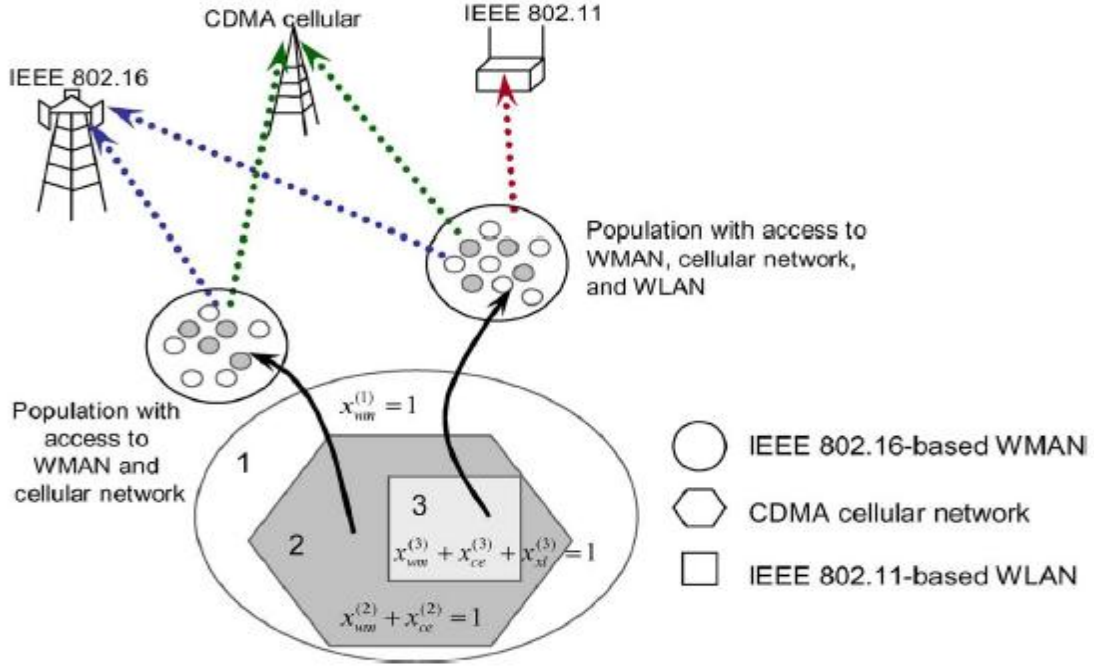


Figure 5.1 Heterogeneous wireless access environment [NH09]

In Figure 5.1, the users in area '1' is served only by a WMAN base station (i.e. the proportion of users selecting WMAN is represented by $x_{wm}^{(1)}$ and is equal to '1'). The users in area '2' have the option to either select CDMA cellular network or IEEE 802.11 based WLAN (i.e. the proportion of users selecting CDMA or WLAN is represented by $x_{ce}^{(2)}$ and $x_{wl}^{(2)}$ respectively and their sum " $x_{ce}^{(2)} + x_{wl}^{(2)}$ " should be equal to '1'). Similarly, the users in area '3' have the option to select WMAN, CDMA cellular network or IEEE 802.11 based WLAN (i.e. the sum of users selecting WMAN, CDMA or WLAN " $x_{wm}^{(3)} + x_{ce}^{(3)} + x_{wl}^{(3)}$ " should be equal to '1').

The service providers use linear pricing function depending on the total number of users (or connections) within the corresponding area. The service provider in the congested area would charge higher price to gain revenue. The amount of bandwidth allocated to each user is used to compute the user payoff for each network in the service area. The network with more users will allocate less bandwidth and the user payoff for that network

will be less as compared to other networks.

The evolutionary game for the network selection problem in heterogeneous wireless network can be described as follows:

- The user in each area who can choose among multiple wireless networks is a player of the game. In Figure 5.1, the users in area ‘2’ and ‘3’ who compete for resources from WMAN, cellular network and WLAN are the players. The users in area ‘1’ are not considered in the game as WMAN is the only wireless access network available to the user.
- The population in this evolutionary game refers to the set of users in a particular area and is assumed to be finite. In Figure 5.1, users in area ‘2’ form a population and users in area ‘3’ forms another population.
- The strategy of each user corresponds to the selection of a wireless access network. In Figure 5.1, the set of strategies for the players in area ‘2’ is {WMAN, Cellular} while that for the players in area ‘3’ is {WMAN, Cellular, WLAN}.
- The payoff of a player is determined by its utility.

The dynamic evolutionary game theory is used to model the network selection because it can capture the dynamics of network selection (i.e. strategy adaptation) based on the available information and bounded rationality of the users. The user slowly evolves the network if its observed payoff is less than the average payoff of all users in the same population. The evolutionary equilibrium is considered a solution where all the users in the same group receive identical payoff (i.e. the payoff of the user is equal to the average payoff of the population).

A concave utility function is used to compute the payoff of the users. The utility of a user in area ‘a’ choosing network ‘i’ can be expressed as follow:

$$\pi_i^{(a)} = U(T_i(n)) - P_i(n) \quad (5.1)$$

The ‘n’ is the total number of users in area ‘a’ choosing network ‘i’, $P_i(n)$ is the pricing function, $T_i(n)$ is the throughput of the user and U denote the utility function similar to the one mentioned in [NH09]. All the users selecting network ‘i’ are allocated equal amounts of bandwidth and this assumption does not hold true in real wireless environment. According to the definition of population, all users requesting same type of service or within the same service area should be allocated equal amount of bandwidth

(or generally same payoff). In order to cater this constraint, two different types of methods are assumed in the simulations namely as Average and Minimum method later in the chapter. The net utility of user selecting network 'i' can be rewritten as follow:

$$\pi_i^{(a)} = U\left(\frac{C_i^{(a)}}{\sum_{a \in A^{(a)}} n_i^{(a)}}\right) - p_i \times \sum_{a \in A^{(a)}} n_i^{(a)} \quad (5.2)$$

The number of users in area 'a' choosing network 'i' is given by $n_i^{(a)} = N^{(a)} \times x_i^{(a)}$. $N^{(a)}$ denote the total number of users in area 'a' and $x_i^{(a)}$ denote the proportion of users choosing network 'i'. The $C_i^{(a)}$ is the network capacity in area 'a' (total capacity of WMAN and/or cellular base station and/or WLAN access point in area 'a'), p_i is the coefficient of linear pricing function used by network 'i' to charge a user and $A^{(a)}$ is the set of subareas in area 'a'. Considering Figure 5.1, for the WMAN area (i.e. area '1') this set can be defined as $A^{(a)} = \{1,2,3\}$.

For three wireless access networks scenario consisting of areas '1', '2' and '3' (in Figure 5.1), the net utility of the users in the coverage area of WMAN can be computed as follows:

$$\begin{aligned} \pi_{wm}^{(1)} &= U\left(\frac{C_{wm}^{(1)}}{\sum_{a \in A^{(a)}} n_{wm}^{(1)}}\right) - p_{wm} \times \sum_{a \in A^{(a)}} n_{wm}^{(1)} \\ \pi_{wm}^{(1)} &= U\left(\frac{C_{wm}^{(1)}}{n_{wm}^{(1)} + n_{wm}^{(2)} + n_{wm}^{(3)}}\right) - p_{wm} \times (n_{wm}^{(1)} + n_{wm}^{(2)} + n_{wm}^{(3)}) \\ \pi_{wm}^{(1)} &= U\left(\frac{C_{wm}^{(1)}}{n_{wm}}\right) - p_{wm} \times (n_{wm}) \end{aligned} \quad (5.3)$$

The number of users choosing WMAN network in the scenario given in Figure 5.1 can be computed as follows:

$$\begin{aligned} n_{wm}^{(1)} &= N^{(1)} \times x_{wm}^{(1)} \\ n_{wm}^{(2)} &= N^{(2)} \times x_{wm}^{(2)} \\ n_{wm}^{(3)} &= N^{(3)} \times x_{wm}^{(3)} \\ n_{wm} &= n_{wm}^{(1)} + n_{wm}^{(2)} + n_{wm}^{(3)} = N^{(1)} \times x_{wm}^{(1)} + N^{(2)} \times x_{wm}^{(2)} + N^{(3)} \times x_{wm}^{(3)} \end{aligned} \quad (5.4)$$

As $x_{wm}^{(1)} = 1$, the (5.4) can be rewritten as

$$n_{wm} = N^{(1)} + N^{(2)} \times x_{wm}^{(2)} + N^{(3)} \times x_{wm}^{(3)} \quad (5.5)$$

Similarly, the net utility of users in the coverage area of cellular network can be computed as follow:

$$\pi_{ce}^{(2)} = U\left(\frac{c_{ce}^{(2)}}{\sum_{a \in A(a)} n_{ce}^{(2)}}\right) - p_{ce} \times \sum_{a \in A(a)} n_{ce}^{(2)} \quad (5.6)$$

$$\begin{aligned} \pi_{ce}^{(2)} &= U\left(\frac{c_{ce}^{(2)}}{n_{ce}^{(1)} + n_{ce}^{(2)} + n_{ce}^{(3)}}\right) - p_{ce} \times (n_{ce}^{(1)} + n_{ce}^{(2)} + n_{ce}^{(3)}) \\ \pi_{ce}^{(2)} &= U\left(\frac{c_{ce}^{(2)}}{n_{ce}}\right) - p_{ce} \times (n_{ce}) \end{aligned} \quad (5.7)$$

$$\begin{aligned} n_{ce}^{(1)} &= N^{(1)} \times x_{ce}^{(1)} \\ n_{ce}^{(2)} &= N^{(2)} \times x_{ce}^{(2)} \\ n_{ce}^{(3)} &= N^{(3)} \times x_{ce}^{(3)} \\ n_{ce} &= n_{ce}^{(1)} + n_{ce}^{(2)} + n_{ce}^{(3)} = N^{(1)} \times x_{ce}^{(1)} + N^{(2)} \times x_{ce}^{(2)} + N^{(3)} \times x_{ce}^{(3)} \end{aligned} \quad (5.8)$$

Similarly, the net utility of users in the coverage area of wireless LAN can be computed as follow:

$$\pi_{wl}^{(3)} = U\left(\frac{c_{wl}^{(3)}}{\sum_{a \in A(a)} n_{wl}^{(3)}}\right) - p_{wl} \times \sum_{a \in A(a)} n_{wl}^{(3)} \quad (5.10)$$

$$\begin{aligned} \pi_{wl}^{(3)} &= U\left(\frac{c_{wl}^{(3)}}{n_{wl}^{(1)} + n_{wl}^{(2)} + n_{wl}^{(3)}}\right) - p_{wl} \times (n_{wl}^{(1)} + n_{wl}^{(2)} + n_{wl}^{(3)}) \\ \pi_{wl}^{(3)} &= U\left(\frac{c_{wl}^{(3)}}{n_{wl}}\right) - p_{wl} \times (n_{wl}) \end{aligned} \quad (5.11)$$

$$\begin{aligned} n_{wl}^{(1)} &= N^{(1)} \times x_{wl}^{(1)} \\ n_{wl}^{(2)} &= N^{(2)} \times x_{wl}^{(2)} \\ n_{wl}^{(3)} &= N^{(3)} \times x_{wl}^{(3)} \\ n_{wl} &= n_{wl}^{(1)} + n_{wl}^{(2)} + n_{wl}^{(3)} = N^{(1)} \times x_{wl}^{(1)} + N^{(2)} \times x_{wl}^{(2)} + N^{(3)} \times x_{wl}^{(3)} \end{aligned} \quad (5.12)$$

In the next iteration, a user observes the net utility of other users in the same area. The iteration users adopts a strategy (i.e. select a network) that gives a higher payoff. The parameter σ controls the speed of user in observing and adapting the network selection and it should be greater than zero. The replicator dynamics equation [KUY03] is used as a condition to see whether it is profitable for a user to move from one network to another network, and is defined as follows:

$$\dot{x}_i^{(a)} = \sigma \dot{x}_i^{(a)} \left(\pi_i^{(a)}(x) - \bar{\pi}^{(a)}(x) \right) \quad (5.13)$$

The average payoff of the users in area ‘a’ is computed as follow:

$$\bar{\pi}^{(a)}(x) = \sum_i x_i^{(a)} \times \pi_i^{(a)}(x) \quad (5.14)$$

Based on the replicator dynamics of the users in area ‘a’, the number of users choosing network ‘i’ increases if their payoff is above the average payoff. The evolutionary equilibrium is considered as the solution to this network selection game. The evolutionary equilibrium is a fixed point of replicator dynamics, at which all users of the same population have identical payoff. It is important to note that in this formulation every user in a particular area is treated the same way, but in reality they will receive different bit rates depending on which part of the area they are in.

5.2.2 Advantages of the proposed approach

In this thesis, wireless context related parameters in payoff calculation (like bit rate and mobility support) are introduced. The initial partition is calculated using AHP which is more realistic than the random selected partition used in [NH09]. The AHP can be used to approximately predict the load within the candidate networks and then hypothetical calculations of network re-configuration can be applied to distribute the extra load from the overloaded network to the least loaded network. This approach can be used as a network planning tool which caters for the load on the networks during different times of a day and find a respective solution to re-configure the networks. The hypothetical iterative calculations consider different distributions of users within the candidate networks and can be utilized to balance the load between the networks. In [NH09] the random function is used to select the user which is a selfish approach with the first user satisfying the considered condition is moved. The inverse cumulative ranking is used to find the lowest ranked user in overloaded network and if the user payoff for that user is greater in another network then the user will be moved from loaded network to the another network. In our work, we select the user with probability proportional to their inverse ranking to move because all users in same population in wireless environment are not same. The probability of selection is proportional to how bad they are in a population (i.e. more chances of less rewarded user being moved).

5.3 Internetworking Architecture

An internetworking architecture [LB07] (as shown in Figure 5.2) including an IP backbone network integrating different RANs like Wi-Fi and WiMAX is assumed in this work and this section describes briefly one such approach. The infrastructures of the Wi-Fi and WiMAX networks are maintained without modifications. The Wi-Fi and the WiMAX networks are directly connected to the IP backbone. In some situations, a gateway may be introduced between the Wi-Fi/WiMAX networks and the IP backbone. The RAN selection should be based on the context information of the user/terminal and the network. The user/terminal context information includes the requested service, quality preference, terminal type, and user/terminal status. The network context information consists of available RANs, network capacity, resource availability, coverage area, and service costs.

As shown in Figure 5.2, a Decision Maker (DM) resides in the IP backbone network. The DM is context aware; it receives and updates user/terminal and network context information, and accepts user service requests. Based on the context information, the DM needs to implement a dynamic evolutionary algorithm to generate an optimized selection and then transfers it back to the user. In order to exchange the service requests and transmit the context information, a specific signalling mechanism should be implemented in a heterogeneous communication environment. For the signalling we presume the SIP protocol, because it is simple, extensible and it can be integrated with the IP technology. In addition to SIP, a signalling network is required to enable the communications between the DM and the user terminals.

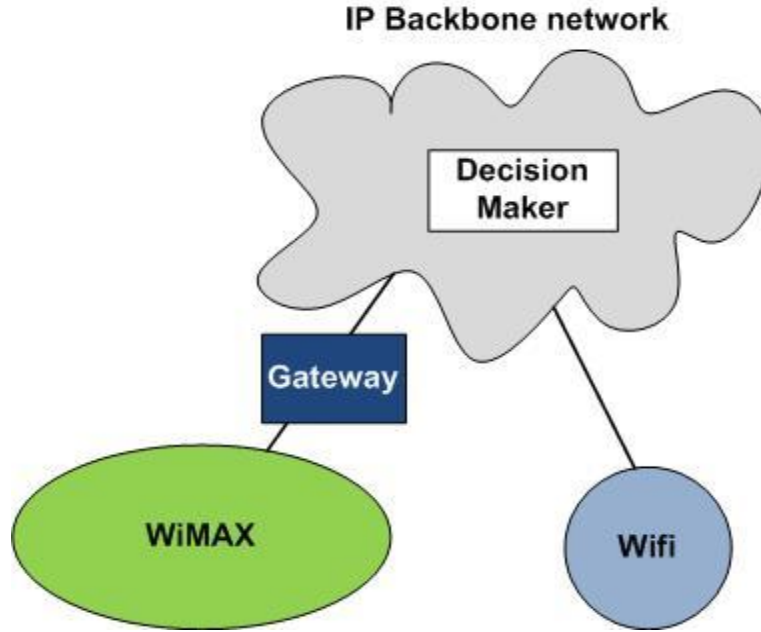


Figure 5.2 Interworking Architecture [LB07].

5.4 System Model

An illustration of our approach as shown in Figure 5.3, where a heterogeneous wireless access environment consisting of IEEE 802.11 based WLAN lying within the geographic region of IEEE 802.16 based WiMAX network is shown. Area 1 is covered by the WiMAX and WLAN network and area 2 covered by WiMAX network only. Area 1 is the main concern of focus. The options available to each user in area 1 are to select either the WiMAX network or WLAN. WiMAX and WLAN exhibit different service capabilities, e.g. they differ in bandwidth capacity, coverage, mobility support, and bit rate offered to users.

Each user within each service area who can choose among multiple wireless networks is a player of the game. For example, in Figure 5.3, the users within the service area ‘1’ are players of the game. The users in area ‘2’ are not considered in the game as there is only one wireless network available i.e. WiMAX. The set of users in a service area is referred as population. The population in the service area is finite. In Figure 5.3, the users within service area ‘1’ form a population and users within service area ‘2’ form another population. The strategy of each user corresponds to the selection of a wireless access network. In Figure 5.3, the set of strategies for the players in area ‘1’ is {WiMAX, WLAN}. The payoff of the player is determined by his or her net utility.

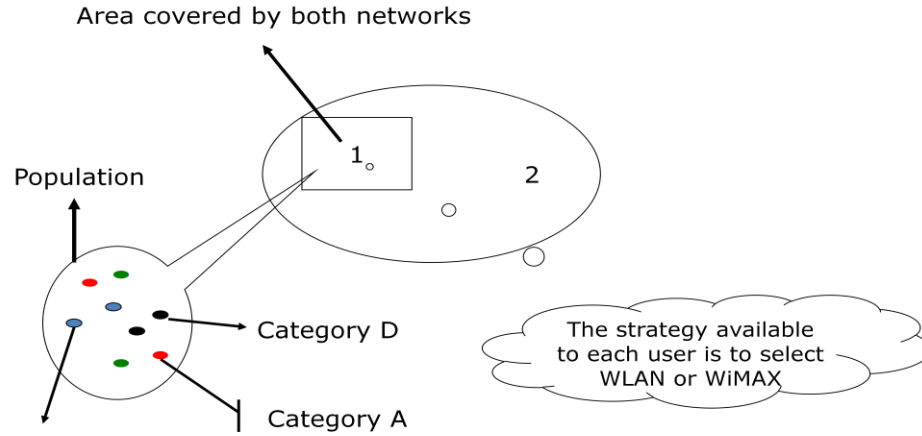


Figure 5.3 Heterogeneous Wireless Environment

5.5 Heterogeneous Wireless Networks Re-configuration using Coverage Adjustment

The network selection problem is modelled using a dynamic evolutionary game. The evolutionary game is used to capture the dynamics of network selection based on the available information and bounded rationality of the users [NH09].

The prediction of the network that would be chosen by a user considering the criterion in the top layer is solved using AHP. The AHP is used to capture the user preferences for the attribute and then using a utility function the preferred network for each user can be computed.

The evolutionary game theory is used to decide the users within the population which will be more likely to move from one network to another network depending on the offered QoS. At the second layer, the payoffs offered to users are related to network configuration so wireless network re-configuration can change user network preference by creating QoS changes to users as compared to other networks providers within the same service area. For example, in the initial configuration of WLAN and WiMAX, if WiMAX provides low radio resource like transmitting power, its bit rate and mobility support may be less than WLAN to users. Under this situation, lots of users may prefer WLAN and hence acquire limited radio resource and lead to low QoS. When WiMAX is re-configured to increase its offering transmitting power, more and more users will prefer WiMAX and release WLAN from load un-balancing. This is an evolutionary approach within heterogeneous wireless networks.

The user slowly evolves the network if its observed payoff is less than the average (or min) payoff of all users in the same population depending on the average (or minimum) method being applied. For this evolutionary game, the evolutionary equilibrium is considered as a solution which makes sure that all users in the same group receive identical payoff.

5.5.1 Formulation of Network Selection Game

In our model we assume a population modelled by four different categories of user, which are represented by four categories, A, B, C, and D of user preferences. All users in each category are given equal importance. A coarse description of user categories is shown below in Table 5.1. The entries in Table 5.1 show whether which attribute the users are most sensitive to. For example, the users in category A are sensitive to reputation and price over the other criterions, so ‘yes’ is shown in the entries of reputation and price in category ‘A’ in Table 5.1. Table 5.1 gives a broad picture of the categories of users used in our experiments but the specification of the user preferences is in fact more detailed.

Table 5.1 Four categories of user and their preferences

Attributes\Categories	A	B	C	D
Reputation	Yes	No	No	Yes
Price	Yes	Yes	No	No
Bit rate	No	No	Yes	Yes
Mobility	No	Yes	Yes	No

We model the WiMAX and WLAN network selection problem by using AHP as described in Chapter 4 and Evolutionary Game Theory [WEI97]. AHP is used to calculate the payoff offered to a user when choosing WiMAX or WLAN. The payoff calculation considers user sensitivity to each of these attributes (reputation, price, bit rate and mobility). The value of each criterion depends on the network configuration, user location and the intention of the user. User sensitivity to each criterion is the property of the user. For example, a user downloading a file using a laptop in a moving car prefers a network that offers the desired bit rate and supports mobility. After the payoff of each candidate network is calculated, evolutionary game theory is applied to decide the proportions of the users that will choose WiMAX or WLAN.

For this problem, as shown in Figure 5.4, AHP is structured into a hierarchy of dependencies. The goal of the problem is represented by the top most node, i.e. select the most suitable network, and the attribute considered in this problem are represented in the second level and the bottom most nodes represent the network technologies being offered, i.e. WiMAX and WLAN.

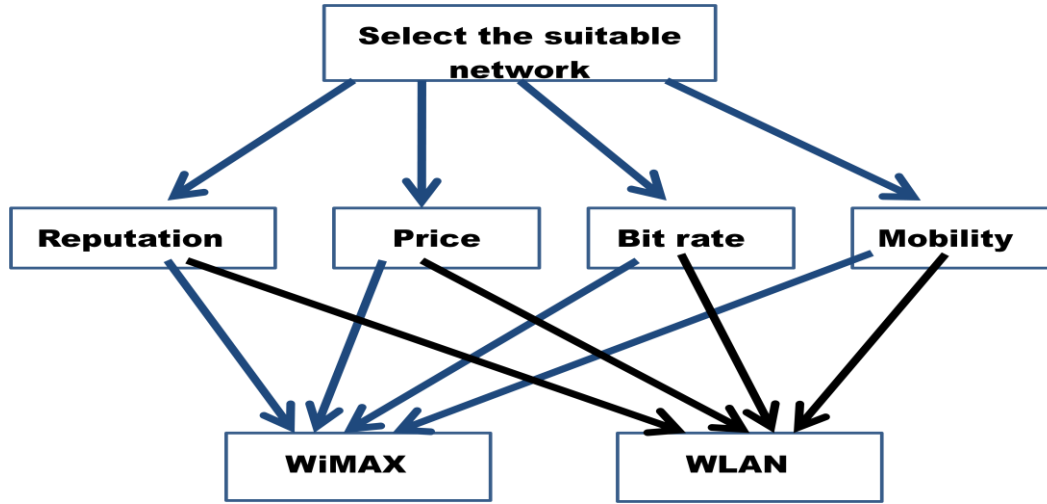


Figure 5.4 Network selection hierarchy of dependencies

Each user performs pair wise comparisons between attributes according to on a 1 to 9 scale. The pair wise comparisons between the attribute result in a square matrix for each user. Each user creates a square matrix C depending on the number of attributes ' n ', whose size is $n \times n$ (4×4 in our proposed model). Hence each user will have a weight value for each of the four attribute. The weight value w_i for each attribute is calculated by applying Equation (4.7) and (4.8) on the square matrix C . Since there are four categories of users there will be four sets of w_i .

5.5.2 Calculating each criterion value offered by candidate network

For every user, the candidate network ($j = 1, 2, \dots, m$) offers different quality levels (between 0 and 1) for each criterion ($i = 1, 2, \dots, n$). These quality levels represent how well each candidate network performs in terms of each criterion. A criterion may be labelled in such a way that the larger the value better or the smaller the value the better. For the criterion *cost* then smaller is better whereas for the *reputation*, *bit rate* and *mobility*, larger is better.

The quality level offered by network ‘j’, for criterion ‘i’ is denoted by ‘ a_{ij} ’. It is computed according to the following relationship:

$$a_{ij} = n_{ij}/n_i^{max} \quad (\text{Larger the Better}) \quad (5.15)$$

$$a_{ij} = n_i^{min}/n_{ij} \quad (\text{Smaller the Better}) \quad (5.16)$$

Where n_{ij} is the *quality level* value of criterion ‘i’ offered by candidate network ‘j’. n_i^{max} is the maximum quality level value of criterion ‘i’ offered among all the candidate networks. n_i^{min} is the minimum quality level value of criterion ‘i’ offered among all the candidate networks. So in our case with two networks e.g. for mobility $n_{mobility}^{max} = \max \{n_{mobility1}, n_{mobility2}\}$. Table 5.2 is an example of the quality level values for both networks and the four attribute. The a_{ij} is a normalization onto [0-1] scale. The quality level value is computed in an attribute dependent manner. For example for cost it is simply the price charged. For bit rate it requires a mechanism to compute the bit rate that the user will experience and this depends on the location of the mobile, SNR of the channel and network type. More detail of the modelling used is described in detail in [DBC04].

In order to show quality level values offered by the two networks to a single user, an example is provided in Table 5.2. The “bit rate” value offered by each network will be variable depending on each user location and SNR. Similarly for the attribute ‘Mobility Support’ the value can be variable if the user is not static (pedestrian or vehicle) otherwise the mobility value is constant and same. The “Cost” offered by the two networks is different in this example. Finally the reputation is assumed constant and the same between the two networks

Table 5.2 An example of criterion quality level value offered by network

Network/Attribute	Reputation	Cost	Bit rate	Mobility Support
WLAN	0.5	0.2	11.6 Mbps	0
WiMAX	0.5	0.3	5.5 Mbps	0.6

Let’s assume the example shown in Table 5.2, the quality level offered by network ‘1’, for criterion reputation, cost, bit rate and mobility is denoted by a_{11} , a_{21} , a_{31} and a_{41} respectively. The quality levels offered by each network are computed according to the

Equations (5.15) and (5.16) depending on the type of attribute (larger the better or smaller the better) as shown below:

$$n_{11} = 0.5 \quad n_{21} = 0.2 \quad n_{31} = 11.6 \quad n_{41} = 0.0$$

$$n_{12} = 0.5 \quad n_{22} = 0.3 \quad n_{32} = 5.8 \quad n_{42} = 0.6$$

$$n_1^{max} = 0.5 \quad n_2^{min} = 0.2 \quad n_3^{max} = 11.6 \quad n_4^{max} = 0.6$$

$$a_{11} = 1 \quad a_{21} = 1 \quad a_{31} = 1 \quad a_{41} = 0.0$$

$$a_{12} = 1 \quad a_{22} = 0.66 \quad a_{32} = 0.5 \quad a_{42} = 1.0$$

The user criterion weight value according to different category in this simulation is described in Table 5.3.

Table 5.3 User criterion weight value in each category in the simulation

Attribute/Category	A	B	C	D
Reputation	0.4227	0.1384	0.1485	0.4151
Cost	0.3575	0.4573	0.0682	0.0903
Bit rate	0.1224	0.364	0.3783	0.042
Mobility	0.0974	0.0403	0.405	0.4526

5.5.3 User received payoff calculation

In a particular service area, a user competes to share resources from different wireless networks depending on the payoff they will receive as a result of their choice. Considering service area ‘1’, let $N^{(1)}$ is the total number of users within the service area ‘1’ constitutes a population. In this example, there are two candidate networks. The strategy available to each user is to either select the WiMAX or WLAN network. The payoff of a user choosing a candidate network in area ‘1’ (the only area considered in this example) is indicated by the following relationship:

$$\pi_j^{(1)} = \left(\sum_{i=1}^n w_i \times a_{ij} \right) \quad (5.17)$$

In all the following equations the superscript refers area (1). The w_i is the criterion ‘i’ weight value of the user calculated using Equation (4.7). For a user, the network ‘j’ with the maximum payoff π_j value is chosen as the preferred network for a user connection

request. Going through all the users $N^{(1)}$ in service area ‘1’ we get the partition $X^{(1)} \in \{x_1^{(1)}, x_2^{(1)}\}$ where $x_1^{(1)}$ is the set of users within service area ‘1’ that prefers network ‘1’ and $x_2^{(1)}$ is the set of users within service area ‘1’ that prefers network ‘2’.

5.5.4 Evolutionary Network Selection using Inverse Rank

In evolutionary game theory, population evolution is used to evolve the proportion of users selecting the available wireless networks. Each user in a particular population is awarded the same payoff. In a real wireless network a set of users, even from the same category, will not receive the same payoff, as the received bit rate (and hence user satisfaction) will depend on the location and other factors determining the signal to noise ratio. A criterion like price can however be same. So according to payoff calculation defined in Equation (5.17), each user can have different payoff we call this the *heterogeneous payoff*. In order to implement population evolution, the payoff of all users within the same population should be the same. To obtain a homogeneous payoff of a user for each population we define a specific utility function where they are treated the same.

In population evolution, each period the user observes the payoff of other user in the same population and in next step adopts a network that offers it a higher payoff. This phenomenon can be represented with the help of replicator dynamics and the following relationship where ‘ σ ’ is the gain for the rate of strategy adaptation and $\bar{U}^{(1)}$ is defined according to the condition (4) of the algorithm:

$$\dot{x}_j^{(1)} = \sigma x_j^{(1)} (U_j^{(1)} - \bar{U}^{(1)}) \quad (5.18)$$

For the areas shown in Figure 5.3, the replicator dynamics can be expressed as follows:

$$\begin{aligned} \dot{x}_{wm}^{(1)} &= \sigma \times x_{wm}^{(1)} (\pi_{wm}^{(1)}(x) - \bar{\pi}^{(1)}(x)) \\ \bar{\pi}^{(1)}(x) &= \sum_i x_i^{(1)} \times \pi_i^{(1)}(x) \end{aligned}$$

For area 1 there are only WiMAX and WLAN network so

$$\begin{aligned} \bar{\pi}^{(1)}(x) &= x_{wm}^{(1)} \times \pi_{wm}^{(1)}(x) + x_{wl}^{(1)} \times \pi_{wl}^{(1)}(x) \\ \dot{x}_{wm}^{(1)} &= \sigma \times x_{wm}^{(1)} \left(\pi_{wm}^{(1)}(x) - (x_{wm}^{(1)} \pi_{wm}^{(1)}(x) + x_{wl}^{(1)} \pi_{wl}^{(1)}(x)) \right) \end{aligned}$$

As $x_{wm}^{(1)} + x_{wl}^{(1)} = 1$ so $x_{wl}^{(1)} = 1 - x_{wm}^{(1)}$

$$\dot{x}_{wm}^{(1)} = \sigma \times x_{wm}^{(1)} \left(\pi_{wm}^{(1)}(x) - \left(x_{wm}^{(1)} \pi_{wm}^{(1)}(x) + (1 - x_{wm}^{(1)}) \pi_{wl}^{(1)}(x) \right) \right)$$

$$\dot{x}_{wm}^{(1)} = \sigma \times x_{wm}^{(1)} \left(\pi_{wm}^{(1)}(x) - x_{wm}^{(1)} \pi_{wm}^{(1)}(x) - (1 - x_{wm}^{(1)}) \pi_{wl}^{(1)}(x) \right)$$

$$\dot{x}_{wm}^{(1)} = \sigma \times x_{wm}^{(1)} \left(\pi_{wm}^{(1)}(x) - x_{wm}^{(1)} \pi_{wm}^{(1)}(x) - \pi_{wl}^{(1)}(x) + x_{wm}^{(1)} \pi_{wl}^{(1)}(x) \right)$$

$$\dot{x}_{wm}^{(1)} = \sigma \times x_{wm}^{(1)} \left((1 - x_{wm}^{(1)}) \pi_{wm}^{(1)}(x) - (1 - x_{wm}^{(1)}) \pi_{wl}^{(1)}(x) \right)$$

$$\dot{x}_{wm}^{(1)} = \sigma \times x_{wm}^{(1)} \times (1 - x_{wm}^{(1)}) \left(\pi_{wm}^{(1)}(x) - \pi_{wl}^{(1)}(x) \right)$$

$$\dot{x}_{wm}^{(1)} = \sigma \left(x_{wm}^{(1)} - (x_{wm}^{(1)})^2 \right) \left(\pi_{wm}^{(1)}(x) - \pi_{wl}^{(1)}(x) \right)$$

$$\dot{x}_{wl}^{(1)} = \sigma \times x_{wl}^{(1)} \left(\pi_{wl}^{(1)}(x) - \bar{\pi}^{(1)}(x) \right)$$

$$\dot{x}_{wl}^{(1)} = \sigma \times x_{wl}^{(1)} \left(\pi_{wl}^{(1)}(x) - \left(x_{wm}^{(1)} \pi_{wm}^{(1)}(x) + x_{wl}^{(1)} \pi_{wl}^{(1)}(x) \right) \right)$$

As $x_{wm}^{(1)} + x_{wl}^{(1)} = 1$ so $x_{wm}^{(1)} = 1 - x_{wl}^{(1)}$

$$\dot{x}_{wl}^{(1)} = \sigma \times x_{wl}^{(1)} \left(\pi_{wl}^{(1)}(x) - \left((1 - x_{wl}^{(1)}) \pi_{wm}^{(1)}(x) + x_{wl}^{(1)} \pi_{wl}^{(1)}(x) \right) \right)$$

$$\dot{x}_{wl}^{(1)} = \sigma \times x_{wl}^{(1)} \left(\pi_{wl}^{(1)}(x) - \pi_{wm}^{(1)}(x) + x_{wl}^{(1)} \pi_{wm}^{(1)}(x) - x_{wl}^{(1)} \pi_{wl}^{(1)}(x) \right)$$

$$\dot{x}_{wl}^{(1)} = \sigma \times x_{wl}^{(1)} \left(-\pi_{wm}^{(1)}(x) + x_{wl}^{(1)} \pi_{wm}^{(1)}(x) + \pi_{wl}^{(1)}(x) - x_{wl}^{(1)} \pi_{wl}^{(1)}(x) \right)$$

$$\dot{x}_{wl}^{(1)} = \sigma \times x_{wl}^{(1)} \left(-(1 - x_{wl}^{(1)}) \pi_{wm}^{(1)}(x) + (1 - x_{wl}^{(1)}) \pi_{wl}^{(1)}(x) \right)$$

$$\dot{x}_{wl}^{(1)} = \sigma \times x_{wl}^{(1)} \times (1 - x_{wl}^{(1)}) \left(\pi_{wl}^{(1)}(x) - \pi_{wm}^{(1)}(x) \right)$$

$$\dot{x}_{wl}^{(1)} = \sigma \left(x_{wl}^{(1)} - (x_{wl}^{(1)})^2 \right) \left(\pi_{wl}^{(1)}(x) - \pi_{wm}^{(1)}(x) \right)$$

$$\dot{x}_{wm}^{(2)} = \sigma \times x_{wm}^{(2)} \left(\pi_{wm}^{(2)}(x) - \bar{\pi}^{(2)}(x) \right)$$

For area '2' there is only WiMAX network so

$$\bar{\pi}^{(2)}(x) = \sum_i x_i^{(2)} \times \pi_i^{(2)}(x)$$

$$\bar{\pi}^{(2)}(x) = x_{wm}^{(2)} \times \pi_{wm}^{(2)}(x)$$

$$\dot{x}_{wm}^{(2)} = \sigma \times x_{wm}^{(2)} \left(\pi_{wm}^{(2)}(x) - \left(x_{wm}^{(2)} \times \pi_{wm}^{(2)}(x) \right) \right)$$

$$\dot{x}_{wm}^{(2)} = \sigma \times x_{wm}^{(2)} \left(\pi_{wm}^{(2)}(x) - x_{wm}^{(2)} \times \pi_{wm}^{(2)}(x) \right)$$

$$\dot{x}_{wm}^{(2)} = \sigma \times x_{wm}^{(2)} \times \pi_{wm}^{(2)}(x) (1 - x_{wm}^{(2)})$$

As $x_{wm}^{(2)} = 1$ so $\dot{x}_{wm}^{(2)} = 0$

There is only one network available to the user that is why all users would select WMAN and the rate of change is zero.

The adjustment during the process of reaching equilibrium is hypothetical. The accumulated hypothetical adjustments can be applied to manage the available networks efficiently when the optimisation process has finished. If the networks are congested in the service area during the peak and off-peak times of the day, these adjustments can be applied to divert the traffic load from the congested network to the uncongested network. The actual selection is performed at the end.

In this approach, an interworking architecture consisting of Wi-Fi and WiMAX networks are proposed. There exists a central selection controller (similar to Decision Maker in [LB07]) which calculates and maintains the payoff information of all users within the same service area. The network selection is based on the current homogeneous payoff and the average payoff of all users within the same area.

For simplicity the user with the lowest rank associated with previous network is transferred to a new network if condition (6) and (7) of the algorithm is satisfied otherwise the user remains within the previous network.

Algorithm:

- 1) For all users, network j is chosen according to heterogeneous payoff calculated through Eq.(5.17) (i.e. $j \in \{\text{WLAN, WiMAX}\}$)
- 2) **loop**
 - 3) A user computes homogeneous payoff $U_j^{(1)}$ by using Eq. (5.20) in case of minimum method and Eq. (5.21) in case of average method. This homogeneous payoff information is sent to the selection controller.
 - 4) The selection controller computes average payoff
$$\bar{U}^{(1)} = (\sum_u U_j^{(1)}) / (N^{(1)})$$
For the users and broadcasts it back to the users. $\{N^{(1)}\}$ is the total number of users in area 1 }
 - 5) Rank each user through Inverse Cumulative Ranking;
 - 6) **If** $(U_j^{(1)} < \bar{U}^{(1)})$ then
 - 7) **If** $(\text{rand}() \in \text{Rankof User } k)$ then
 - 8) **If** $(\pi_i^{(1)} > \pi_j^{(1)})$ {Where $\pi_i^{(1)}$ and $\pi_j^{(1)}$ is the Heterogeneous payoffs offered by network i and j to

User k, calculated by using Eq. (5.17)}
 9) User k chooses network 'i';
 10) End if
 11) End if
 12) End if
 13) End loop for all users in all groups

5.5.5 Selecting a user

The switching of a user 'k' from the current network to another network is dependent on the probability proportional to T_k . The rank is decided by the heterogeneous payoff of users through computing the Inverse Cumulative Rank.

Considering Figure 5.3, the switch process of a user from WLAN to WiMAX network or vice versa depends on their relative rank from all the users within the service area '1'. The inverse Cumulative Ranking method is demonstrated with the help of a simple example. Suppose the WiMAX heterogeneous payoff for users within service area '1' is referred as U_n and the total number of users within service area '1' is denoted by $k \in \{1, 2, \dots, 100\}$. The inverse rank T_k is a relationship which determines the relative importance of a user within a network and is computed by the following relationship:

$$T_k = \frac{1}{U_k + 1} \quad (5.19)$$

The lower the heterogeneous payoff of a user; the more is their inverse rank i.e. more chance the user has of being shifted from current network to another network. The complete procedure of rank calculation using Inverse Cumulative Raking is shown below in Table 5.4.

Table 5.4 Inverse Cumulative Ranking

Index	Cumulative Distribution of T_k
1	$T_1 / \sum_{i=1}^n T_i$
2	$(T_1 + T_2) / \sum_{i=1}^n T_i$
3	$(T_1 + T_2 + T_3) / \sum_{i=1}^n T_i$
\vdots	\vdots
N (100 in the example)	$(T_1 + T_2 + T_3 + \dots + T_k) / \sum_{i=1}^n T_i$

Example 5.1: The procedure of Inverse Cumulative Ranking with the help of a simple example in which five users with their heterogeneous payoffs ' U_k ' and their respective ' T_k ' are shown below in Figure 5.5 and Figure 5.6 respectively.

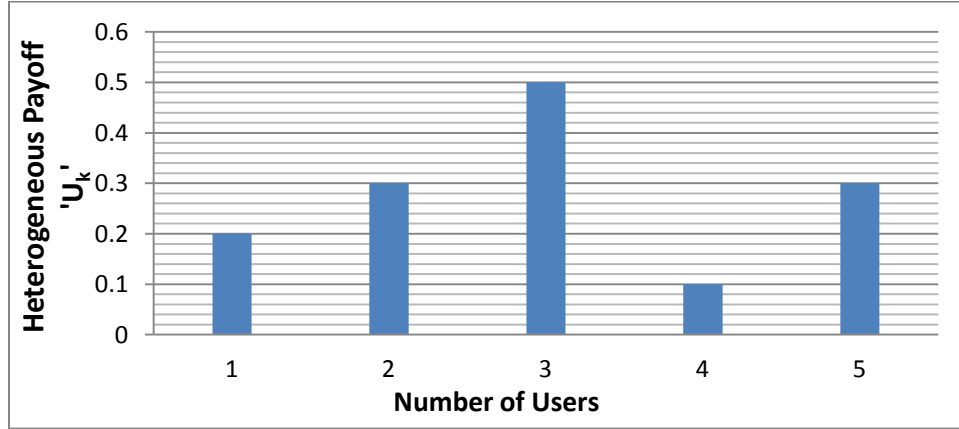


Figure 5.5 The heterogeneous payoffs of five users

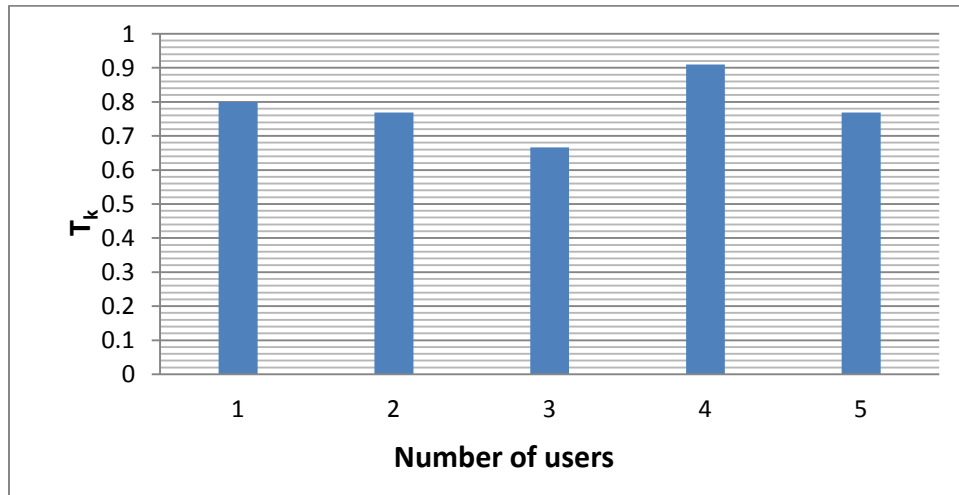


Figure 5.6 The inverse rank of the five users

The rank of user using the procedure mentioned in Table 5.4 is shown below in Figure 5.7.

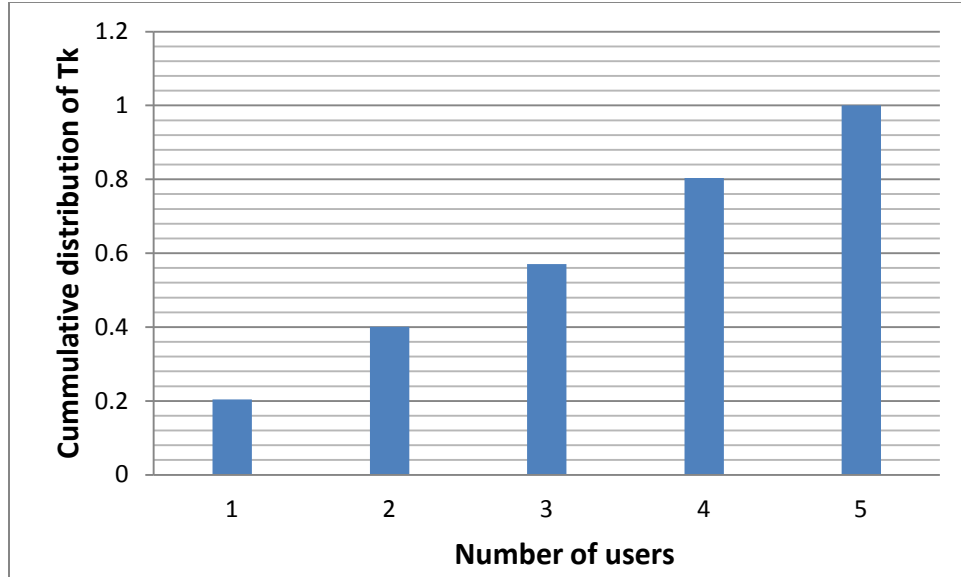


Figure 5.7 Rank of five users

5.6 Performance Evaluation of Inverse Rank Approach

In the simulations to illustrate the approach it is assumed that network offered reputation remains constant throughout the simulation. The bit rate offered to users is decided through the Adaptive Modulation and Coding (AMC) scheme for the WiMAX and Wi-Fi networks. AMC makes use of Signal to Noise Ratio (SNR) to decide the user bite rate. Normally, the further the user is away from the Base Station (BS) or Access Point (AP), the lower bit rate will be offered. The WiMAX and Wi-Fi networks offer different prices to the users and the simulation is carried out for the three cases:

- Same price offered by both networks
- Price offered by WiMAX network is greater than the price offered by Wi-Fi network and
- Price offered by WiMAX network is less than the price offered by Wi-Fi network.

The price does not change within the simulation. The mobility in WiMAX and Wi-Fi is related to the position of user in the coverage area of WiMAX or Wi-Fi. The calculation of reputation, bit rate, mobility and price mentioned above provides the quality level values defined in Equation (5.17).

The WiMAX network re-configuration is implemented through increasing the base station antenna transmit power in the sector covered by the WiMAX, whereas no re-configuration is applied to the WLAN. So the homogeneous and heterogeneous payoffs

offered by WiMAX always increase as physical adjustments are made for this to be so, while WLAN offered payoffs always remain constant. In this way more and more users gradually choose WiMAX. The base station antenna transmit power increase enhances the modulation scheme offered by WiMAX to the user and which in turn enhances the bit rate. The quality level values offered by WiMAX for the bit rate and mobility criterion changes, which in effect change the respective heterogeneous payoff.

5.6.1 Parameter Settings

The heterogeneous wireless environment consider of two networks (i.e. WiMAX and Wi-Fi) and group of users (i.e. population). The heterogeneous wireless environment is divided into two areas namely as '1' and '2'. The Wi-Fi is one typical example of WLAN and makes use of CSMA/CA access technology, and is supported by IEEE 802.11g standard. The total bandwidth available to Wi-Fi network is 7MHz bandwidth. The WiMAX is supported by IEEE 802.16 standard and makes use of 512 FFT size OFDMA access technologies. The total bandwidth available to WiMAX network is 5MHz. The Wi-Fi has 300 meters radius coverage area covering the whole area '1' and lying within the coverage area of the WiMAX. The WiMAX coverage has minimum 1000 meters radius and maximum 2000 meters radius covering both area '1' and '2'. The whole environment is 15000 meters in width and 15000 meters height.

The total number of users in the heterogeneous wireless environment is 200 and uniformly distributed within service area '1' and '2'. For analysis purpose, we assume that ($N^{(1)} = 100$) is the number of users lying within the overlapping coverage area of WiMAX and Wi-Fi (i.e. service area '1') requesting the same service type with same demand. In this simulation, the partition is defined as the proportion of users selecting Wi-Fi (i.e. $partition = \frac{\text{Number of users selecting WiFi in service area '1'}}{N^{(1)}}$).

5.6.2 Numerical Results

5.6.2.1 Minimum method

In this method, the homogeneous payoff for each user is computed using Equation (5.20) and the simulation is run for three different cases of price being offered.

Let $\pi_j^{(1)}$ be the set of the payoffs associated with all the users choosing network 'j' in service area '1'. The homogeneous payoff for each user in a population can be expressed as follows:

$$U_j^{(1)} = \text{Min} (\pi_j^{(1)}) \quad (5.20)$$

In case 1, the price offered by both networks is same. In case 2, the price offered by WLAN is more as compared to the price offered by WiMAX. In case 3, the price offered by WiMAX network is more as compared to the price offered by WLAN. The homogeneous payoffs of Wi-Fi and WiMAX and the minimum payoff in different WiMAX re-configuration simulation time in case 1, 2 and 3 are shown below in Figures 5.8, 5.9 and 5.10 respectively.

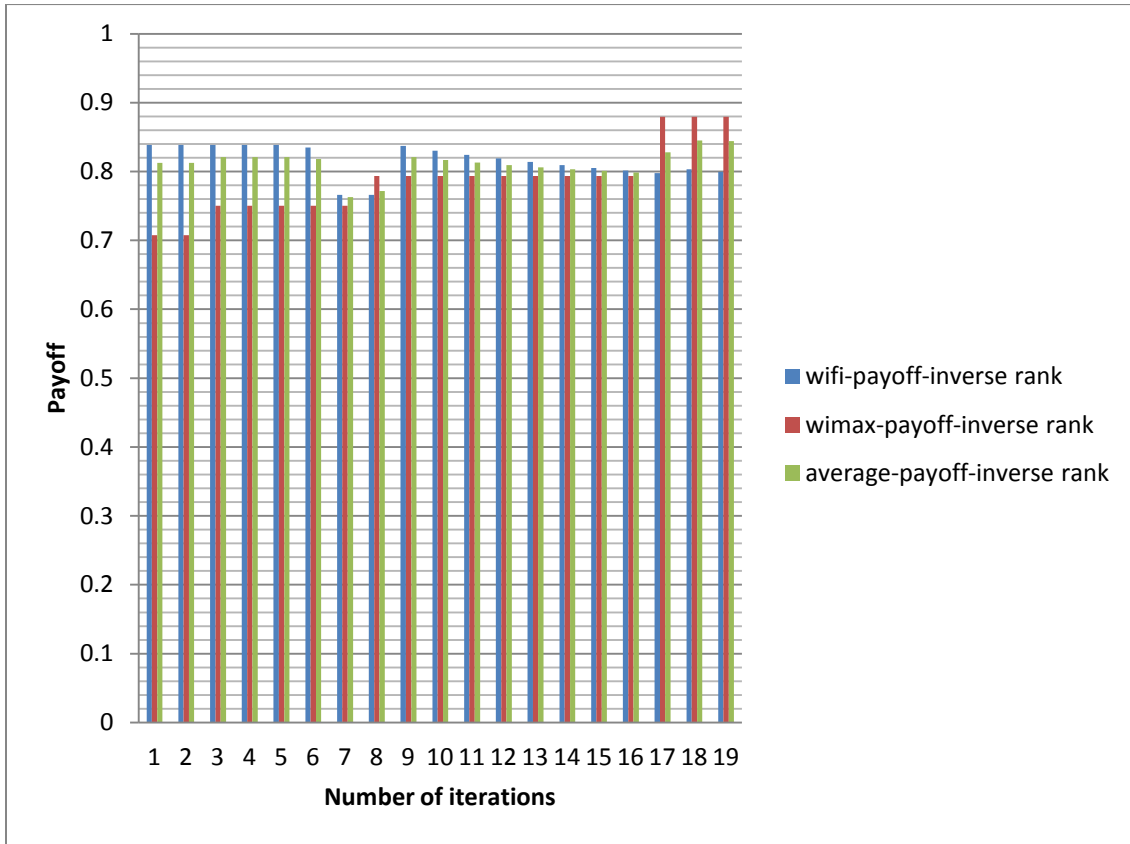


Figure 5.8 Payoffs of Inverse rank approach for case 1 (Minimum method)

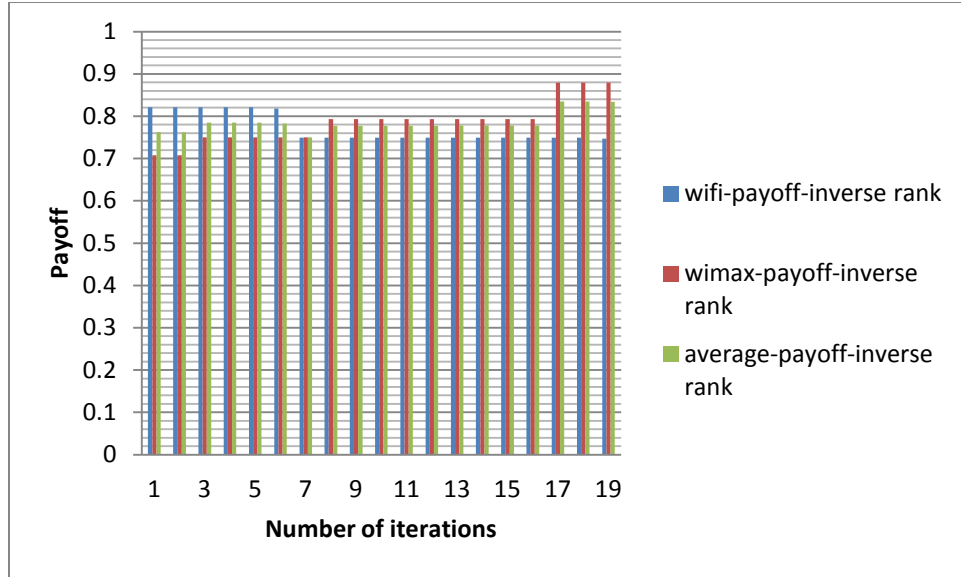


Figure 5.9 Payoffs of Inverse rank approach for case 2 (Minimum method)

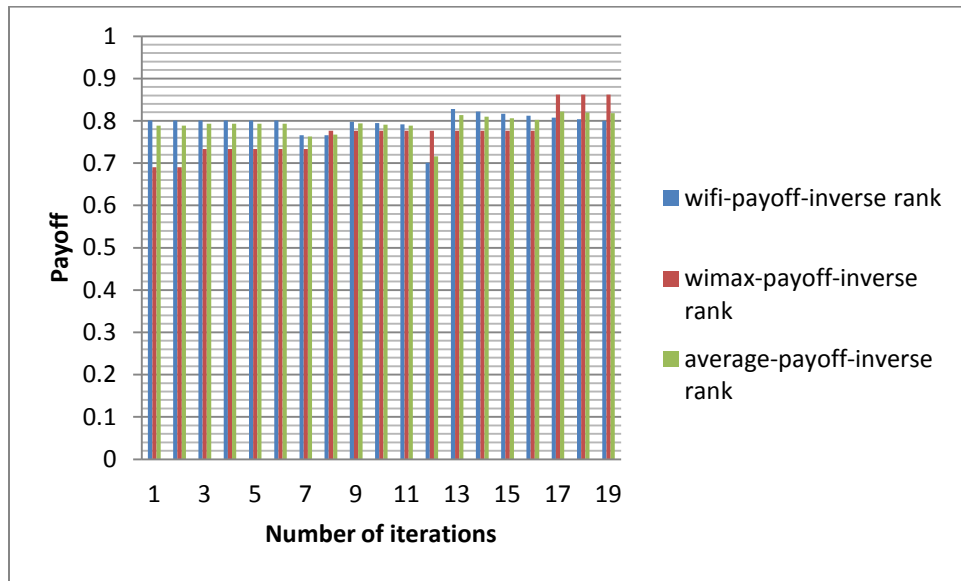


Figure 5.10 Payoffs of Inverse rank approach for case 3 (Minimum method)

The impact of change in price being charged by network providers on partition for three different cases within service area '1' is shown in Figure 5.11. The partition is the ratio of users preferring one network to the total number of users within service area '1'. Basically the partition shows the proportions of users that prefer Wi-Fi as compared to WiMAX. If more users prefer WiMAX than Wi-Fi, the proportion of users in partition for WiMAX will be more and vice versa.

As the WiMAX re-configuration simulation time increases, the transmitting power of WiMAX base station antenna becomes higher whereas the transmitting power of Wi-Fi remains constant. Under this situation, the user received homogeneous payoff of choosing WiMAX increases while homogeneous payoff of choosing Wi-Fi decreases. Based on evolutionary network selection algorithm, more and more users will prefer WiMAX, so the proportions of users for WiMAX in partition increases and the system blocking rate will keep on decreasing due to less number of users need to be served by Wi-Fi.

The impact of change in partition on system blocking rate is shown in Figure 5.12. The system blocking rate demonstrates the QoS provided by wireless networks to the users and is closely related to the proportions of users for each network in the partition. In this simulation, if the proportion of users for Wi-Fi in partition is high leading to more call requests being blocked by Wi-Fi due to low capacity. As a result, if proportion of users for Wi-Fi in partition decreases, the system blocking rate decreases as well and vice versa.

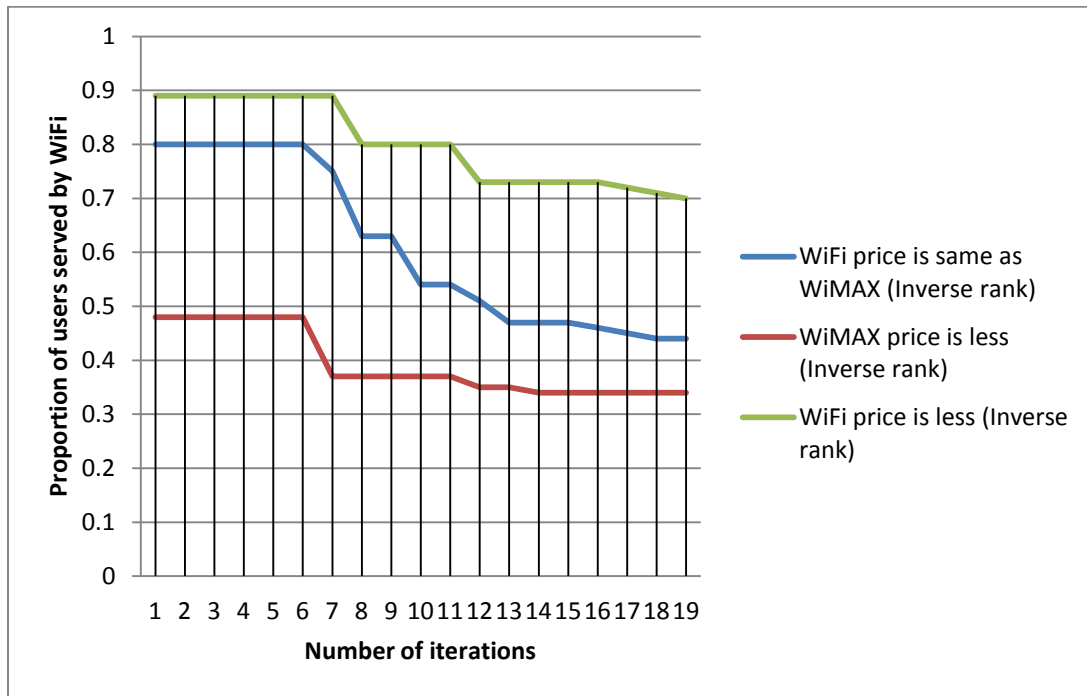


Figure 5.11 User preference partition of Inverse rank approach in different price cases (Minimum method)

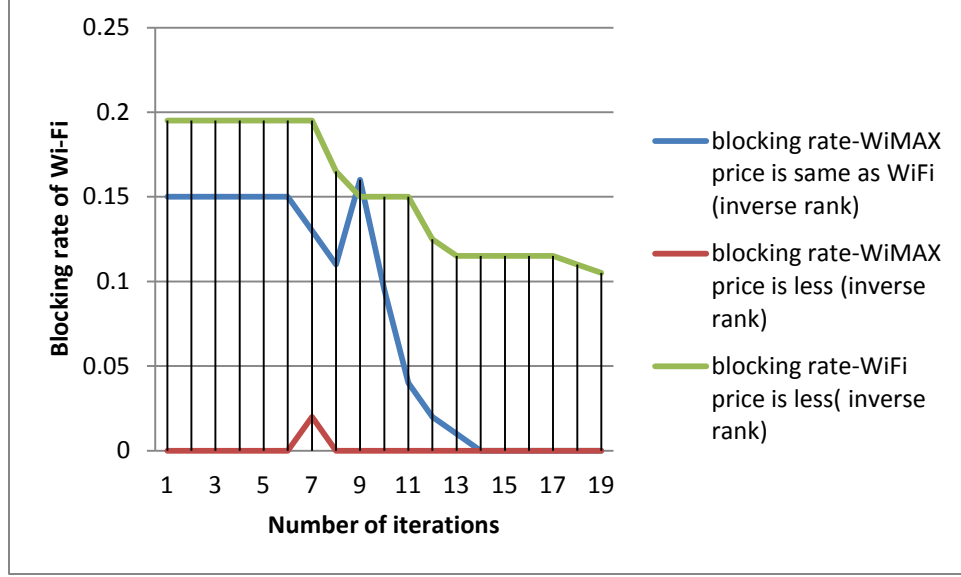


Figure 5.12 System blocking rate of Inverse rank approach in different price cases (Minimum method)

5.6.2.2 Average method

In this method, the homogeneous payoff for each user is computed using (5.21) mentioned below:

$$U_j^{(1)} = (\sum_j \pi_j^{(1)}) / (N^{(1)}) \quad (5.21)$$

The simulation is run for three different cases of price being offered by both networks. In case 1, the price offered by both networks is same. In case 2, the price offered by WLAN is more as compared to the price offered by WiMAX. In case 3, the price offered by WiMAX network is more as compared to the price offered by WLAN. The homogeneous payoffs of Wi-Fi and WiMAX and the minimum payoff in different WiMAX re-configuration simulation time in case 1, 2 and 3 are shown in Figures 5.13, 5.14 and 5.15 respectively. The impact of change in price being charged by network providers on partition for three different cases within service area '1' is shown in Figure 5.16. The impact of change in partition on system blocking rate is shown in Figure 5.17.

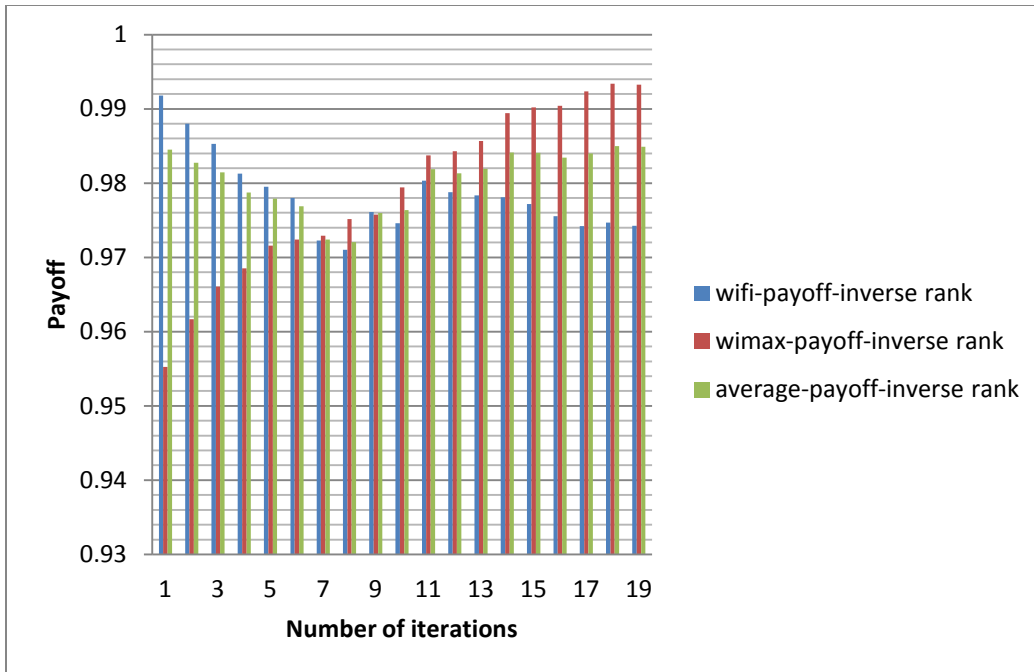


Figure 5.13 Payoffs of Inverse rank approach for case1 (Average method)

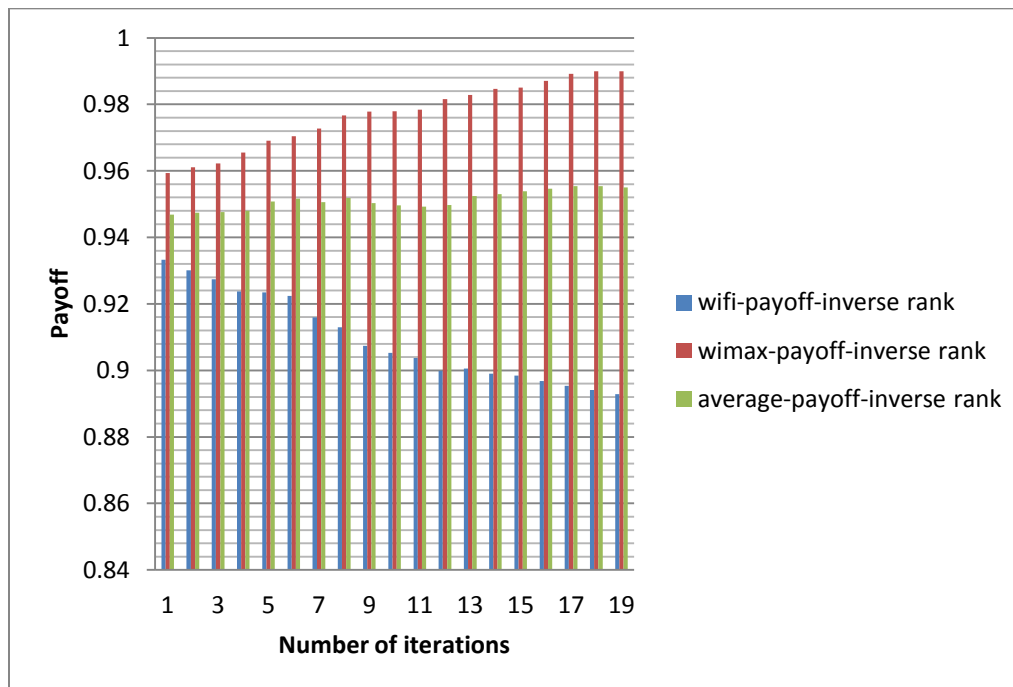


Figure 5.14 Payoffs of Inverse rank approach for case 2 (Average method)

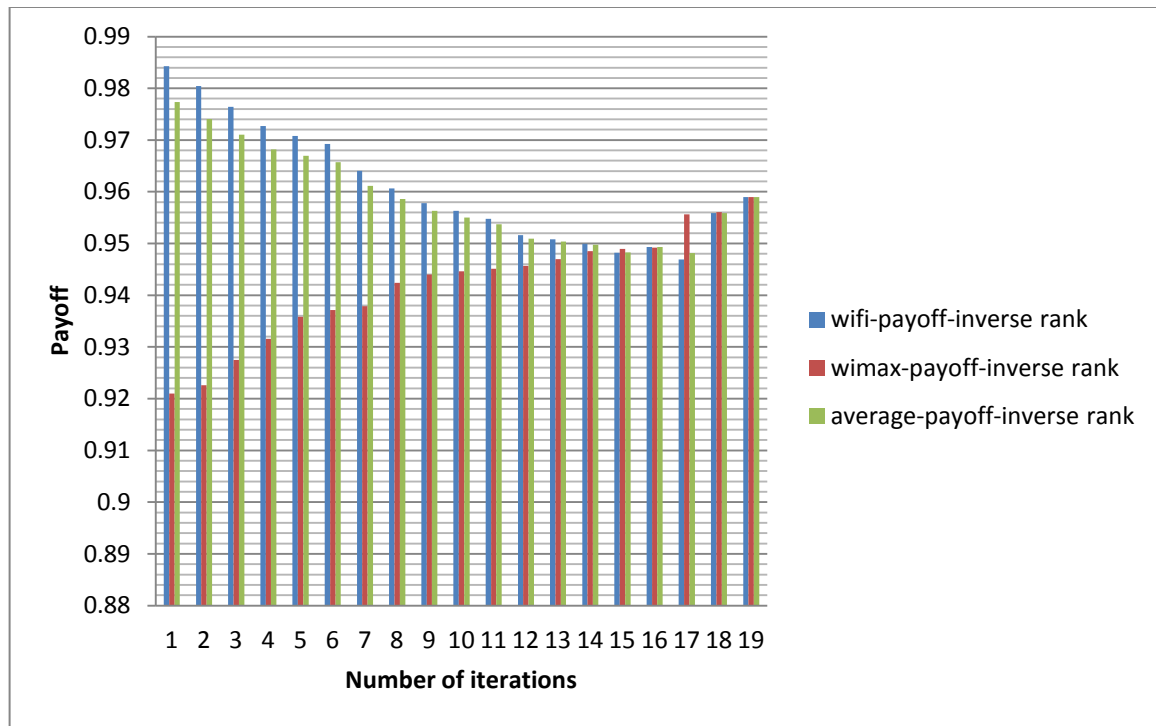


Figure 5.15 Payoffs of Inverse rank approach for case 3 (Average method)

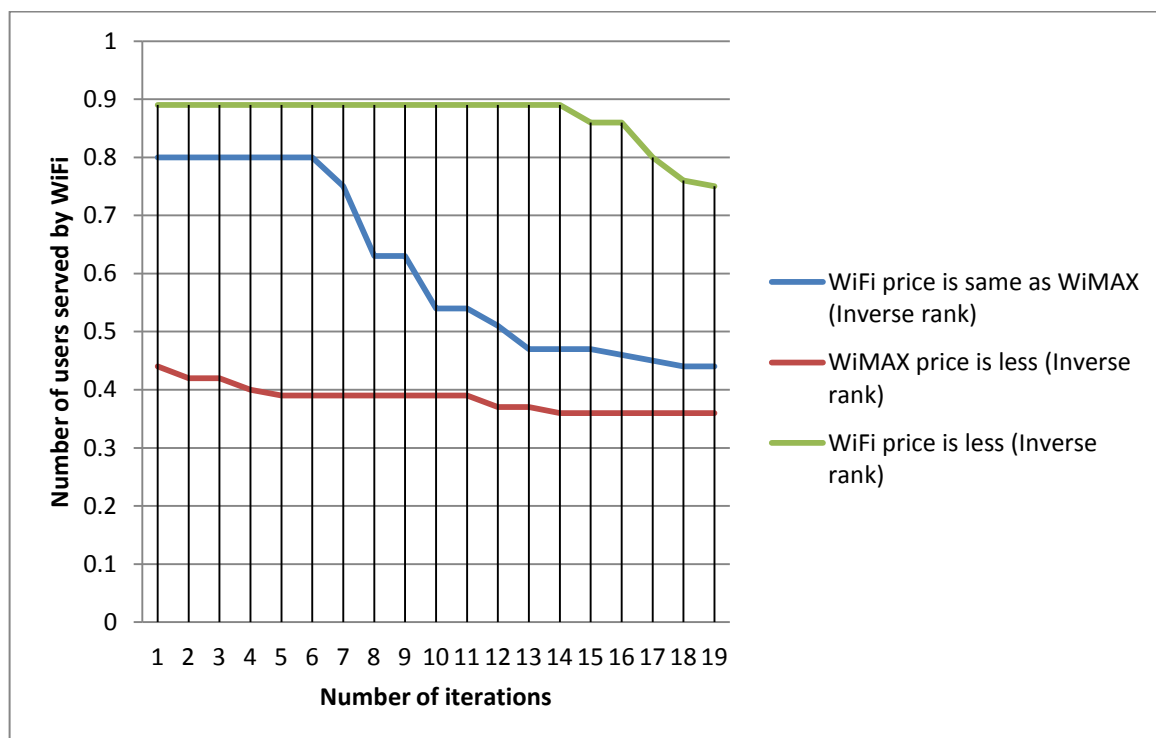


Figure 5.16 User preference partition of Inverse rank approach in different price cases (Average method)

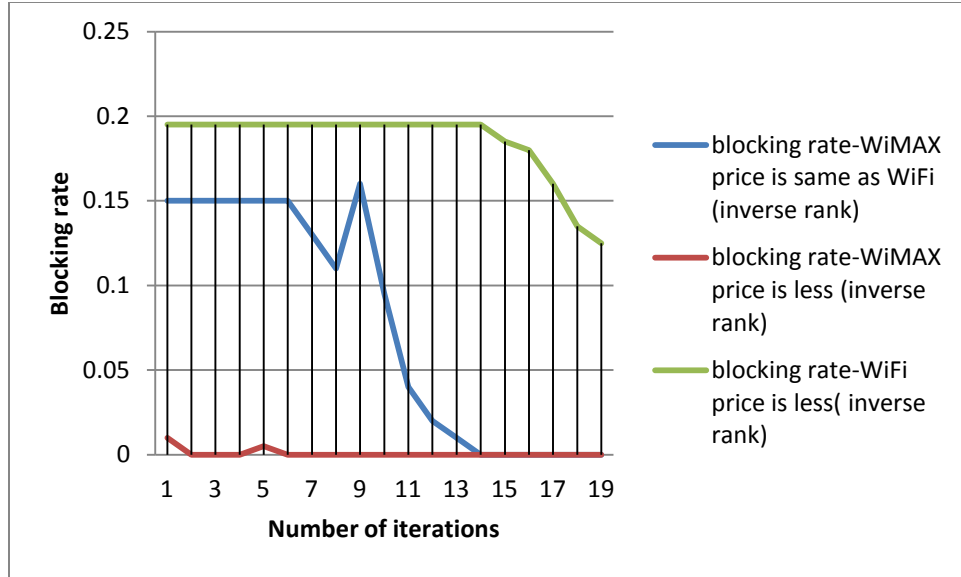


Figure 5.17 System blocking rate of Inverse rank approach in different price cases (Average method)

5.6.3 Results of Dusit Niyato's Evolutionary game theoretic approach

In [NH09], the population evolution algorithm with random selection is used to select the user to be moved. The population evolution algorithm is evaluated for both minimum and average methods with same network parameters and settings used for Inverse rank approach. The homogeneous payoffs of Wi-Fi and WiMAX network along with their average payoff in different WiMAX re-configuration iterations (minimum method) for Dusit Niyato approach [NH09] in case 1, 2 and 3 are shown below in Figures 5.18, 5.19 and 5.20 respectively. The impact of change in price being charged by network providers on partition (minimum method) for three different cases within service area '1' is shown below in Figure 5.21. The impact of change in partition on system blocking rate (minimum method) is shown below in Figure 5.22.

The homogeneous payoffs of Wi-Fi and WiMAX network along with their average payoff in different WiMAX re-configuration iterations (average method) for Dusit Niyato approach [NH09] in case 1, 2 and 3 are shown below in Figures 5.23, 5.24 and 5.25 respectively. The impact of change in price being charged by network providers on partition (average method) for three different cases within service area '1' is shown below in Figure 5.26. The impact of change in partition on system blocking rate (minimum method) is shown below in Figure 5.27.

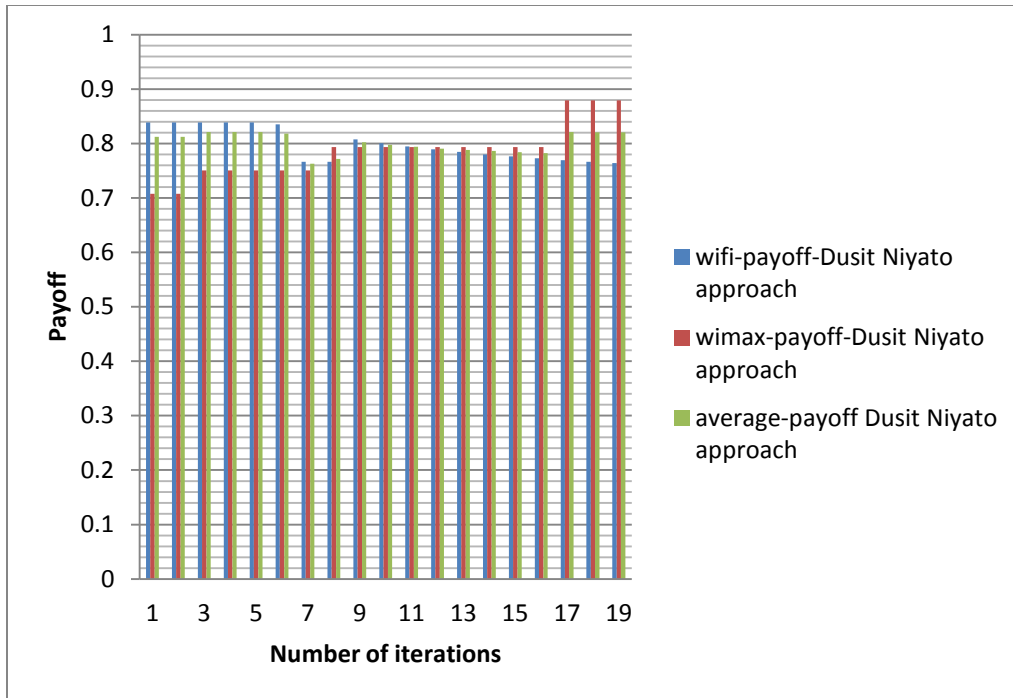


Figure 5.18 Payoffs of Dusit Niyato approach for case 1(Minimum method)

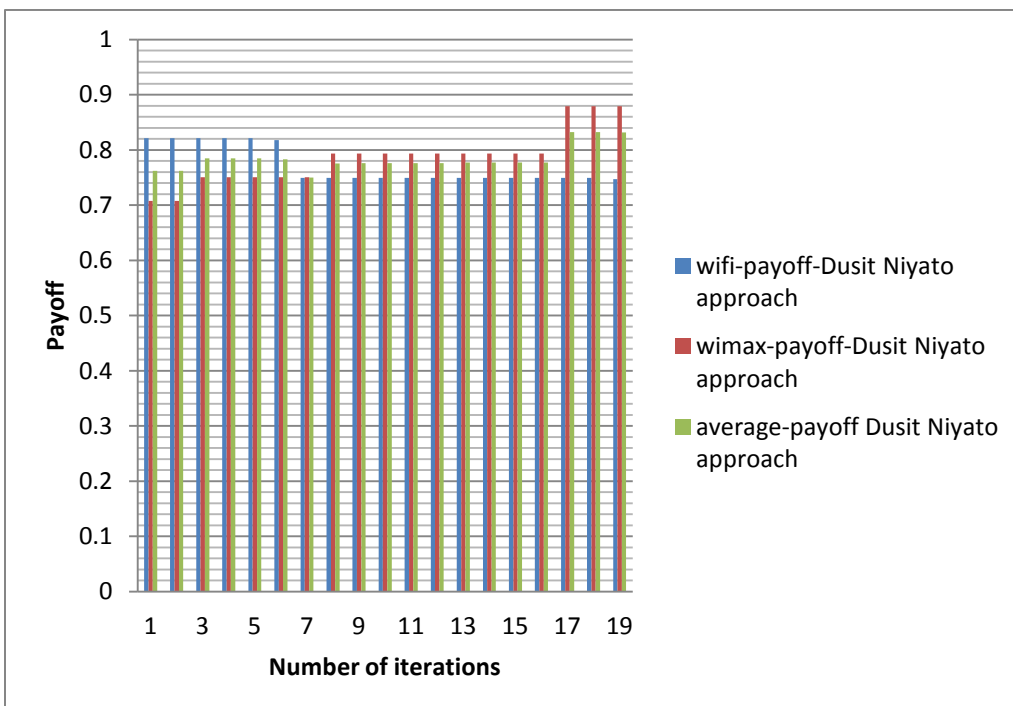


Figure 5.19 Payoffs of Dusit Niyato approach for case 2(Minimum method)

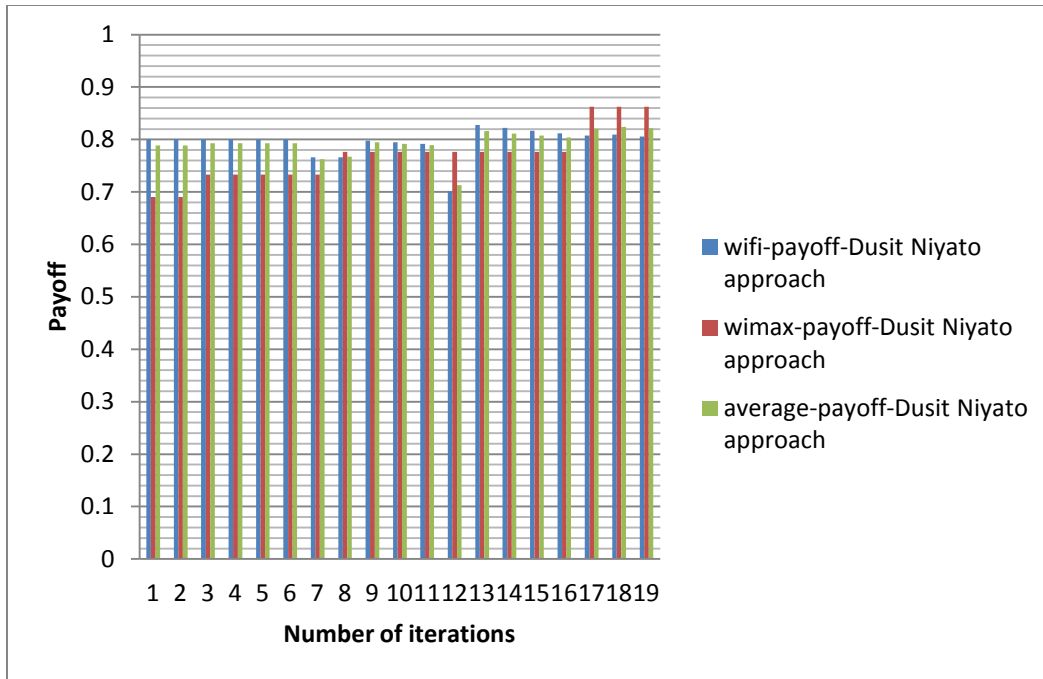


Figure 5.20 Payoffs of Dusit Niyato approach for case 3(Minimum method)

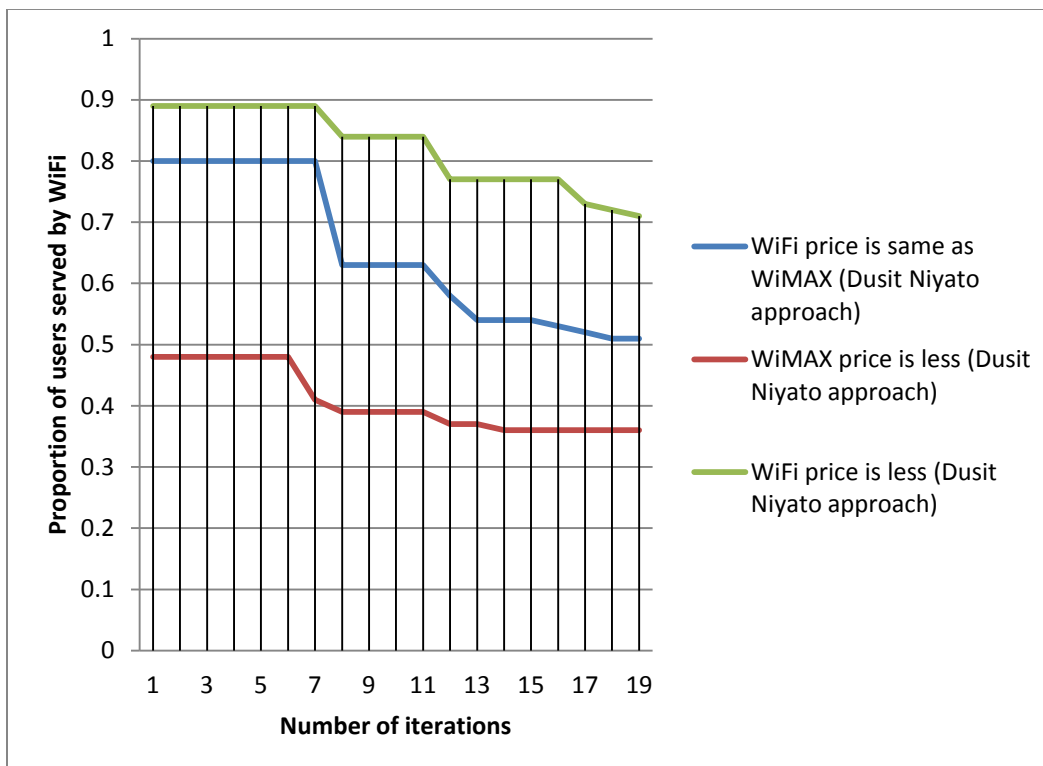


Figure 5.21 User preference partition of Dusit Niyato approach in different price cases (Minimum method)

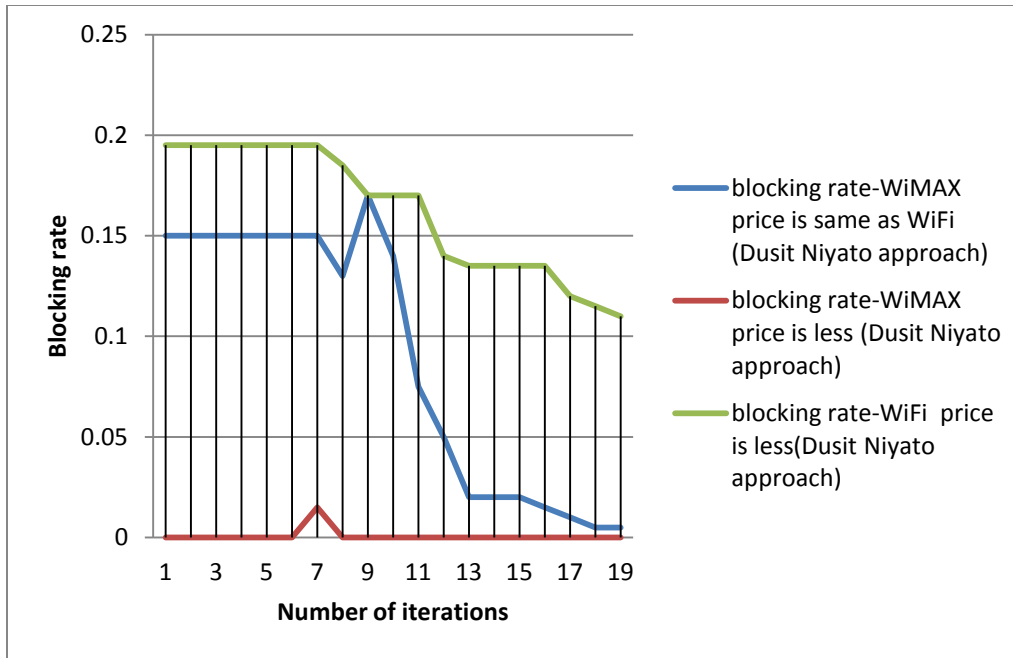


Figure 5.22 System blocking rate of Dusit Niyato approach in different price cases (Minimum method)

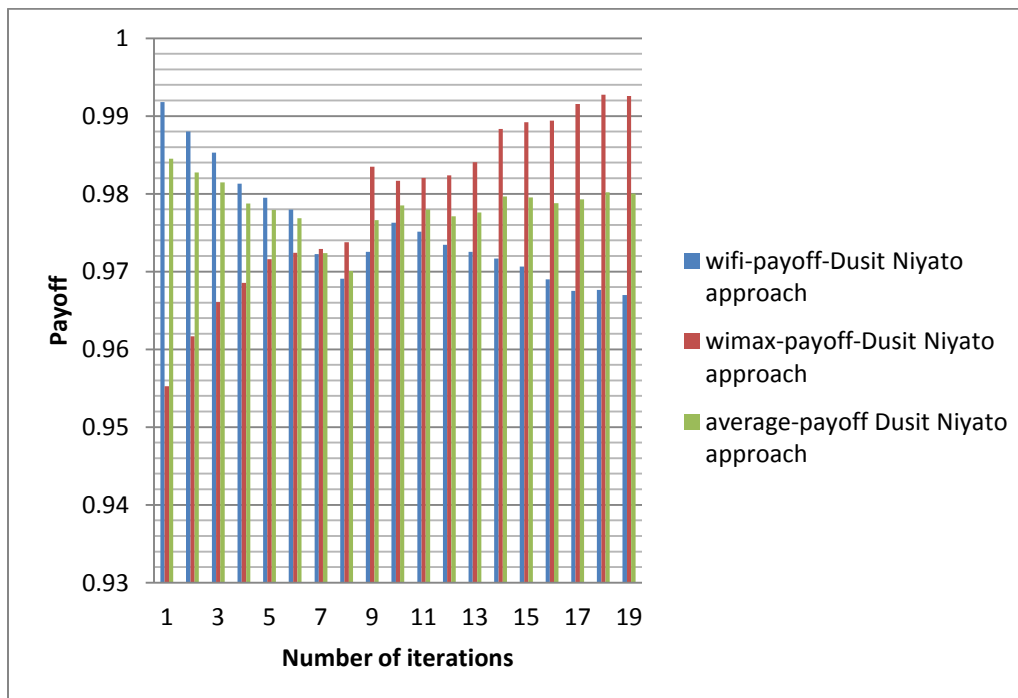


Figure 5.23 Payoffs of Dusit Niyato approach for case 1(Average method)

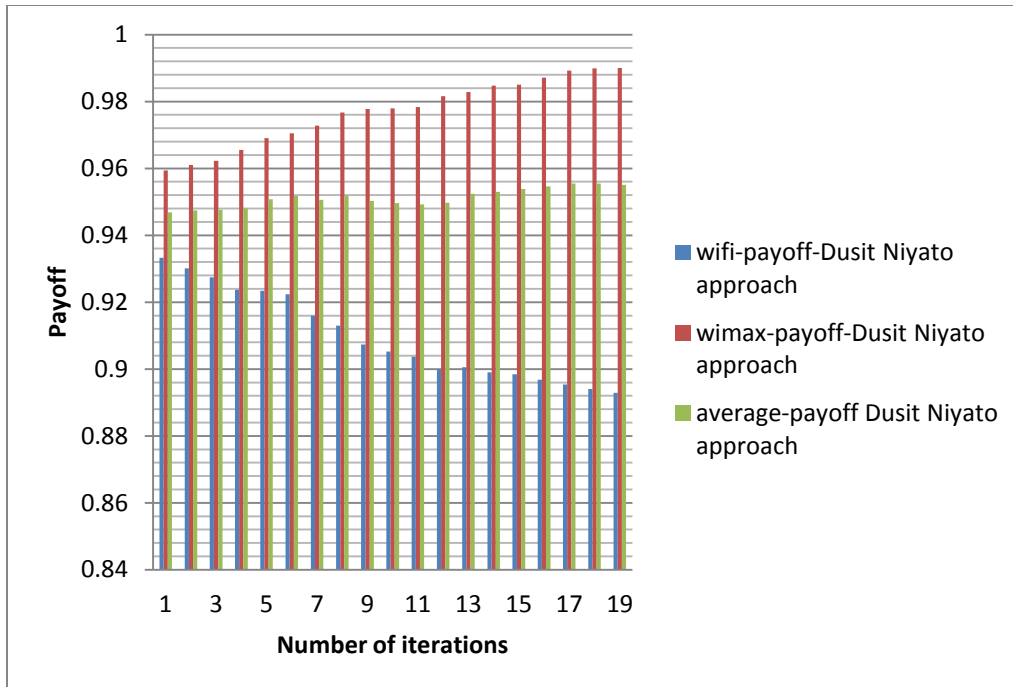


Figure 5.24 Payoffs of Dusit Niyato approach for case 2(Average method)

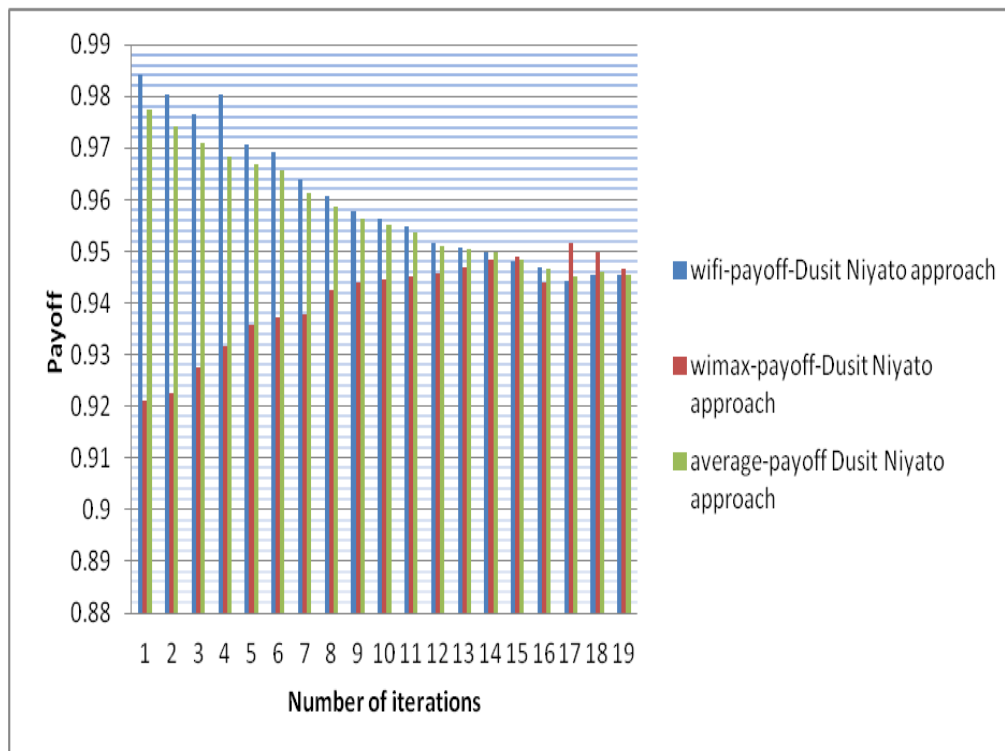


Figure 5.25 Payoffs of Dusit Niyato approach of for case 3(Average method)

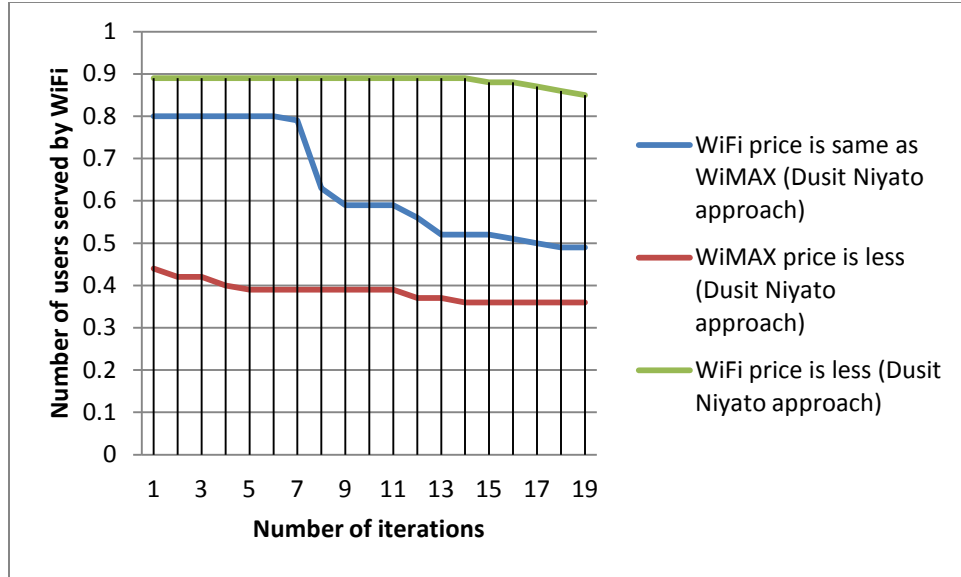


Figure 5.26 User preference partition of Dusit Niyato approach in different price cases (Average method)

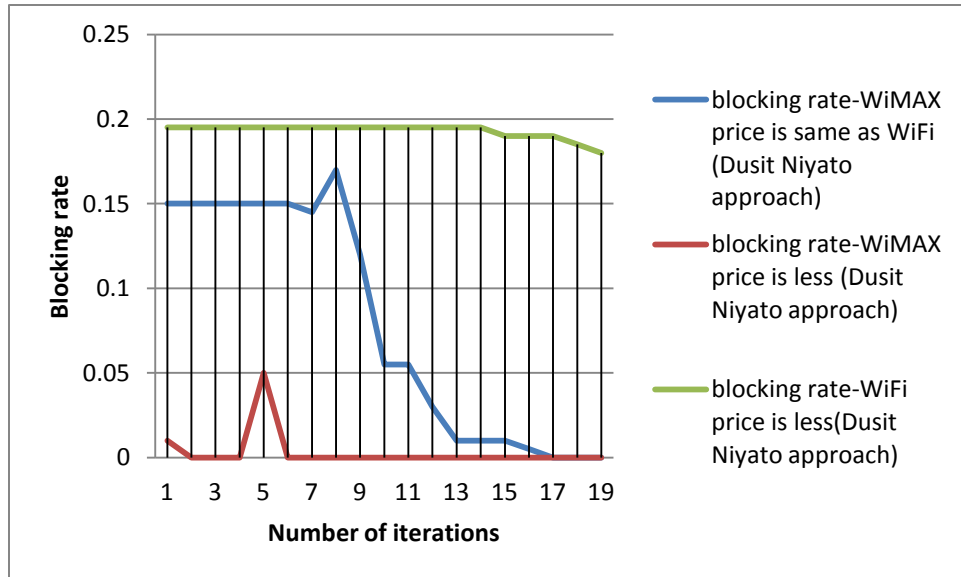


Figure 5.27 System blocking rate of Dusit Niyato approach in different price cases (Average method)

5.6.4 Comparison between Inverse rank and Dusit Niyato approach

In order to evaluate the proposed inverse rank approach, the results are compared with the Dusit Niyato approach [NH09]. The performance of blocking rates and number of users served by Wi-Fi (partition) for inverse rank and Dusit Niyato approach (WiMAX price is same as Wi-Fi price) is shown below in Figure 5.28. The number of users served by Wi-

Fi for both approaches in average and minimum method is same till iteration ‘9’ but after that the number of users served by Wi-Fi in inverse rank approach outperforms the Dusit Niyato approach. The Dusit Niyato approach better in terms of blocking rate in average method till iteration ‘11’ but after that inverse rank approach outperforms. The inverse rank approach outperforms the Dusit Niyato approach after iteration ‘6’ in minimum method.

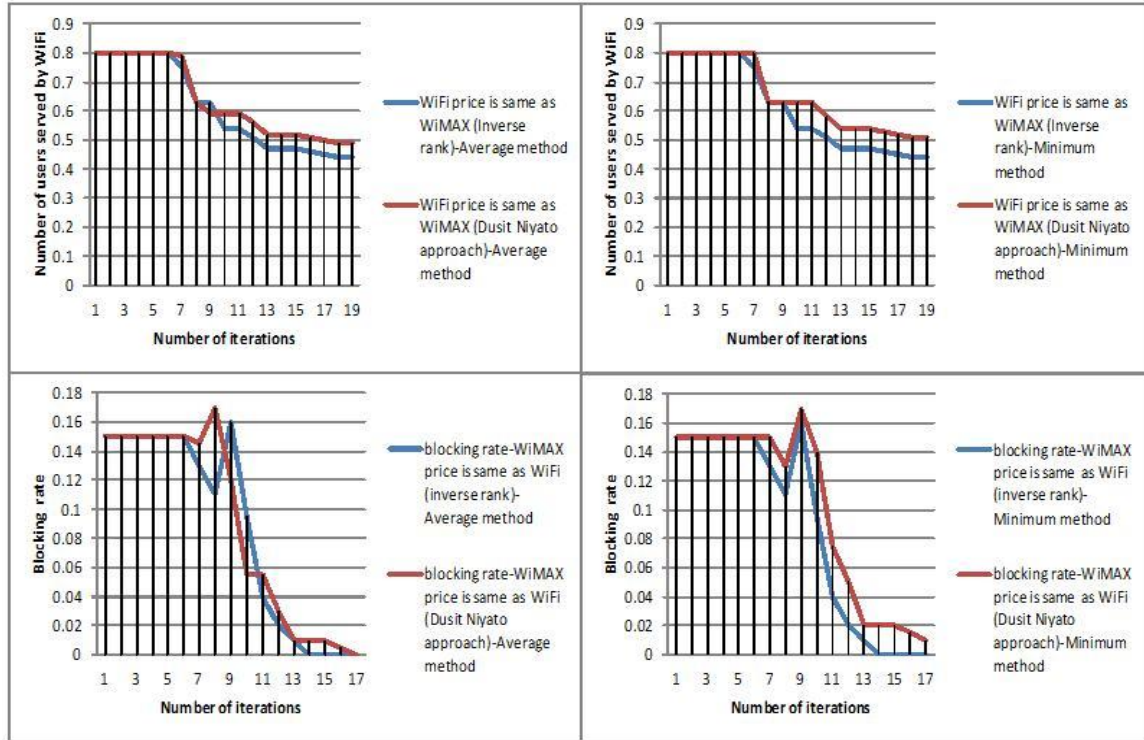


Figure 5.28 Blocking rates and number of users served by Wi-Fi (Partition) of Inverse rank approach with Dusit Niyato approach for the case 1

The performance of blocking rates and number of users served by Wi-Fi (partition) for inverse rank and Dusit Niyato approach (Wi-Fi price is less than WiMAX price) is shown below in Figure 5.29. The number of users served by Wi-Fi for both approaches in average method is same till iteration ‘14’ but after that the number of users served by Wi-Fi in inverse rank approach decreases very rapidly outperforming the Dusit Niyato approach. The number of users served by Wi-Fi for both approaches in minimum method is same till iteration ‘8’ but after that the number of users served by Wi-Fi in inverse rank approach decreases very gradually but in the end both approaches achieve the same

performance. The same performance is achieved by both approaches in average and minimum method.

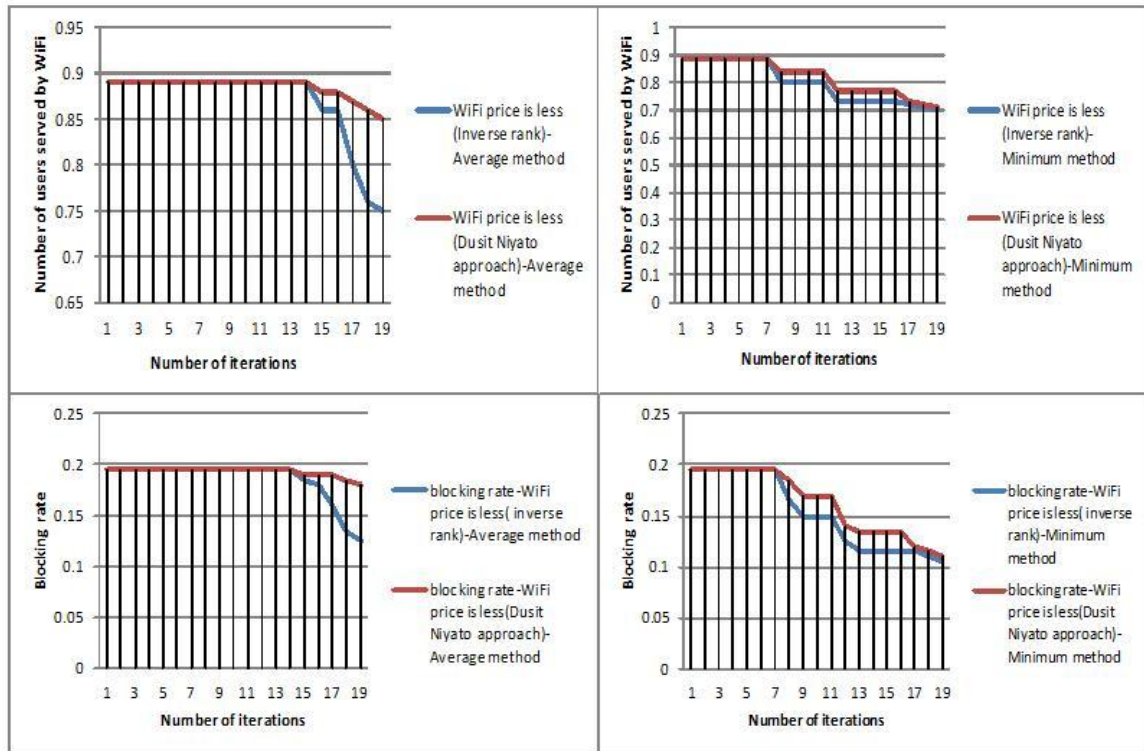


Figure 5.29 Blocking rates and number of users served by Wi-Fi (Partition) of Inverse rank approach with Dusit Niyato approach for the case 3

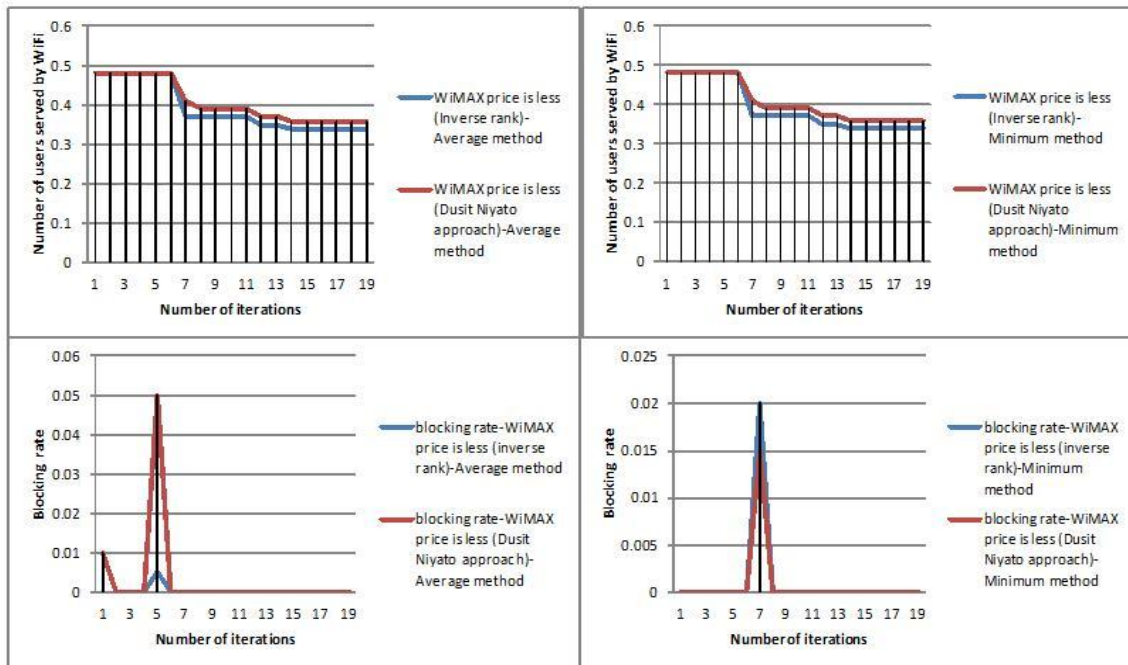


Figure 5.30 Blocking rates and number of users served by Wi-Fi (Partition) of Inverse rank approach with Dusit Niyato approach for the case 2

The performance of blocking rates and number of users served by Wi-Fi (partition) for inverse rank and Dusit Niyato approach (WiMAX price is less than Wi-Fi price) is shown in Figure 5.30. The inverse rank approach outperforms the Dusit Niyato approach in average and minimum method where WiMAX price is less than Wi-Fi price. It can be easily concluded that the inverse rank approach performs far better than Dusit Niyato approach for average method of all three cases whereas for the minimum method the inverse rank approach performs marginally better than the Dusit Niyato approach.

5.6.4.1 Simulation Process

The basic flowchart for the simulation process is shown below in Figure 5.31. The equilibrium partition step makes use of the population evolution algorithm mentioned in Section 5.4.4.

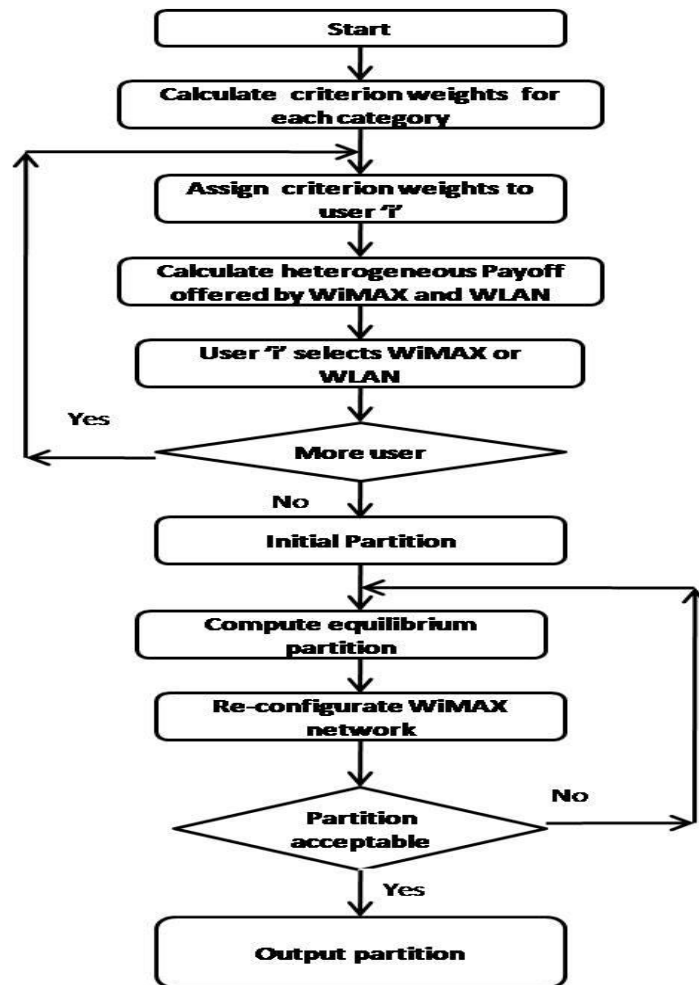


Figure 5.31 Simulation Process

5.6.5 Dynamic Behaviour of Users

We first analyze the dynamic behaviour of users by using the phase plane of replicator dynamics (for $p_{WiMAX} = p_{WLAN}$). This phase plane shows the evolution of proportions of users from different networks toward the evolutionary equilibrium (e.g., starting with $x_1^{(1)}(0) = 0.8$ and $x_2^{(1)}(0) = 0.2$). The evolutionary equilibrium is a point such as $(x_1^{(1)*}, x_1^{(2)*})$ where all the users receive an identical payoff.

The evolutionary equilibrium is considered a solution to this game. The replicator equation for the proposed network selection model in area '1' with $\sigma = 1$ is given as

$$\dot{x}_j^{(1)} = x_j^{(1)}(U_j^{(1)} - \bar{U}^{(1)})$$

The evolutionary equilibrium is defined as the stable fixed point of the replicator dynamics. When a population of players evolves over time (i.e., based on the replicator dynamics), it may converge to the evolutionary equilibrium. At this evolutionary equilibrium, none of the players wants to change the strategy since its payoff is equal to the average payoff of the population it belongs to. This evolutionary equilibrium (or fixed points) can be obtained mathematically by solving

$$\dot{x}_j^{(1)} = 0 \quad \forall j$$

The fixed point z is a point x_j at which payoff of all users in area '1' are identical i.e. rate of strategy adaptation $\dot{x}_j^{(1)}$ is equal to zero. The fixed points for replicator equation are $z_j = 0$ or $U_j^{(1)} = \bar{U}^{(1)}$.

Example 5.2: Consider an example of replicator dynamics for two different types in a population ($n=2$). There are x number of users of type '1' and $1-x$ number of users of type 2 i.e. $x_1 = x$ and $x_2 = 1 - x$. For simplicity, the payoff function is assumed as $\pi_j = m_{j1}x_1 + m_{j2}x_2$. Let the matrix $M = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \begin{bmatrix} 0 & a \\ b & 0 \end{bmatrix}$ denote the payoffs for each type of users within a population. The replicator equation for this case will be as follows:

$$\dot{x} = x[(m_{11}x_1 + m_{12}x_2) - \{x_1(m_{11}x_1 + m_{12}x_2) + x_2(m_{21}x_1 + m_{22}x_2)\}]$$

$$\dot{x} = x[(m_{12}x_2) - \{x_1(m_{12}x_2) + x_2(m_{21}x_1)\}]$$

$$\dot{x} = x[(ax_2) - \{x_1(ax_2) + x_2(bx_1)\}]$$

$$\begin{aligned}\dot{x} &= x \times x_2[a - \{ax_1 + bx_1\}] \\ \dot{x} &= x \times x_2[a - x_1\{a + b\}] \\ \dot{x} &= x \times (1 - x)[a - x(a + b)]\end{aligned}$$

Putting $\dot{x} = 0$

$$x \times (1 - x)[a - x(a + b)] = 0$$

The fixed points are $z=0$, 1 or $\frac{a}{(a+b)}$ provided $ab > 0$.

The fixed point $z_j=0$ is Nash equilibrium if $U_j^{(1)} \leq \bar{U}^{(1)}$. The fixed points can be stable, attractive or asymptotically stable. Trivially, every interior fixed point is Nash equilibrium. At a boundary fixed point \mathbf{z} , the difference of $U_j^{(1)} - \bar{U}^{(1)}$ is an Eigenvalue for the Jacobian matrix of the replicator equation.

Hence a fixed point \mathbf{z} is Nash equilibrium if all its Eigen values are non-positive. This yields a proof for the existence of Nash equilibrium in terms of population dynamics [HS03].

- If \mathbf{z} is a Nash equilibrium it is a fixed point
- If \mathbf{z} is a strict Nash equilibrium, then it is asymptotically stable
- If the fixed point \mathbf{z} is stable, then it is Nash equilibrium.

5.6.6 Stability of Evolutionary equilibrium

In [TD97] the authors explained the conditions of stability for evolutionary equilibrium by analyzing the following Jacobian matrix

$$\begin{aligned}J &= \begin{bmatrix} \frac{\partial \sigma x_{wm}^{(1)}(\pi_{wm}^{(1)} - \bar{\pi}^{(1)})}{\partial x_{wm}^{(1)}} & \frac{\partial \sigma x_{wm}^{(1)}(\pi_{wm}^{(1)} - \bar{\pi}^{(1)})}{\partial x_{wm}^{(2)}} \\ \frac{\partial \sigma x_{wm}^{(2)}(\pi_{wm}^{(2)} - \bar{\pi}^{(2)})}{\partial x_{wm}^{(1)}} & \frac{\partial \sigma x_{wm}^{(2)}(\pi_{wm}^{(2)} - \bar{\pi}^{(2)})}{\partial x_{wm}^{(2)}} \end{bmatrix} = \begin{bmatrix} J_{1,1} & J_{1,2} \\ J_{2,1} & J_{2,2} \end{bmatrix} \\ \dot{x}_{wm}^{(1)} &= \sigma \times x_{wm}^{(1)} \left(\pi_{wm}^{(1)}(x) - \left(x_{wm}^{(1)} \pi_{wm}^{(1)}(x) + x_{wl}^{(1)} \pi_{wl}^{(1)}(x) \right) \right) \\ \sigma \times x_{wm}^{(1)} \left(\pi_{wm}^{(1)}(x) - \left(x_{wm}^{(1)} \pi_{wm}^{(1)}(x) + x_{wl}^{(1)} \pi_{wl}^{(1)}(x) \right) \right) &= 0 \\ \left(\sigma \times x_{wm}^{(1)} \times \pi_{wm}^{(1)}(x) - \sigma \times x_{wm}^{(1)} \times \left(x_{wm}^{(1)} \pi_{wm}^{(1)}(x) + x_{wl}^{(1)} \pi_{wl}^{(1)}(x) \right) \right) &= 0\end{aligned}$$

$$\begin{aligned}
\sigma \times x_{wm}^{(1)} \times \pi_{wm}^{(1)}(x) &= \sigma \times x_{wm}^{(1)} \times (x_{wm}^{(1)} \pi_{wm}^{(1)}(x) + x_{wl}^{(1)} \pi_{wl}^{(1)}(x)) \\
x_{wm}^{(1)} &= \frac{\sigma \times (1 - x_{wl}^{(1)}) \times ((1 - x_{wl}^{(1)}) \pi_{wm}^{(1)}(x) + x_{wl}^{(1)} \pi_{wl}^{(1)}(x))}{\pi_{wm}^{(1)}(x)} \\
J_{1,1} &= \frac{\partial \sigma x_{wm}^{(1)} (\pi_{wm}^{(1)} - \bar{\pi}^{(1)})}{\partial x_{wm}^{(1)}} = \sigma (\pi_{wm}^{(1)} - \bar{\pi}^{(1)}) \times \frac{\partial x_{wm}^{(1)}}{\partial x_{wm}^{(1)}} + \sigma x_{wm}^{(1)} \frac{\partial (\pi_{wm}^{(1)} - \bar{\pi}^{(1)})}{\partial x_{wm}^{(1)}} \\
J_{1,2} &= \frac{\partial \sigma x_{wm}^{(2)} (\pi_{wm}^{(1)} - \bar{\pi}^{(1)})}{\partial x_{wm}^{(2)}} = \sigma (\pi_{wm}^{(1)} - \bar{\pi}^{(1)}) \times \frac{\partial x_{wm}^{(1)}}{\partial x_{wm}^{(2)}} + \sigma x_{wm}^{(1)} \frac{\partial (\pi_{wm}^{(1)} - \bar{\pi}^{(1)})}{\partial x_{wm}^{(2)}} \\
J_{2,1} &= \frac{\partial \sigma x_{wm}^{(2)} (\pi_{wm}^{(2)} - \bar{\pi}^{(2)})}{\partial x_{wm}^{(1)}} = \sigma (\pi_{wm}^{(2)} - \bar{\pi}^{(2)}) \times \frac{\partial x_{wm}^{(2)}}{\partial x_{wm}^{(1)}} + \sigma x_{wm}^{(2)} \frac{\partial (\pi_{wm}^{(2)} - \bar{\pi}^{(2)})}{\partial x_{wm}^{(1)}} \\
J_{2,2} &= \frac{\partial \sigma x_{wm}^{(2)} (\pi_{wm}^{(2)} - \bar{\pi}^{(2)})}{\partial x_{wm}^{(2)}} = \sigma (\pi_{wm}^{(2)} - \bar{\pi}^{(2)}) \times \frac{\partial x_{wm}^{(2)}}{\partial x_{wm}^{(2)}} + \sigma x_{wm}^{(2)} \frac{\partial (\pi_{wm}^{(2)} - \bar{\pi}^{(2)})}{\partial x_{wm}^{(2)}}
\end{aligned}$$

The next step is to calculate the Eigen value of a matrix J. Let $J = \begin{bmatrix} J_{1,1} & J_{1,2} \\ J_{2,1} & J_{2,2} \end{bmatrix}$ the characteristic polynomial can be written as follows:

$$\begin{aligned}
\det \begin{bmatrix} J_{1,1} - \lambda & J_{1,2} \\ J_{2,1} & J_{2,2} - \lambda \end{bmatrix} &= \lambda^2 - (J_{1,1} + J_{2,2})\lambda + (J_{1,1} \times J_{2,2} - J_{1,2} \times J_{2,1}) \\
\lambda &= \frac{J_{1,1} + J_{2,2}}{2} \pm \sqrt{\frac{(J_{1,1} + J_{2,2})^2}{4} + (J_{1,2} \times J_{2,1}) - (J_{1,1} \times J_{2,2})}
\end{aligned}$$

The two Eigen values of a matrix J is given as follows:

$$\lambda = \frac{J_{1,1} + J_{2,2}}{2} \pm \frac{\sqrt{4(J_{1,2} \times J_{2,1}) + (J_{1,1} - J_{2,2})^2}}{2}$$

The Evolutionary Equilibrium is stable if these two Eigenvalues have negative real part.

5.7 Summary

In this chapter, modelling approach for network selection in heterogeneous networks environment have been presented and illustrated using a Wi-Fi hotspot within a WiMAX network. The proposed scheme considered multiple decision factors and multiple optimization objectives. Lack of information about performance obtained from different service providers or inadequate information about decision of other users, a user

gradually learns and changes his decision on choosing a particular wireless network. The results are analyzed in form of changes in partition, system blocking rates and payoffs for both networks in three different price settings. The mechanism of network reconfiguration in heterogeneous wireless networks appears to be a basis for a reasonable network choice for users (partition comes to equilibrium i.e. no user can change their payoff) even when the strict assumptions are not adhered to.

6 Game Theory Concepts

In this chapter, background on relevant research fields is introduced. The application of the theory presented here is in Chapter 7. Topics covered include basics of game theory, non-cooperative game theory and cooperative game theory. In section 6.1, some essential principles of coalitional game theory are described and review their state of art in the literature given. Finally, section 6.2 summarizes this chapter.

6.1 Coalitional Game Theory

6.1.1 Basic Definitions

A coalitional game consists of two elements: a set of players ' N ' and the coalition value ' v '. The set N represents the players that interact in order to form coalitions to have mutual benefit. The coalition value v quantifies the utility of a coalition in a game. In general the coalition value can be in three different forms:

- Characteristic form
- Partition form
- Graph form

In any coalition game (independent of the form), the *value* of a coalition and payoff received by a player are two different terms. The value of a coalition represents the amount of utility that a coalition as a whole can obtain. The payoff of a player represents the amount of that utility that a player within the coalition will *obtain*.

- Definition of Coalitional game:

A coalitional *game* is a pair (N, v) , where N is a finite *set* of players and v is a function mapping subsets of N to real valued numbers.

Definition of Coalitions: Let $N = \{1, 2, \dots, n\}$ be a set of n players. Any subset $S \subseteq N$ is called a coalition of players, i.e., a coalition is one of the $2^n - 1$ subsets of N . A coalition structure s is a partition of players into coalitions.

$$s = \{C_1, C_2, \dots, C_k\} \text{ where } \bigcup_{i \in \{1,2,\dots,k\}} C_i = N \text{ and } i \neq j \rightarrow C_i \cap C_j = \emptyset$$

Intuitively, the coalition structure s contains one or more coalitions from S such that all the members of N are part of the coalition structure. The 'k' is the number of coalitions included in coalition structure s from the set of coalitions S .

Example 6.1:

Let $N = \{1, 2, 3\}$

Possible coalitions = $\{1\}, \{2\}, \{3\}, \{1,2\}, \{1,3\}, \{2,3\}, \{1,2,3\}$

Coalition structures = $\{\{1\}, \{2\}, \{3\}\}, \{\{1\}, \{2,3\}\}, \{\{1,2\}, \{3\}\}, \{\{1,3\}, \{2\}\}, \{\{1,2,3\}\}$

- Definition of Grand Coalition:

A grand coalition is a coalition that includes all of the players.

Example: For a three player game such as $N = \{1,2,3\}$, the grand coalition is $\{1, 2, 3\}$ while $\{\{1, 2\}, \{3\}\}$ is not a grand coalition.

6.1.2 Types of coalition game

The coalitional game can be either with transferable utility (TU) or with non-transferable utility (NTU). A TU game implies that the total coalitional value received by any coalition $S \subseteq N$ can be distributed in any manner between the members of S . The non-transferable utility was first introduced by Aumann and Peleg using non-cooperative strategic games as a basis [MYE91], [PM60]. In a NTU game, the payoff that each user in a coalition S receives is dependent on the joint actions that the players of coalition S select. Hence, in a NTU game, the value of a coalition S is no longer a function over the real line but a set of payoff vectors. For example, in an NTU game in characteristic form, the value of a coalition S would be given by the set $v(S) \subseteq \mathbb{R}^S$, where each element x_i of a vector $\mathbf{x} \in v(S)$ represents a payoff that user $i \in S$ can obtain when acting within coalition S given a certain strategy.

In this chapter whenever we mention coalitional game it is related to transferable utility (TU). Fuller definitions of non-transferable utility (NTU) coalitional games are given in [MYE91], [PM60].

6.1.2.1 Characteristic Function

The characteristic form is the most commonly used in game theory and introduced by Von Neuman and Morgenstern [NM44]. The coalition form of an n player game is given by the pair (N, v) , where v is the characteristic function. The characteristic function is a function denoted by ' v ' that associates with every subset S of N , a number denoted by $v(S)$. The number $v(S)$ is interpreted as the value created when the members of S come together and interact. The value of coalition S in characteristic form depends only on the members of that coalition.

- A characteristic function is additive if for any two disjoint coalitions S and T

$$v(S) + v(T) = v(S \cup T)$$

- A characteristic function is super-additive if for any two disjoint coalitions S and T the following relation holds:

$$v(S) + v(T) \leq v(S \cup T)$$

For super-additive games, it is to the joint benefit of the players to always form the *grand coalition* N , i.e. the coalitions of all the users in N , since the payoff received from $v(N)$ is at least as large as the amount received by the players in any disjoint set of coalitions they could form. As a result, whether a game is super-additive or not strongly impacts the approach used to solve the game.

- A characteristic function is strictly super-additive if for any two disjoint coalitions S and T the following relation holds:

$$v(S) + v(T) < v(S \cup T)$$

- A characteristic function is convex if for any two disjoint coalitions S and T the following relation holds:

$$v(S) + v(T) \leq v(S \cup T) + v(S \cap T)$$

6.1.2.2 Allocation

For a coalitional game (N, v) , an allocation is a collection of real valued payoffs $x = \{x_1, x_2, \dots, x_n\}$ representing the payoff to each player ' i ' under coalition structure ' S ' from the division of $v(S)$. This is also called the payoff vector for S .

- i. Rational

An allocation (x_1, x_2, \dots, x_n) for S is individually rational if $x_i \geq v(\{i\}) \forall i$

ii. Efficient

Given the grand coalition N , an allocation (x_1, x_2, \dots, x_n) for S is efficient if

$$\sum_{i=1}^n x_i = v(N)$$

6.1.2.3 Imputation

An imputation 'x' is a real valued payoff vector (x_1, x_2, \dots, x_n) satisfying the conditions for both rational and efficient allocation. An imputation 'x' is said to be unstable through coalition S if $v(S) > \sum_{i \in S} x_i$ i.e. the players have incentive to form coalition S and reject the proposed 'x'. Specifically, if the imputation is unstable, there is at least one player who is unsatisfied due to the coalition.

6.1.3 Payoff distribution methods

Cooperative game theory offers several solution concepts. There are different possible methods for dividing the coalition value to the members of a coalition and these can be classified as follows:

6.1.3.1 Equal share

The most simple division method [SHDH08] is to divide the extra payoff equally among the players in the coalition. In other words, the payoff of a player 'i' among a coalition S is

$$x_i = \frac{1}{|S|} (v(S) - \sum_{j \in S} v(\{j\})) + v(\{i\}) \text{ ('i' is a member of S)}$$

6.1.3.2 Proportional share

The extra payoff can be divided among the members of coalition in accordance with weights according to the player's willingness to cooperate in the coalition [SHDH08].

$$x_i = w_i \left(v(S) - \sum_{j \in S} v(\{j\}) \right) + v(\{i\})$$

Where $\sum_{i \in S} w_i = 1$ and within the coalition

$$\frac{w_i}{w_j} = \frac{v(\{i\})}{v(\{j\})}$$

This allows values for each w_j to be computed, e.g. as follows:

$$\begin{aligned}
w_1 + w_2 + w_3 &= 1 \\
\frac{w_1}{w_3} + \frac{w_2}{w_3} + 1 &= \frac{1}{w_3} \\
\frac{v(1)}{v(3)} + \frac{v(2)}{v(3)} + 1 &= \frac{1}{w_3} \\
w_3 &= \frac{1}{1 + \frac{v(1)}{v(3)} + \frac{v(2)}{v(3)}}
\end{aligned}$$

6.1.3.3 The Core

The core is the set of all imputations x for which $x(S) \geq v(S) \forall S \subseteq N$. An allocation in the core of a game will always be an efficient allocation. The set of stable imputations is called the core. Consequently given the grand coalition N , *the core* of a coalitional game (N, v) in characteristic form with TU is defined as [FER]

$$C_{TU} = \left\{ x: \sum_{i \in N} x_i = v(N) \text{ and } \sum_{i \in S} x_i \geq v(S) \forall S \subseteq N \right\}$$

Whenever one is able to find a payoff allocation that lies in the core, then the grand coalition is a stable and optimal solution for the coalitional game. However, the core of a coalitional game suffers from several drawbacks. On one hand, in many games, the core is empty, and thus, there does not exist an allocation that can stabilize the grand coalition. On the other hand, even when it exists, the core might be a huge set and selecting a fair allocation out of this set is a big challenge.

6.1.3.4 Power index methods

The solution of an N -person game can be obtained by several power index methods. A power index (or value) is commonly used to measure the influence of a player on the formation of coalitions and most importantly on the outcome of the game [AKJPS09]. There are several power index methods proposed in the literature (e.g., Shapley-Shubik value ϕ (abbreviated as SSPI) [SCSM08], the Banzhaf value β (abbreviated as BPI) [BR07], Holler–Packel index η (abbreviated as HPI) [HAR], Popularity Power Index ζ (abbreviated as PPI)[AKJPS09]) and the numerical behaviour of all these power indices were examined by Josephina Antoniou and co-authors in [AKJPS09].

However, we choose Shapley-Shubik value for the distribution of coalitional value since the computational complexity of this method is small. Shapley defines a value for games to be a function that assigns to each game v a number $\phi(v)$ for each player ' i '. The Shapley value $\phi = [\phi_1, \dots, \phi_i, \dots, \phi_n]$ can be computed as follows:

$$\phi_i(N, v) = \frac{1}{n!} \sum_{S \subseteq N, i \in N} (|S| - 1)! (|n| - |S|)! [v(S) - v(S/i)]$$

The summation ranges over all the subsets S of N . A coalition that includes ' i ' is denoted as $v(S)$ and a coalition without i is denoted as $v(S/i)$.

6.1.3.5 Marginal Contribution Principle

Given a cooperative game (N, v) , the quantity $v(N)$ specifies the overall amount of value created. Given the set of players N and a particular player ' i ', let $N \setminus \{i\}$ denote the subset of N consisting of all the players except player ' i '. The marginal contribution of player ' i ' denoted by MC_i [BRA07] can be computed as follow:

$$MC_i = v(N) - v(N \setminus \{i\})$$

An (individually rational and efficient) allocation (x_1, x_2, \dots, x_n) satisfies the Marginal Contribution Principle if $x_i \leq MC_i \forall i$. The marginal contribution principle is explained with the help of buying and selling game for three players i.e. $N = \{1, 2, 3\}$. The player '1' is the seller and player '2' and '3' are two potential buyers. Player '1' has a single unit to sell at a cost of \$4. Each buyer is interested in buying at most one unit. Player '2' has a willingness to pay \$9 for player 1's product, while player '3' has a willingness to pay \$11 for player 1's product.

This cooperative game of network selection can be solved in the following manner:

$$v(\{1,2\}) = \$9 - \$4 = \$5$$

$$v(\{1,3\}) = \$11 - \$4 = \$7$$

The $v(\{2,3\}) = \$0$ cannot create any value by coming together as each is looking for seller not any other buyer

$$v(\{1\}) = v(\{2\}) = v(\{3\}) = \$0$$

$$v(\{1,2,3\}) = \$7$$

The value of $\{1, 2, 3\} = \$7$ instead of $\$5 + \$7 = \$12$ as there is only one unit to sell by player '1' so it can interact with only one buyer so it prefer player '3'. Considering the same example again the marginal contribution for each player can be calculated as follow:

$$MC_1 = v(\{1,2,3\}) - v(\{2,3\}) = \$7 - \$0 = \$7$$

$$MC_2 = v(\{1,2,3\}) - v(\{1,3\}) = \$7 - \$7 = \$0$$

$$MC_3 = v(\{1,2,3\}) - v(\{1,2\}) = \$7 - \$5 = \$2$$

Considering the same example again the overall value created is \$7. The marginal contribution values show that player '2' has \$0 where as for player '3' it is \$2. This implies that player '1' can get minimum \$5 whereas the player '3' cannot get more than \$2. The fair solution will be to divide the remaining \$2 equally between player '1' and player '3'. To conclude the player '1' will get \$6 and player '3' will get \$1.

6.1.4 Modelling Resource Management as Standard Bankruptcy model

The standard bankruptcy game model including the solution of a game, coalition form and characteristic function for N-person cooperative game is presented. The stability of a game is analyzed through the core of a game. Assume a company becomes bankrupt and it owns money to N creditors. This money need to be divided among these creditors. The sums of the claims by the creditors are larger than the money of the bankrupt company. The N-person game can be used to resolve this conflict by finding an equilibrium points to divide the money between the players. A detailed survey on the bankruptcy game model was presented in [NEI82].

The standard bankruptcy game can be expressed [PSL02] for a finite set of agents A , a real positive number P which denotes the amount of bankrupt company money and a nonnegative vector $d_i \in R^N$ of claimed money by agents, where the condition $\sum_{i \in A} d_i \geq P$. To satisfy every network, the solution of the bankruptcy game must have the following two properties:

- The payoff must be completely distributed
- Each network has to obtain nonnegative money not exceeding their claimed money.

If x_i denotes the solution (i.e., the amount of company money to be distributed to the agents i), the rule of this game can be expressed as follows:

$$0 \leq x_i \leq d_i \quad \forall i \in A$$

$$\sum_{i \in A} x_i = P$$

In case of the N-person bankruptcy game with transferable utility, the characteristic function can be defined [FER] for a coalition S ($S \subseteq A$) as follows:

$$v(S) = \text{Max} \left(0, P - \sum_{j \in \bar{S}} d_j \right)$$

Analyzing the above equation we can also see that the value of $v(S)$ is higher if the value of $d_j > d_{\bar{j}} \quad \forall j \in S \text{ and } \bar{j} \in \bar{S}$ where ‘ j ’ represent the players involved in the coalition ‘ S ’ whereas \bar{j} represent the players not involved in the coalition ‘ S ’. It is worthwhile to mention, higher value of $v(S)$ means higher contribution in the coalition and will receive the higher claim from the coalition.

In [NH06], the author has modelled the bandwidth allocation algorithm based on the standard bankruptcy model. The set of wireless networks is assumed as the agents and requested bandwidth is assumed as the company money to be distributed among the agents. This approach considers three wireless networks namely as WLAN, cellular network and the WMAN respectively. When a new connection request arrives the central controller decided the amount of bandwidth to be allocated by each network. The bandwidth allocated by each network is assumed as the agent’s claims. The networks offer different bandwidths for different classes of mobile subscriptions considering their bandwidth requirements. Based on the offered bandwidth by the networks, the characteristic value of each network for the new connection request is calculated. The solution of the game can be found using the Shapley value or the core calculation. The solution found by both Shapley value calculation and the core is stable. This approach proposes a cooperative strategy for users requesting a service which cannot be admitted completely by a preferred network.

Example 6.2: A man has three wives and he is committed to a contract that specifies that they should receive 100, 200 and 300 units after his death. If total amount of α units are

left after the man's death, the three wives can only claim 100,200 and 300 units respectively out of α units. If after man dies the amount of money left is not enough for this distribution [SHDHB09].

- i. If $\alpha=100$ then how much each wife will get
- ii. If $\alpha=200$ then how much each wife will get
- iii. If $\alpha=300$ then how much each wife will get

The claims for each wife is represented as

$$c_i = \{(100 * i) \text{ for } i = 1,2,3\}$$

The characteristic function for this situation in the form of bankruptcy game can be represented as:

$$v(S) = \max \left(0, \alpha - \sum_{i \in N \setminus \{S\}} c_i \right), \text{ where } \alpha \in \{100,200,300\}$$

Nucleolus solution:

- i. Each wife gets 100/3 when $\alpha=100$
- ii. Wife 1 gets 50, wife 2 and 3 gets 75 each when $\alpha=200$
- iii. Wife 1 gets 50, wife 2 gets 100 and wife 3 gets 150 when $\alpha=300$

6.1.5 Coalition formation process

Coalition formation is a process of finding a coalitional structure that either maximizes the total utility in case of Transferable Utility (TU) game or finding a structure with Pareto optimal payoff distribution for the players in case of Non-Transferable Utility (NTU) game. The concept of Pareto optimality occurs in a number of areas of economics. The allocation of resources in an economy is Pareto optimal, often called Pareto efficient, if it is not possible to change the allocation of resources in such a way as to make some people better off without making others worse off. In game theory a Pareto optimal outcome is one in which no player could be better off without another becoming worse off.

The coalition formation process considers of the following three phases [RAH07] as follow:

- **Coalitional Value Calculation** – to calculate the value of every possible coalition that can be formed. In this thesis, the linear programming is used to calculate the coalitional value by solving the linear equation with unknown number of variables under specific constraints.
- **Coalition Structure Generation** – compute the set of disjoint coalitions that can have the maximum total utility.
- **Payoff Distribution** – distribute the rewards that each agent in a coalition should obtain as a result of the actions taken by the coalition as a whole.

A number of algorithms have been proposed for calculating the value of coalitions. The calculation of coalitional value is dependent on the problem under investigation and its complexity varies from linear [SK98] to exponential [SL97]. One of the main issues is the number of coalitional values need to be calculated. The efficient way is to distribute these coalition value calculations among the agents [RJ07]. In literature, an SK algorithm [SK95][SK96][SK98] which negotiates with agents to decide which coalitional value need to be calculated by whom. This algorithm does not consider the case where the coalitions of particular size are desirable. This algorithm is decentralized in nature, requires alot of messages for communication among the agents, redundant coalitional value calculation (same coalitional value calculated more than once), massive memory requirements and does not guarantee the fair distribution among the agents.

Given the coalitional values, the next challenge is to partition the set of players into exhaustive and disjoint coalitions. This problem in the coalition formation process is named as Coalition Structure Generation (CSG). In characteristic form games, the value of a coalition only depends on the members within the coalition whereas in normal form game with positive and negative externalities the value of a coalition also depends on the non-members. The authors in [RRDGJ07] use the concept of complete set partitioning to optimally partition the space of all potential coalitions into sub-space which contain similar coalition structures depending on the same criterion (i.e. integer partition). The CSG problem can also be related to winner determination problem in combinatorial auction [SLAST99]. Such auctions involve a number of assets being simultaneously

offered for an auction to a number of bidders. The bidders are allowed to place bids on combinations of these assets. Once the auction is closed, the auctioneer needs to partition the set of assets, given the placed bid on every combination of these assets, such that the overall sum of bids (i.e. the auctioneer's revenue) is maximized [CSS07]. For a special case where the bids were allowed on every possible combination of assets, then this becomes very similar to the CSG problem. In CSG problem, the space of possible solutions grows very rapidly with the number of agents and finding an optimal solution is NP complete [SLAST99].

The existing algorithms in literature to solve the CSG problem can be classified into low complexity algorithms (return an optimal solution), fast algorithms (no guarantee of solutions) and anytime algorithms (returns a solution within bound from an optimal solution). Dynamic programming (DP) can be used to solve the optimal sub-structure and overlapping sub-problems [CLRS01]. It solves every sub-problem once and stores the calculated values in the table in order to avoid the re-calculation.

A DP algorithm was developed by authors in [RPH95] for solving the winner determination problem in combinatorial auctions which can be easily applied to CSG problem. This algorithm starts from the coalitions of size '2' and calculate the values for each coalition of size '2'. Based on the calculated values, it determines whether it is better to split the coalition or not. The coalitions are split if the sum of their calculated values on its own is better than the value of a coalition. This algorithm maintains two tables, one for the solution and the second one for its value. The solution can be either a coalition or two agents on its own. Similarly, the same procedure is repeated for coalition of size '3' to 'n'. The last step is to find an optimal coalition structure of 'A' where it is the total number of agents. The process considers the solution table to see whether it is better to split 'A' into two sub-partitions A_1 and A_2 or not. This process is repeated until a coalition structure is found which cannot be split anymore. The complexity of this algorithm is $O(3^n)$. This algorithm does not generate results at any time.

The genetic algorithms [SD00] have also been applied in the CSG problem. This decentralized algorithm consists of number of iterative stages and maintains a list of permitted coalitions. At each stage, the coalition with highest value with all permitted coalitions is selected. The different rules exist for the disjoint and the overlapping

coalitions. In the case of disjoint coalitions, once a coalition is selected then all the coalitions containing the members of the selected coalition is removed from the list. In the case of overlapping coalitions, the only agents removed from the list are those who have exhausted their resources in previously formed coalitions. This algorithm provides the solution within a bound from the best possible combination of all permitted solutions. The process of selecting the best permitted coalition is carried out using the SK algorithm.

The first anytime algorithm was proposed in [SLAST99]. The CSG problem is modelled as a search through the coalition structure graph where each level LV_i contains the coalition structures having ' i ' coalitions. Intuitively the coalition formation process can be thought as the search through all the possible coalition structures as shown below for $N=3$ and 4 in Figure 6.1 and 6.2 respectively. The arrows in downward direction indicate the merge of two coalitions whereas the arrows in upward direction indicate the split of two coalitions. Initially, the first two levels of coalition structure graph namely LV_1 and LV_2 are searched to find an initial coalition solution. The breadth-first search algorithm is applied to search from bottom of the graph. This search continues until time permit or the entire graph is searched. The coalition structure with the highest reward is accepted as a solution. The limitation of this approach is to search through the entire graph and the bounds provided by the algorithm are impractical.

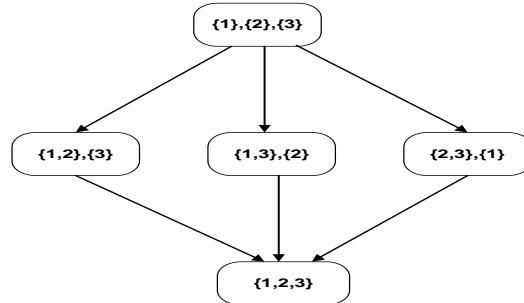


Figure 6.1 Search Space for $N=3$

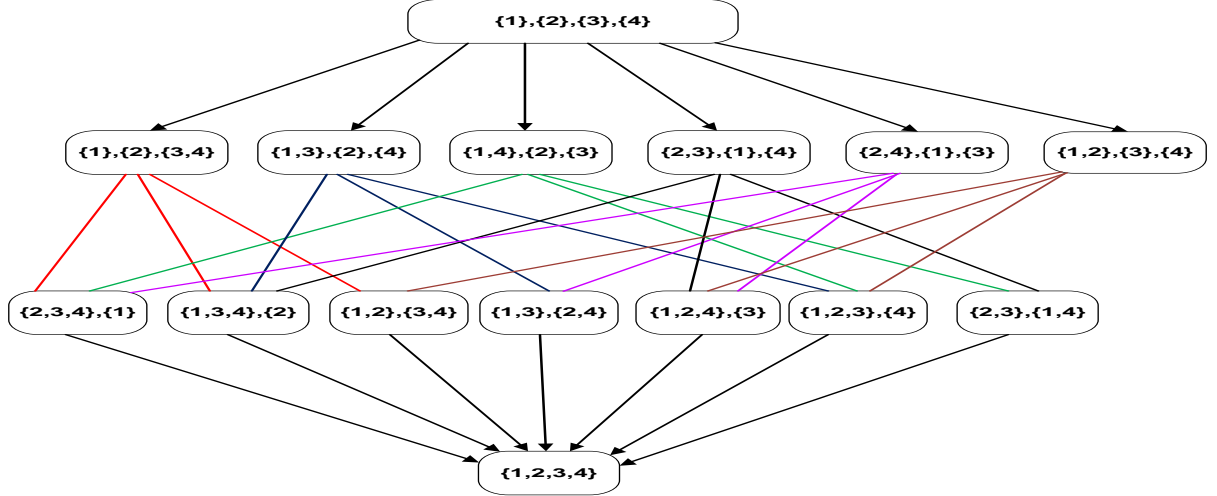


Figure 6.2 Search Space for N=4

The payoff distribution is the division of coalitional value among the agents within that coalition. The coalition is stable if no agent can deviate from the coalition it belongs to. Different stability concepts like core, the Shapley value and kernel are proposed to distribute the coalitional value among the agents of a coalition.

Coalition formation process can be either centralized or distributed. In a centralized approach, all partitions of the players N need to be iterated to find an optimal partition. The total number of partitions for a set N can be found using Bell number [SLAST99] as shown below:

$$D_n = \sum_{j=0}^{n-1} \binom{n-1}{j} D_j \text{ such that } n \geq 1 \text{ and } D_0 = 1$$

Example 6.3: For N=3 the total number of possible partitions for the set N is computed as follows:

$$D_0 = 1 \quad D_1 = \binom{2}{0} D_0 = \frac{2!}{0!(2-0)!} \times 1 = 1 \quad D_2 = \binom{2}{1} D_1 = 2$$

$$D_3 = \binom{2}{0} D_0 + \binom{2}{1} D_1 + \binom{2}{2} D_2 = \binom{2}{0} + \binom{2}{1} + \binom{2}{2} \times 2 = 1 + 2 + 2 = 5$$

This implies that the number of partitions of set N grows exponentially with the number of players in N. For N=10, the total number of partitions need to be iterated by such a centralized approach will be 115975. Hence finding an optimal partition in centralized approach is computationally complex and impractical.

A more desirable approach would be distributed in nature in which all players autonomously decide whether to join a coalition or not. The approaches used for distributed coalition formation in literature range from heuristic approaches [SLAST99], Markov chain-based methods [RAY07], Set theory based methods [AS09] and bargaining theory or negotiation techniques approaches from economics [AS02].

The authors in [SLAST99] study the coalition formation in characteristic form games where the value of each coalition S (non-negative) is given by a characteristic function. A coalition structure CS is a partition of agents, A , into disjoint, exhaustive coalitions. In other words, in a coalition structure each agent belongs to exactly one coalition, and some agents may be alone in their coalitions. The set of all coalition structures are named as M . The value of a coalition structure is given as $v(CS) = \sum_{S \in CS} v_S$. The goal is to find an optimal coalition structure which maximizes the social welfare of the agents $CS^* = \operatorname{argmax}_{CS \in M} v(CS)$. The issue of finding an optimal coalition structure is computationally complex and is dependent on the number of agents (the number of coalition structures grows rapidly with an increase in the number of agents). Most work in the literature on coalition structure generation is carried out in super-additive and sub-additive games. This work focuses on the coalitional games which are neither super-additive nor sub-additive. The authors also explain the minimal search algorithm to establish a bound in fewer steps as compared to any other algorithm in the literature. The bound can be established by only searching the bottom two levels of the search space and can be further reduced using anytime algorithm. The results outperform in evaluation when compared to algorithms for characteristic form games in literature (Merging algorithm and Splitting algorithm). The authors also define a mechanism for distributing the search space within the agents as the search done in parallel is more efficient.

The coalition formation approaches can be fully reversible, partially reversible or irreversible [RAY07]. In irreversible coalition formation approach, the members within the formed coalitions are not allowed to leave. In a fully reversible approach, the players can join and leave coalitions with no restrictions. On one hand, a fully reversible approach is practical and flexible; however, deriving such an approach can be complicated.

In [AS09] an abstract approach to coalition formation that focuses on transforming coalitions using simple merge and split rules has been proposed. The merge and split rules only take place if it is better for a player to leave (or join) any other partition for potential gains with respect to comparison relation on partitions satisfying few natural properties namely as irreflexivity, transitivity and monotonicity. The paper identifies conditions under which every iteration of merge and split rules yield unique partition which lead to a natural notion of a stable partition. The results are parameterized by a preference relation between partitions of a group of players and naturally apply to coalitional TU-games, hedonic games and exchange economy games. It provides generic framework to derive coalition formation algorithms in different scenarios and can be tailored to develop distributed algorithm.

6.1.6 Stable partitions

Let $N = \{1, 2, 3, \dots, n\}$ be a set of players called the grand coalition and let (v, N) be a coalitional TU-game. The coalition consists of non-empty set of elements of N . The ‘ v ’ is a characteristic function which determines a value to the members of a coalition.

A collection is any family $C = \{C_1, C_2, \dots, C_l\}$ of mutually disjoint coalitions of N (such as $C_i \cap C_j = \emptyset$ for all $i \neq j$) and l is called its size. A collection does not need to include all players. A partition $P = \{P_1, P_2, \dots, P_k\}$ is the set of mutually disjoint coalitions of N i.e. $\bigcup_{i=1}^k P_i = N$.

The collection C of size l in the frame of P of size k denoted by $C[P]$ can be defined for collection C and partition P as follows:

$$C[P] = \left\{ P_1 \cap \left(\bigcup_{j=1}^l C_j \right), \dots, P_k \cap \left(\bigcup_{j=1}^l C_j \right) \right\} \setminus \{\emptyset\}$$

A collection can be of different forms, varying from singleton (single element), $C \subseteq P$ or C as partition of N ($\bigcup_{j=1}^l C_j = N$).

- i. If $C = \{A\}$ then
$$C[P] = \{P_1 \cap A, \dots, P_k \cap A\} \setminus \{\emptyset\}$$
- ii. If C is a partition of N then $C[P] = P$
- iii. If $C \subseteq P$ (i.e. C consists some coalitions of P) then $C[P] = C$.

Example 6.4:

$$N = \{1,2,3\}$$

$$v(S) = \begin{cases} 0 & \text{if } |S| < 2 \\ |S| & \text{otherwise} \end{cases}$$

Possible Coalitions:

$$S_1 = \{1\} \quad S_4 = \{1,2\} \quad S_5 = \{1,3\}$$

$$S_2 = \{2\} \quad S_6 = \{2,3\}$$

$$S_3 = \{3\} \quad S_7 = \{1,2,3\}$$

Partition

$$P_1 = \{S_1, S_2, S_3\}$$

$$P_2 = \{S_1, S_6\}$$

$$P_3 = \{S_2, S_5\}$$

$$P_4 = \{S_3, S_4\}$$

$$P_5 = \{S_7\}$$

Characteristic function values:

$$v(S_1) = v(S_2) = v(S_3) = 0$$

$$v(S_4) = v(S_5) = v(S_6) = 2$$

$$v(S_7) = 3$$

$$v(P_1) = v(P_2) = v(P_3) = v(P_4) = v(P_5) = 3$$

Given a partition $P = \{P_1, P_2, \dots, P_k\}$,

i. A coalition S of N is P -compatible if and only if

$$\text{for some } i \in \{1, 2, \dots, k\} \text{ such that } S \subseteq P_i$$

ii. A coalition S of N is P -incompatible if and only if

$$\text{for some } i \in \{1, 2, \dots, k\} \text{ such that } S \not\subseteq P_i$$

iii. A partition $Q = \{Q_1, Q_2, \dots, Q_m\}$ is P -homogeneous

a. If for each $j \in \{1, 2, \dots, m\}$ some $i \in \{1, 2, \dots, k\}$ exists such that either

$$Q_j \subseteq P_i \text{ Or } P_i \subseteq Q_j$$

The stability of partition is conceptually related with the defection function. Intuitively, given a partition P such as $\{P_1, P_2, \dots, P_k\}$, the defection function $D(P)$ consists of all the

collections $C = \{C_1, C_2, \dots, C_l\}$ whose players can leave the partition P by forming a new, separate, group of players $\bigcup_{j=1}^l C_j = N$ divided according to the collection C .

Let D be a defection function, A partition P is said to be D -stable if

$$v(C[P]) \geq v(C) \quad \forall C \in D(P) \quad (6.1)$$

If C is a partition of N , then Equation (6.1) can be rewritten as follows:

$$v(P) \geq v(C)$$

A partition P is D -stable if no group of players are interested in leaving P when the players who wish to leave can only form collections allowed by the defection function $D(P)$. There are three notions of the defection functions which are classified as follows:

- **D_c stability**

The defection function D_c allows any group of players to leave P and create an arbitrary collection in N . $D_c(P)$ is the family of all collections in N . A partition P is D_c stable if it satisfies the following two conditions:

- for each $i \in \{1, 2, \dots, k\}$ and each pair of disjoint coalitions S_1 and S_2 i.e. $S_1 \cup S_2 \subseteq P_i$*

$$v(S_1 \cup S_2) \geq v(S_1) + v(S_2)$$

- For each P -incompatible coalition $T \subseteq N$

$$\sum_{i=1}^K v(P_i \cap T) \geq v(T)$$

- **D_p stability**

The defection function $D_p(P)$ for each partition P is the family of all partitions of N . It allows a group of players to leave P only as the group of players to form an arbitrary partition of N . The partition P is D_p stable if and only if

$$v(P) = \max_Q v(Q) \quad \forall Q \in N$$

- **D_{hp} stability**

The defection function $D_{hp}(P)$ for each partition P is the family of all P -homogeneous partitions in N . The D_{hp} allows the players to leave the partition P by only means of split or merge.

$$v(P) = \max_Q v(Q) \quad \forall Q \in N \text{ where maximum is taken over all} \\ - \text{homogeneous partitions } Q \text{ in } N$$

The partition P is D_{hp} stable if and only if

- i. For each $i \in \{1, 2, \dots, k\}$ and for each partition $\{C_1, C_2, \dots, C_l\}$ of the coalition P_i

$$v(P_i) \geq \sum_{j=1}^m v(C_j)$$

- ii. For each $T \subseteq \{1, 2, \dots, k\}$

$$\sum_{i \in T} v(P_i) \geq v\left(\bigcup_{i \in T} P_i\right)$$

7 Investigating the concept of Coalitions of Base stations

In Chapter 5, only one network could adjust its RF coverage to improve user coverage and in effect all the decision making was done by the wider coverage (here the WiMAX) network. In this chapter adjacent BS or networks can both make adjustments and the use of coalitions of networks and of users. A coalition is simply a subset of the set of players which forms in order to coordinate strategies and to agree on how the total payoff is to be divided among the members. The cooperation between the providers can be classified as either intra-provider or inter-provider. In intra-provider cooperation, base stations belonging to the same provider cooperate by borrowing channels. In inter-provider cooperation, networks belonging to different providers using the same RAT share the spectrum. More detail regarding inter-provider cooperation is explained in Section 7.3.

As part of the optimisation of radio resource distributed hybrid frequency allocation algorithm utilizing channel borrowing considering the co-channel interference is a commonly considered tool. In this thesis, the intention is to build on and utilize state of art hybrid frequency allocation algorithms rather than develop a new hybrid frequency allocation algorithm. Rather in this thesis, intra-provider cooperation is proposed and will be implemented. A linear programming approach analogous to [ASSK09] is modelled. Coalitions of base stations (or sectors) are considered and a linear programme under specific resource constraints is solved for every coalition to calculate their value. The objective of each member in the coalition becomes the optimization of the coalition objective subject to operating constraints.

The search space can be partitioned into subspaces using the Anytime Integer Partition Algorithm (AIPA) and this search through all the subspaces heuristically using a branch and bound approach and using the lower and upper bounds to constraint the search space. The algorithm has the capability to provide the solution at anytime and hence can be classified as an anytime algorithm. This algorithm also finds a solution within 95% of the optimal solution. The AIPA algorithm is classified into three stages (shown in Figure 7.3) namely as 1) input processing 2) calculating the bounds and pruning the subspace and 3) searching within a subspace to find a near optimal partition.

The optimal coalition structure found by AIPA needs to be checked for stable partition condition D_{hp} as mentioned in Section 6.2.6. If the optimal coalition structure is not stable, then the next optimal coalition structure is examined. The search objective is to find a stable partition as compared to the optimal partition.

7.1 Related Work

In [ZY89], different channel assignment strategies like simple borrowing (SB), hybrid assignment (HA), borrowing with channel ordering (BCO), locally optimized dynamic assignment (LODA) and borrowing with directional channel locking (BDCL) were examined. Their simulations were carried out in a 49-cell network for both uniform and non-uniform traffic using blocking probability as a parameter to measure the efficiency of these strategies. All cells are assigned with ten nominal channels. The channel reuse distance in the system is assumed to be three cell units. The call distribution is exponentially distributed with a duration mean call of 3 min. The traffic load is increased by 10% to 150% above the base load and the blocking probability is measured for the channel assignment strategies. The SB and HA strategies have always higher blocking rates as compared to all other channel assignment strategies. The BDCL strategy has the lowest blocking probability for both uniform and non-uniform traffic. The LODA strategy has blocking probability comparable to BCO in non-uniform traffic condition while BCO has far lower blocking probability under uniform traffic conditions. This comparative study did not consider sectors within the cells. In this thesis, six sectors within a cell are considered.

7.2 Optimal Frequency Allocation as a coalitional game

In this section, the base station cooperation and frequency allocation is modelled as a coalitional game. The coalitional game is used to model the benefits of cooperation between the base stations (intra-provider) or networks (inter-providers). The important aspect is the formation of coalitions in the game. The coalitional game is explained below.

7.2.1 Problem Formulation

Consider a multi-cell wireless network with k base stations (BS's). Let M_{ik} denote the set of mobile users associated with the sector i of the base station ' k '. The instantaneous bit rates mobile users receive on different channels depend on the quality of the channel and the current position of the mobile users. We assume that whenever mobile user j is served by channel l , the mobile user receives a bit rate R_{lj} , which is a function of the state of the channel l and position of mobile user j . For simplicity we assume that the cost of using a channel l is negligible i.e. $c_{li}=0$. A channel $l \in C_i$ (the channels in sector i) can serve mobile user j only when both are associated with the same sector or the sectors associated with them are in coalition (i.e. channel is borrowed from the neighbouring sector). Let the random variable $\alpha_{lj} \in [0,1]$ be the fraction of time channel l serves mobile user j . Let $N = \{1,2,\dots,n\}$ denote the set of sectors seeking to provide resources to the congested sector within the multi-cell network owned by the same provider. Any subset $S \subseteq N$ is called a coalition and those subsets that only contain one sector, i.e., $\{i|i \in N\}$ are called singleton coalitions. The partition comprising all the members on the set N is called the coalition structure. For mathematical tractability of the investigated problem, it is also assumed that each user will be allocated a single channel. The cost of borrowing a channel from the neighbouring or adjacent sectors is ignored because all the cells are owned by the same provider. Each sector forms a coalition with neighbouring or adjacent sectors (i.e. from which it can borrow a channel). On joining a coalition, the sector ' ik ' will contribute towards the coalitional utility and in return will receive a pay-off denoted by p_{ik} . In order to avoid singleton coalitions, the coalitional value is set to $v(\{i|i \in N\}) = 0$ and to prevent singleton coalitions from joining other singleton coalitions, the coalitional value is set to $v(\{i|i \in N, j|j \in N\}) = 0$.

Each formed coalition should represent the mutual benefit (coalition value) to the sectors. The main objective is to calculate coalitional value $v(S)$ for any coalition $S \subseteq N$ (*set of sectors from whom the channel can be borrowed*) if feasible, else $v(S) = -\infty$. This problem can be formulated as an optimization problem which returns coalition value for any coalition $S \subseteq N$ (*set of sectors from whom the channel can be borrowed*) as shown below:

$$O(S):- \text{Maximize: } \sum_{\substack{l \in C_S \\ j \in M_S}} \alpha_{lj} \times R_{lj}$$

7.2.1.1 Constraints

The service specific constraints under which the problem needs to be optimized are shown as below:

Constraint 1:

Suppose we want an allocation of resource that maximises the bit rate allocated to all the users that satisfies the minimum bit rate of each user denoted by m_j . This condition is justified with the help of the following constraint:

$$\begin{aligned} \sum_{l \in C_S} \alpha_{lj} \times R_{lj} &\geq m_j \text{ where } j \in M_{in} \\ \sum_{l \in C_S} \alpha_{lj} \times R_{lj} &\leq M_j \text{ where } j \in M_{in} \end{aligned}$$

Constraint 2:

A channel can serve at most the whole fraction of time given by the following constraint

$$\sum_{l \in C_S} \alpha_{lj} \leq 1, \quad j \in M_{in}$$

Constraint 3:

Also the user cannot receive a message for more than the time period from each channel l given by following constraint.

$$\sum_{j \in M_{in}} \alpha_{lj} \leq 1, \quad l \in C_S$$

Constraint 4:

$$\alpha_{lj} \geq 0, \forall l, j.$$

This is a linear programming problem and so a solution can be found unless there is no feasible solution.

7.2.1.2 Example

In the context of cooperation between the sectors within the base stations, the benefits of the cooperation are evaluated for a 7-cell environment. Initially, the sector S_1 has channels $\{c_1, c_2, \dots, c_6\}$. There are 7 users within the sector S_1 . The sector S_1 has un-

served user for whom it can borrow channels from the sector S_3 or S_5 of the same base station or neighbouring base stations. If the sector S_1 cooperates (or borrows) from the sector S_3 or S_5 , there are two possible channels available to S_1 to serve its mobile user labelled 'a' and 'b' respectively. The bit rate received by all the mobile users (*belonging to S_1*) would be dependent on the state of the channels $\{c_1, c_2, \dots, c_6\}$ and channel 'a' or channel 'b' and their relative positions. In general terms, the bit rate received by mobile users j in the non-cooperative case (does not borrow) in sector S_1 would be as follows:

$$b_j = \sum_{l \in C_i, j \in M_{in}} \alpha_{lj} \times R_{lj} \quad \forall |j| \leq |C_i| \quad (7.1)$$

The bit rate received by mobile users j in sector S_1 while forming coalition S (i.e. borrow from sector S_3 and S_5) is given below:

$$b_j = \sum_{l \in C_S} \alpha_{lj} \times R_{lj} \quad \text{where } C_S = C_i \cup CH a \cup CH b \quad (7.2)$$

The bit rate received by mobile users j in sector S_1 while forming coalition S (i.e. borrow from sector S_3 or S_5) is given in (7.3) and (7.4) respectively:

$$b_j = \sum_{l \in C_S} \alpha_{lj} \times R_{lj} \quad \text{where } C_S = C_i \cup CH a \quad (7.3)$$

$$b_j = \sum_{l \in C_S} \alpha_{lj} \times R_{lj} \quad \text{where } C_S = C_i \cup CH b \quad (7.4)$$

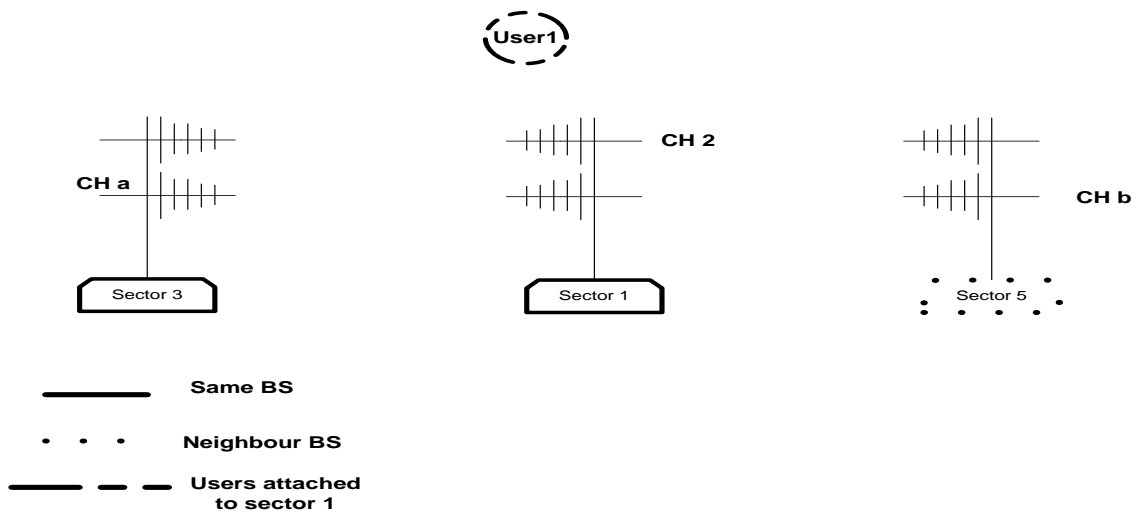


Figure 7.1 Cooperation between adjacent or neighbouring sectors

The case where the sector S_1 borrows channels from both S_3 and S_5 as an optimization problem subject to the following constraints are shown in (7.5):

$$O(S):- \text{Maximize: } \sum_{l \in C_S} \alpha_{lj} \times R_{lj} \text{ where } C_s = C_i \cup CH a \cup CH b \quad (7.5)$$

The cases where the sector S_1 borrows channels from either S_3 or S_5 as an optimization problem subject to the following constraints are shown in (7.6) and (7.7) respectively:

$$O(S_3):- \text{Maximize: } \sum_{l \in C_S} \alpha_{lj} \times R_{lj} \text{ where } C_s = C_i \cup CH a \quad (7.6)$$

$$O(S_5):- \text{Maximize: } \sum_{l \in C_S} \alpha_{lj} \times R_{lj} \text{ where } C_s = C_i \cup CH b \quad (7.7)$$

Example 7.1: In Figure 7.1, there are three players involved (i.e. sectors S_1 , S_3 and S_5). The possible coalitions are $\{S_1\}, \{S_3\}, \{S_5\}, \{S_1, S_3\}, \{S_3, S_5\}, \{S_1, S_5\}, \{S_1, S_3, S_5\}$. The (7.1) can be solved for sector S_1 using allocated *six* channels to serve *seven* users using linear programming techniques (i.e. $v(\{S_1\})$). Similarly Equation (7.1) can be solved for sector S_3 and S_5 to get the coalition value $v(\{S_3\})$ and $v(\{S_5\})$ respectively. For the coalition $\{S_1, S_3\}$, the Equation (7.6) can be solved to get the coalition value $v(\{S_1, S_3\})$. For the coalition $\{S_1, S_5\}$, the Equation (7.7) can be solved to get the coalition value $v(\{S_1, S_5\})$. For the coalition $\{S_1, S_3, S_5\}$, the Equation (7.5) can be solved to get the coalition value $v(\{S_1, 5\})$. The coalition formation is considered in regards to S_1 so the coalition values of $\{S_3, S_5\}$ is $v(\{S_3, S_5\}) = -\infty$.

7.2.2 Searching through Coalition Structures

The next activity in the coalitional game is the Coalition Structure Generation (CSG) which heuristically searches through all the possible coalition structures to find an optimal solution. The search space increases exponentially with the number of agents involved in the coalition. The searching mechanism needs to search the space by applying heuristics to find a near to optimal solution in a reasonable time.

The search space P can be partitioned into sub-spaces which contain coalition structures which are similar according to some criterion. The considered criterion is based on the integer partitions of the number of agents (or players). An integer partition of n is a multi-set of positive integers that add up to exactly n .

Example 7.2: For $n=4$ the different ways of portioning the search space into sub-spaces based on integer partitions are shown as follows:

$$\begin{aligned}
[4] &= \{a_1, a_2, a_3, a_4\} \\
[3,1] &= \left\{ \begin{aligned} &\{\{a_1\}, \{a_2, a_3, a_4\}\} \\ &\{\{a_2\}, \{a_1, a_3, a_4\}\} \\ &\{\{a_3\}, \{a_1, a_2, a_4\}\} \\ &\{\{a_4\}, \{a_1, a_2, a_3\}\} \end{aligned} \right\} \\
[2,2] &= \left\{ \begin{aligned} &\{\{a_1, a_2\}, \{a_3, a_4\}\} \\ &\{\{a_1, a_3\}, \{a_2, a_4\}\} \\ &\{\{a_1, a_4\}, \{a_2, a_3\}\} \end{aligned} \right\} \\
[2,1,1] &= \left\{ \begin{aligned} &\{\{a_1\}, \{a_2\}, \{a_3, a_4\}\} \\ &\{\{a_1\}, \{a_3\}, \{a_2, a_4\}\} \\ &\{\{a_1\}, \{a_4\}, \{a_2, a_3\}\} \\ &\{\{a_2\}, \{a_3\}, \{a_1, a_4\}\} \\ &\{\{a_2\}, \{a_4\}, \{a_1, a_3\}\} \\ &\{\{a_3\}, \{a_4\}, \{a_1, a_2\}\} \end{aligned} \right\} \\
[1,1,1,1] &= \{\{a_1\}, \{a_2\}, \{a_3\}, \{a_4\}\}
\end{aligned}$$

For instance, the coalitions structures $\{\{a_1\}, \{a_2, a_3, a_4\}\}$ can be mapped to the integer partition $[3, 1]$ since they each contain one coalition of size 1 and the second coalition of size 3. The sub-space noted as P_G contains all the coalition structures that correspond to the same integer partition G . The number of possible integer partitions grows exponentially with n . The sub-spaces are categorized into levels based on the number of parts within the integer partitions. Specifically, level P_i contains all the sub-spaces that correspond to integer partition with i parts as shown below:

$$P_i = \{P_G : |G| = i\}$$

Considering the four agent example again, the level '1' would have all the sub-spaces with only one part i.e. $[4]$. Similarly, the level 2,3 and 4 would have all the subspaces with two ($[2,2]$ & $[3,1]$), three ($[2,1,1]$) and four parts ($[1,1,1,1]$) respectively.

$$P_1 = P_{|4|}$$

$$P_2 = P_{|2,2|} \& P_{|3,1|}$$

$$P_3 = P_{|2,1,1|}$$

$$P_4 = P_{|1,1,1,1|}$$

The Anytime Integer Partition based Algorithm (AIPA) [RRJG09] could be used to search through the entire graph using upper and lower bounds on every sub-space. The lower bound would be used to prune the search space. This algorithm also uses the conventional branch and bound principle.

Now, let $A = \{a_1, a_2, \dots, a_i, \dots, a_n\}$ be the set of agents, where n is the number of agents. In order to allow for any limitations on the coalitional sizes, we assume there is a set S of the permitted coalitional sizes. Also, let L_s be an ordered list of possible coalitions of size $s \in S$, and N_s be the number of coalitions in L_s (i.e. $N_s = |L_s|$).

Finally, let $C_{i,s} = \{c_{i,s}^1, c_{i,s}^2, \dots, c_{i,s}^s\}$ denote the coalition located at index i in the list L_s , where each element $c_{i,s}^j$ is an integer representing agent $a_{c_{i,s}^j}$ (For example, $C_{i,s} = \{1, 3, 4\}$ corresponds to the coalition of agents a_1, a_3, a_4). Now for any $s \in S$, we define the order in the list L_s as follows:

- The first coalition in the list is: $\{n - s + 1, \dots, n\}$
- The last coalition in the list is: $\{1, 2, \dots, s\}$

L_1	L_2	L_3	L_4
4	3,4	2,3,4	1,2,3,4
3	2,4	1,3,4	
2	2,3	1,2,4	
1	1,4	1,2,3	
	1,3		
	1,2		

The coalitions would be ordered into lists L_s of size s according to the ordering technique used by Talal Rahwan and Jennings in Distribution of Coalitional Value to Coalitions (DCVC) [RJ07]. The coalitions in L_s are ordered lexicographically. The representation

for input can only use a list containing only the values of these ordered coalitions. The scanning of sub-spaces P_G can be classified into the following steps:

Step 1:

First of all the value of coalition structure of size 'n' ($P_{|n|}$) is scanned which is the only sub-space in level P_1 . Secondly the value of coalition structure of size '1' ($P_{|1, 1, 1, 1|}$) is scanned which is the only sub-space in level P_n . The two sub-spaces have been scanned and we can select the maximum value of coalition structure as a current best coalition structure CS' .

Scan all sub-spaces in P_G where G is an integer partition which consists of two parts (in example 7.2 for four agents, $G = [2, 2]$ & $[3, 1]$) and for six agents, $G = [1, 5], [2, 4], [3, 3], [4, 2], [5, 1]$). The ordering technique imply that any two complimentary coalitions C and \hat{C} in a coalition structure $CS = \{C, \hat{C}\}$ are always diametrically positioned in the coalition lists $L_{|C|}$ and $L_{|\hat{C}|}$ even if $|C| = |\hat{C}|$. Considering example 7.2 again, the coalitions $\{a_1\}$ and $\{a_2, a_3, a_4\}$ are diametrically positioned in the lists L_1 and L_3 respectively, and the coalitions $\{a_1, a_2\}$ & $\{a_3, a_4\}$ can be found at the bottom and top of the list L_2 (diametrically positioned in the same list).

As mentioned before G is an integer partition which consists of two parts as $G = [g_1, g_2]$ where $g_1 = s$ and $g_2 = n - s$. Considering example 7.2 again, the level P_2 would have all the subspaces i.e. $P_{|2, 2|}$ & $P_{|3, 1|}$. The sub-space $P_{|2, 2|}$ contains all the coalition structures of size '2' and in our ordering technique these lie in list L_2 . Similarly $P_{|3, 1|}$ contains the coalition structures of size '3' and '1' so these lie within the list L_3 and L_1 respectively. In order to compute the values of all the coalition structures in the level P_G by summing the values of the coalitions as a process of scanning the lists $v(L_s)$ and $v(L_{n-s})$ starting at different points for each of the list. Once both lists $v(L_s)$ and $v(L_{n-s})$ are scanned, it is possible to get maximum values of coalition for each of the lists and these two values constitute the best coalition structure CS' found so far. It is also possible to found the indices of these maximum values in their respective lists. As the input ordered list only consists of the values of the coalition structure (i.e. $v(L_s)$ and $v(L_{n-s})$), an algorithm developed by Rahwan and Jennings [RJ07] can be used to return a coalition C given its position in the ordered list $L_{|C|}$. In the end, the new generated coalition structure CS' is

compared against the previous best coalition structure and updated if it is better than the previous one.

Step 2:

After scanning the lists $v(L_s)$ and $v(L_{n-s})$, it is possible to compute an upper and lower bounds. Let \max_s , \min_s and avg_s as well as \max_{n-s} , \min_{n-s} and avg_{n-s} be the computed maximum, minimum and average value of the coalitions in $v(L_s)$ & $v(L_{n-s})$ respectively. Given an integer partition G , let S_G be the Cartesian product of the lists L_s : $s \in G$.

$$S_G = \prod_{s \in G} (L_s)^{G(s)}, \text{ where } G(s) \text{ is the multiplicity of } s \text{ in } G$$

For example, given $G = [2, 1, 1]$, we have $S_G = (L_2)^1 \times (L_1)^2$. We can now calculate the upper bound UB_G by summing the maximum value of each coalition list involved in a set S_G as shown below:

$$UB_G = \sum_{s \in G} \max_s \times G(s)$$

In a similar way it is possible to define a lower bound as follow:

$$LB_G = \sum_{s \in G} \min_s \times G(s)$$

However a better lower bound would be the average of the values of these coalition structures. Let AVG_G be the average value of all the coalition structures in P_G . It is possible to obtain the average value of a sub-space without going through any coalition structure. The average would be a better lower bound because having a greater lower bound allows more pruning of the search space. Let the avg_s be defined as the sum of the values of all coalition of size 's' and divided by the total number of coalitions of size 's' and can be computed as a part of the input scanning process.

$$AVG_G = \sum_{s \in G} G(s) \times \text{avg}_s$$

$$\text{avg}_s = \frac{1}{|v(L_s)|} \sum_{s=1}^{|v(L_s)|} v(L_s)$$

Considering $G = [2, 1, 1]$, then $UB_G = \max_2 + 2 \times \max_1$, $LB_G = \min_2 + 2 \times \min_1$ & $AVG_G = \text{avg}_2 + 2 \times \text{avg}_1$. From now onwards the AVG_G would be used as a lower bound.

Step 3:

The upper and lower bound for each sub-space P_G is calculated in step 2. After that the optimal lower bound LB^* would be assigned as follow:

$$LB^* = \max(v(CS'), AVG_G^*)$$

In the above equation the AVG_G^* is the highest lower bound out of all the sub-spaces and $v(CS')$ is the value of the best coalition structure obtained after scanning the input in step 1. Similarly, the optimal upper bound UB^* would be assigned as follow:

$$UB^* = \max(v(CS'), MAX_G^*)$$

In the above equation MAX_G^* is the highest upper bound out of all the sub-spaces. Hence all the sub-spaces where $UB_G < LB^*$ would be pruned. This scanning procedure allows us to compute a worse case bound β on the value of CS' as follow:

$$\beta = \min\left(\frac{n}{2}, \frac{UB^*}{v(CS')}\right)$$

It is also possible to specify a bound $\beta^* \geq 1$ and if the best solution found so far fits within the specific bound such that $\beta \leq \beta^*$ and then there is no need for further search.

Step 4:

In order to verify CS' is an optimal solution, we need to search sub-spaces where the upper bound is greater than $v(CS')$. This can be done by selecting the next sub-space to be searched using the following rule:

$$Select\ G = \underset{G \in G}{\operatorname{argmax}}(UB_G)$$

As a result of this, all the sub-spaces with an upper bound lower than $v(CS')$ will not be searched. Another reason for using this selection rule is that it only terminates when there are no sub-spaces left to be searched or the maximum upper bound has been reached. This approach is used to find an optimal solution.

Step 5:

Given $G = \{g_1, g_2, \dots, g_{|G|}\}$, we define the following set of agents: $A_1, A_2, \dots, A_{|G|}$: where A_1 contains n players and $A_k: 2 \leq k \leq |G|$ contains $n - \sum_{i=1}^{k-1} g_i$ players. Moreover, list LC_s^i is the list of possible combinations of size s taken from the set $\{1, 2, \dots, i\}$. The list LC_3^4 would contain the following

combinations $\{1,2,3\}, \{1,2,4\}, \{1,3,4\}$ and $\{2,3,4\}$. It is also worth mentioning $\{1,2,3\}$ implies the 1st, 2nd and 3rd element of the corresponding A and is represented by C.

Let the memory $M = \{M_1, M_2, \dots, M_{|G|}\}$ required to store one coalition structure at a time. In more detail, M_1 is assigned to one of the combinations in $LC_{g_1}^{|A_1|}$. After that M_2 is used to cycle through $LC_{g_2}^{|A_2|}$ until a combination that does not overlap with M_1 is found. After that M_3 is used to cycle through $LC_{g_3}^{|A_3|}$ until a combination that does not overlap with $\{M_1, M_2\}$ is found. This is repeated until each $M_k \in M$ is assigned to a combination in list $LC_{g_k}^{|A_k|}$. The M_k is only updated once all the possible instances of $\{M_{k+1}, \dots, M_{|G|}\}$ whose corresponding $\{C_{k+1}, \dots, C_{|G|}\}$ does not overlap with $\{C_1, C_2, \dots, C_k\}$ are examined. For example, the $M_1 = \{1, 2\}$ implies that $C_1 = \{1^{\text{st}} \text{ element of } A_1, 2^{\text{nd}} \text{ element of } A_2\}$. The M_2 is only updated once all the possible instances of M_3 whose corresponding C_3 that do not overlap with $\{C_1, C_2\}$ are examined.

In this case M would be a valid coalition structure belonging to a sub-space. The value of this coalition structure is then calculated and compared with the maximum value found so far. The cycling technique is explained with the help of the following example:

Example 7.3: Given $n = 6, G = [2,1,3]$ i.e. $g_1 = 2, g_2 = 1, g_{|G|} = 3$ where $|G| = 3$ and $A_1 = 6, A_2 = 6 - g_1 = 4, A_3 = A_2 - g_2 = 3$.

$LC_{g_1}^{ A_1 } = LC_2^6$	$LC_{g_2}^{ A_2 } = LC_1^4$	$LC_{g_3}^{ A_3 } = LC_3^3$
5,6		
4,6	4	
4,5		
3,6		
3,5	3	
3,4		
2,6		1,2,3
2,5	2	
2,4		
2,3		

1,6	
1,5	
1,4	1
1,3	
1,2	

The A_1 consist of 'n' i.e. $A_1 = \{1,2,3,4,5,6\}$ and having $M_1 = \{1,2\}$ from the list LC_2^6 means that C_1 contains the 1st and 2nd elements of A_1 i.e. $C_1 = \{1,2\}$. By knowing C_1 we can easily compute the A_2 which will include all the players excluding the $C_1(A_1/C_1)$ and $A_2 = \{3,4,5,6\}$. The M_2 will cycle through all the possible coalitions of the size '1' out of A_2 (LC_1^4) and would never overlap with C_1 . The M_2 can be either 1st element of A_2 {3}, 2nd element of A_2 {4}, 3rd element of A_2 {5} or 4th element of A_2 {6} because it does not overlap with $C_1 = \{1, 2\}$. If $M_2 = \{2\}$ then C_2 will be {4} and similarly, A_3 will include all the players which do not belong to C_1 or C_2 i.e. $A_3 = \{3,5,6\}$. The M_3 will cycle through all the possible coalitions of the size '3' out of A_3 (LC_3^3) and select the one coalition which does not overlap with C_1 or C_2 . However, whenever the A_k is updated, the same combination in $LC_{g_k}^{|A|}$ would correspond to a different coalition.

Using the above technique, the same coalition structure can be generated twice and in order to remove this redundancy the following rules are defined as follows:

- i. M_k cycles through the combinations in $LC_{g_k}^{|A_k|}$ that start with 'j'
 - a. M_{k+1} only cycles through the combinations in $LC_{g_{k+1}}^{|A_{k+1}|}$ that start with values equal to or greater than 'j'
- ii. M_k can only cycle through the combinations in $LC_{g_k}^{|A_k|}$ that start with 'j' such that

$$1 \leq j \leq (|A_{k+1}| - g_{k+1} + 1)$$

Step 6:

As mentioned in step 5, we only update M_k once all the possible instances of $\{C_{k+1}, C_{k+2}, \dots, C_{|G|}\}$ are examined which do not overlap with $\{C_1, C_2, \dots, C_k\}$. If none of the coalition structures in $\{M_{k+1}, M_{k+2}, \dots, M_{|G|}\}$ have a value greater than the maximum value found so far we could update M_k without going through any of the

possible instances of $\{C_{k+1}, C_{k+2}, \dots, C_{|G|}\}$. In order to update M_k straight away we need to calculate the upper bound on the remaining coalition structures from $\{C_{k+1}, C_{k+2}, \dots, C_{|G|}\}$.

As we had already computed \max_s for every possible coalitions of size $s \in \{1, 2, \dots, n\}$ in step 1, we can easily compute the upper bound denoted by UB as follows:

$$UB_{\{g_{k+1}, \dots, g_{|G|}\}} = \sum_{i=k+1}^{|G|} \max_{g_i}$$

If we define $v(\{C_1, C_2, \dots, C_k\})$ as the sum of the values of coalitions C_1, C_2, \dots, C_k so $t(\{C_1, C_2, \dots, C_k\}) = \sum_{i=1}^k v(C_i)$. Now let CB be the value of the current best solution found so far. There exist no solution starting with coalition structures starting with $\{C_1, C_2, \dots, C_k\}$ and end with coalition structures $g_{k+1}, \dots, g_{|G|}$ better than the current found solution 'CB' if the following condition is satisfied:

$$CB > V\{C_1, C_2, \dots, C_k\} + UB_{\{g_{k+1}, \dots, g_{|G|}\}}$$

On the other hand, if $CB \leq V\{C_1, C_2, \dots, C_k\} + UB_{\{g_{k+1}, \dots, g_{|G|}\}}$ implies that there could be a coalition that starts with $\{C_1, C_2, \dots, C_k\}$ and end with coalition structures $g_{k+1}, \dots, g_{|G|}$ better than the current found solution 'CB'. However still we do not need to examine all the coalition structures from $g_{k+1}, \dots, g_{|G|}$. In the next list there might be some coalition structures which are not better than the current best will be pruned. This branch and bound principle is explained below in Figure 7.2.

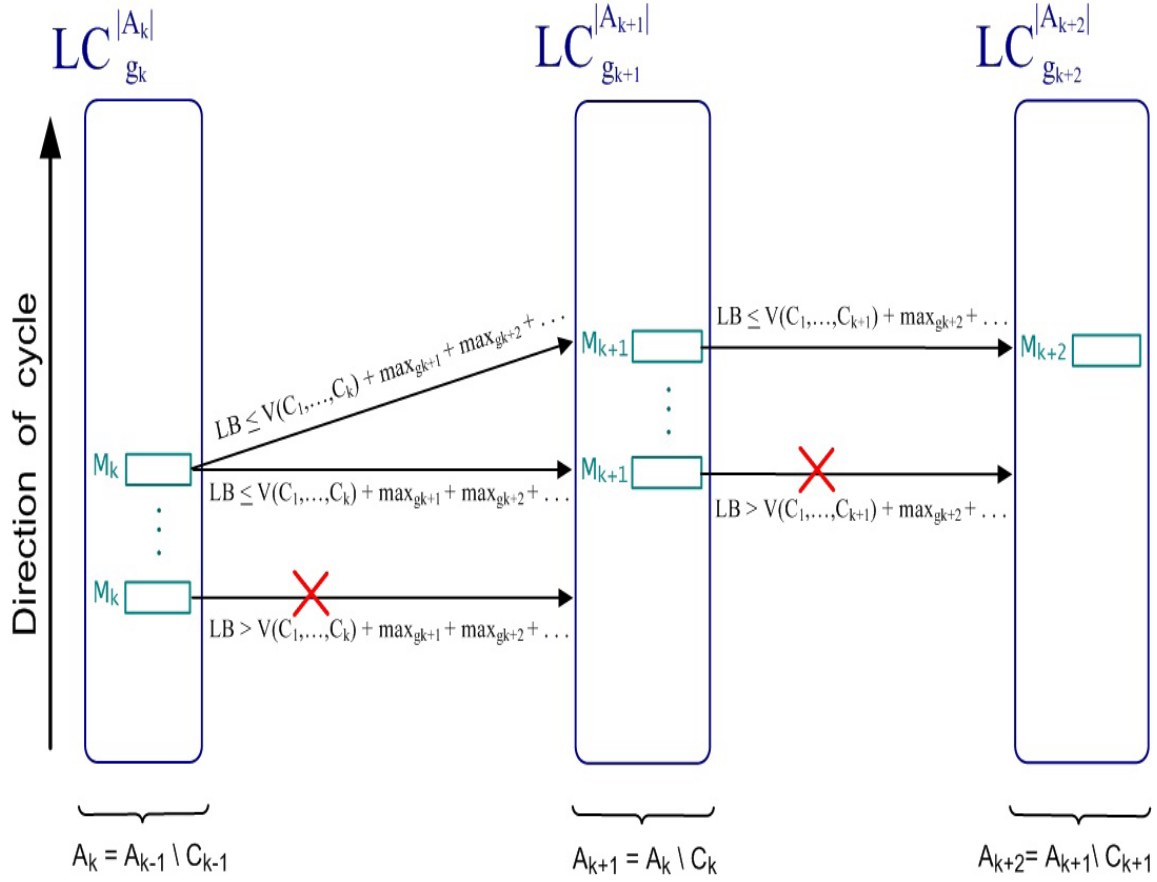


Figure 7.2 Applying Branch and Bound while searching through the sub-space [RRJG09]

7.2.3 Distribution of coalitional value among the members

The last activity in the coalitional game is the distribution of coalitional value among the base stations involved in the selected stable partition. The concept of payoff distribution methods are mentioned in Section 6.2.3. In this thesis, the core and Shapley value would be used for the payoff distribution.

Example 7.4: To distribute the payoff between the members of the coalition the calculation of core $C = \{(x_1, x_2, x_3) : x_1 + x_2 + x_3 = P + Q\}$ of this game subject to the following constraints is shown below:

$$C_1: x_i \geq Q \quad i \neq 1$$

$$C_2: x_1 + x_2 \geq P$$

$$C_3: x_1 + x_3 \geq P$$

$$C_4: x_2 + x_3 \geq 2Q$$

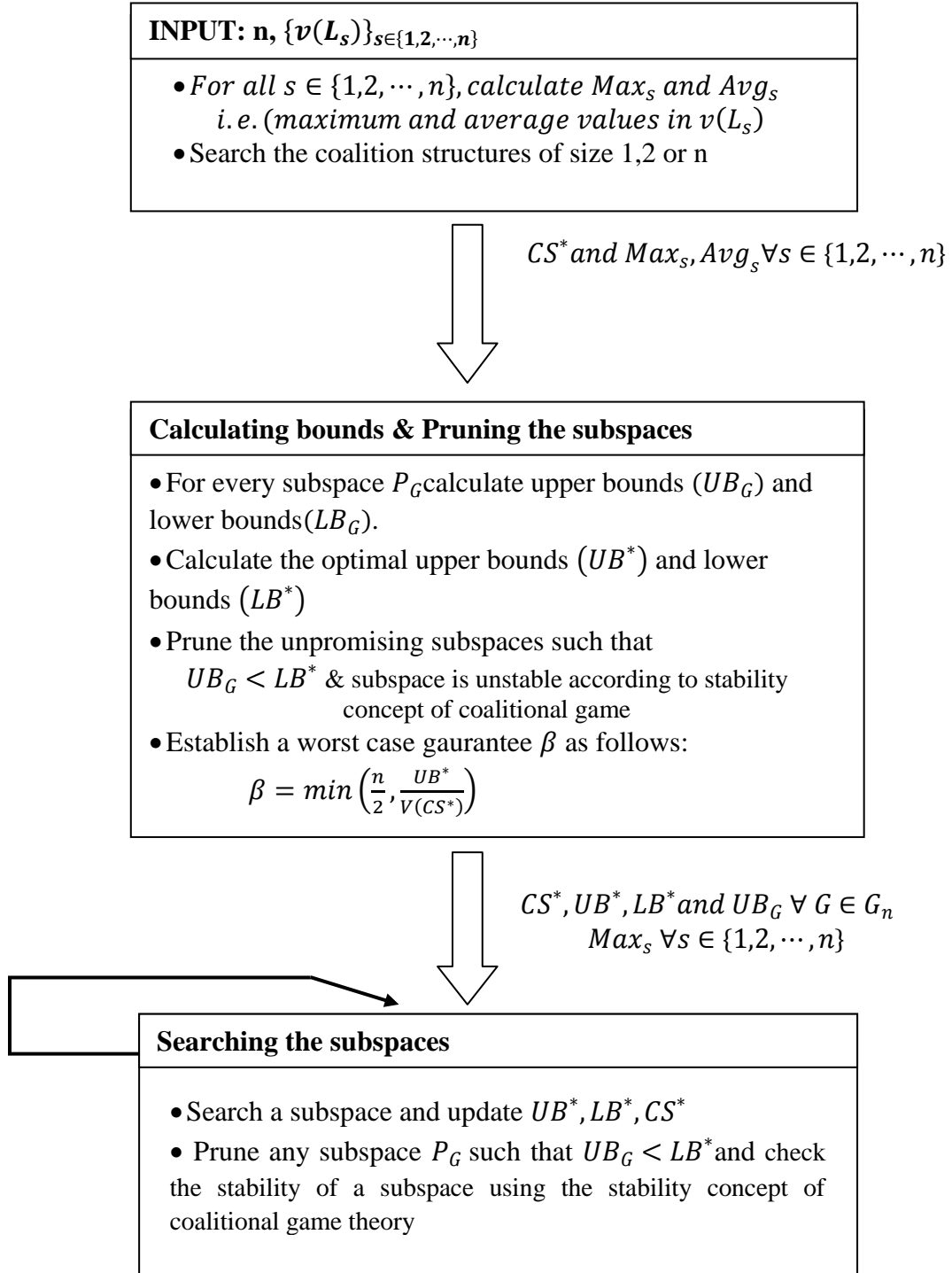


Figure 7.3 Anytime Integer Partitioning Flowchart

Using linear programming technique the solution of this game (core) can be computed as follows:

$$x_1 + x_2 + x_3 = P + Q$$

Using C_4

$$x_1 + 2Q = P + Q$$

$$x_1 = P - Q$$

Using C_2

$$P + x_3 = P + Q$$

$$x_3 = Q$$

Using C_3

$$P + x_2 = P + Q$$

$$x_2 = Q$$

In fact the core of this game $C = \{(x_1, x_2, x_3)\} = \{(P - Q, Q, Q)\}$.

7.2.4 Proposed Experiment

To evaluate the benefits of modelling resource allocation as a coalition game, intended to do comparisons with other approaches need to be made. To make comparisons, the simulations will be carried out to measure the performance metrics for different traffic distributions. A suitable simulator is a LTE system level simulator capable of simulating LTE Single Input Single Output (SISO) and Multiple Input Multiple Output (MIMO) networks using Open Loop Spatial Multiplexing (OLSM) and Transmission Diversity (TxD) transmission modes that has been developed by the Institute of Communications and Radio Frequency Engineering, Vienna University of Technology, Austria.

A simulation would consist of three main components: the network initialization, the optimization and LTE system level simulator. The simulation would calculate performance metrics for the traffic configuration, as illustrated in Figure 7.4.

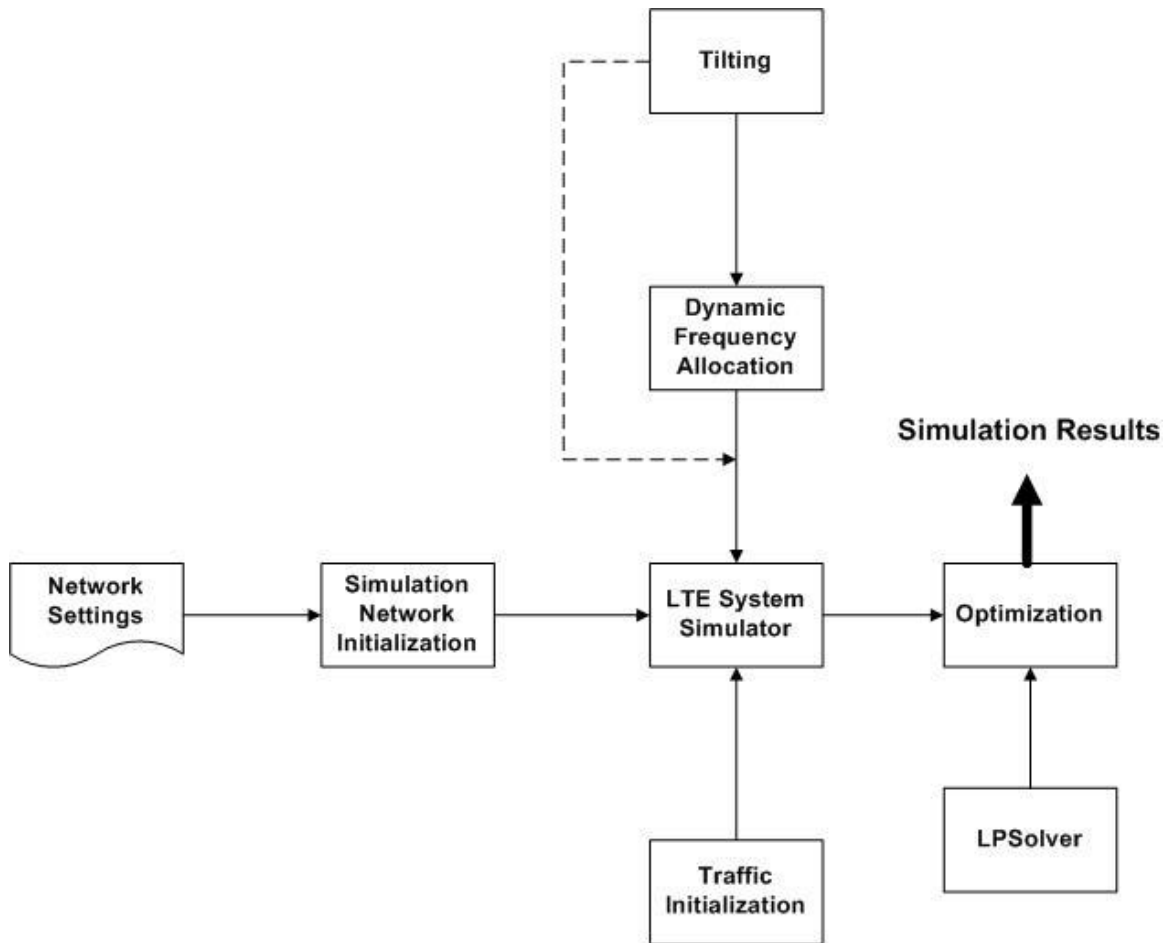


Figure 7.4 Simulation Setup

At first, the simulation network needs to be initialised with a network topology (the locations of BSs) and antenna model. According to the traffic scenario setting, such as hotspot locations, number of hotspots, population in hotspot area, etc, a set of traffic scenarios will be built. After the network initialization, the dynamic frequency allocation algorithm and tilting mechanisms are applied. The tilting mechanism or dynamic frequency allocation can be applied in different order depending on the network configuration. The Matlab based open source LTE system simulator will be run for each traffic scenario, the network simulation evaluates the QoS performance metrics of the simulation network. Lastly, the coalition between base stations is modelled as an optimisation problem and the optimisation module consisting of Matlab based LP solver capable of solving linear programming under specific constraints is applied. Experiments can then be performed for the network under the same traffic conditions for the state of art approaches to compare the results with our proposed approach.

The benefits of cooperation in context of the base station and user coalitional game will be evaluated. Initially, the optimal frequency allocation scheme (including hybrid frequency allocation and the convex optimisation problem) would be verified for symmetric settings as mentioned in [AS09]. In symmetry setting, all base stations and users receive equal pay off so the payoff profile turns out to be in core [AS09]. The allocation that maximizes the aggregate payoffs of all participants (base station and users) is referred to as socially optimal. Users' payoffs should decrease with increase in number of users 'j' for any given number of base station 'n' as each user needs to contend with more users for sharing the same amount of resource. The trend should be opposite for base stations' payoffs as demand increases with increase in 'j'. The aggregate base stations' payoffs increase with increase in n, j [AS09].

The coalitional game based on the optimal frequency allocation scheme would be evaluated in terms of user throughput, cell throughput and the bit rates achieved by users with Non-Cooperative Resource Allocation (NCRA) scheme [PNB08] and the base association approach mentioned in [JPW08]. In [JPW08], the authors describe the association between base stations and selfish users in multi-network environment. The resource allocated by BS using a simple scheduling policy is explained for two different cases. Each BS performs intra-cell optimization and the total utility of the users are maximized at Nash Equilibrium. In our proposed experiment, the core is considered as the optimal distribution of payoff between base stations or sectors within the coalitions. The throughput of the user within each cell and the total utility of all users in our proposed experiment would be compared with results in [JPW08] and [PNB08].

7.3 Inter-Provider cooperation (Dynamic Spectrum Access case)

The inter-provider cooperation studies the spectrum sharing (or cooperation) between networks belonging to different providers using the same Radio Access Technology (RAT). The inter-provider cooperation requires a mechanism by the networks to sense their spectrum and pool the channels available to be utilized by other networks at a particular instant of time.

There are two major types of spectrum sharing namely as Dynamic Spectrum Allocation (DSA) and Dynamic Spectrum Selection (DSS) [HWBSYH09]. The DSA is used when sharing is controlled by collaborating network providers whereas in Dynamic Spectrum Selection (DSS) the sharing is implemented by the User Equipment (UE) negotiating access with a number of networks. In DSA, the providers are able to support their user requests on another network. The providers are able to temporarily allocate their resources to a user associated with a different network.

The spectrum sharing can be classified as either pool or non-pool based. In pool based spectrum sharing [SQT08], the resource is available to be shared jointly in a pool manner without prioritized access between the two providers. Hence, there is no notion of primary and secondary providers in pool based spectrum sharing. In non-pool based spectrum sharing [HWBSYH09], a provider has spare capacity that can be temporarily assigned to a capacity limited secondary system. It is assumed that both providers cover the same geographical area. The providers are assumed as primary and secondary providers. The primary provider (PO) is defined as the provider which has instantaneous spare capacity to support the secondary provider (SO) during a capacity crisis. The secondary provider suffers capacity problems and requires additional resources from another network for a given period of time. It is important to note that the process is dynamic in time (i.e op A and op B may interchangeably be PO or SO) based on traffic demand.

To facilitate spectrum sharing between providers, collaboration is implemented at a network level. The sharing of Radio Network Controller (RNC) minimizes delays and signalling between the providers. It also implies that spectrum sharing can happen on a very fast time scale (order of milliseconds) [SQT08].

This section focuses on a centralized mechanism for pool based spectrum sharing between two providers using the same technology as shown in Figure 7.5. The traffic demand of Network Provider '1' is given by $(D_{11}, D_{21}, \dots, D_{N1})$ at time interval (t_1, t_2, \dots, t_n) and similarly for Network Provider '2'; the traffic demand is given by $(D_{12}, D_{22}, \dots, D_{N2})$ at time interval (t_1, t_2, \dots, t_n) . In particular, different providers may form a coalition and pool their resources such as spectrum. For the centralized model, a meta-provider owns and manages a common pool of spectral

resources in a specific region. The authors in [SAGDB08] refer to the common spectrum pool notation as (Coordinated Access Band or CAB).

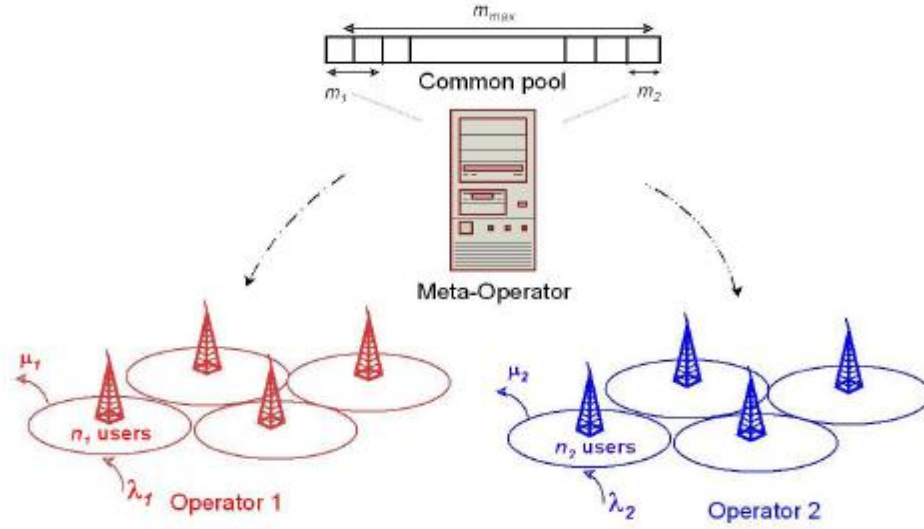


Figure 7.5 Centralized Intra-provider model [KCG09]

7.3.1 Example of Cooperation between different providers

Consider a network with a set of providers N and a set of mobile users within the network coverage area. The mobile users associated to a particular network 'N' is represented by M_N . Each provider uses its base stations to serve mobile users through a set of channels it has access to. Each mobile user negotiates the minimum bit rate (m_j) and maximum bit rate (M_j) with its provider beforehand. We assume each base station k can have access to a set of channels C_k . The base station k is allowed to use any subset of channels in C_k . We also assume that no base stations in vicinity can have access to the same channel i.e. $C_{k_1} \cap C_{k_2} = \emptyset$ for $k_1 \neq k_2$ if k_1 and k_2 are in the vicinity in order to avoid interference between the communications of different base stations for different mobile users. One of the networks is assumed to be a primary network and the secondary network can utilize the spectrum of the primary network during the inactivity of primary users.

The instantaneous bit rate mobile users receive on different channels depends on the quality of the channel and the current position of the mobile users. We assume that whenever mobile user 'j' is served by channel 'l', the mobile user receives a bit rate R_{lj} , which is a function of the state of the channel 'l' and position of mobile user 'j'. For simplicity we assume that the cost of using a channel 'l' by the provider 'i' i.e. $c_{li}=0$. A

channel $l \in C_k$ can serve mobile user 'j' only when both are associated with the same provider or the providers associated with them are in coalition. Let random variable $\alpha_{lj} \in [0,1]$ be the fraction of time channel l serves mobile user j .

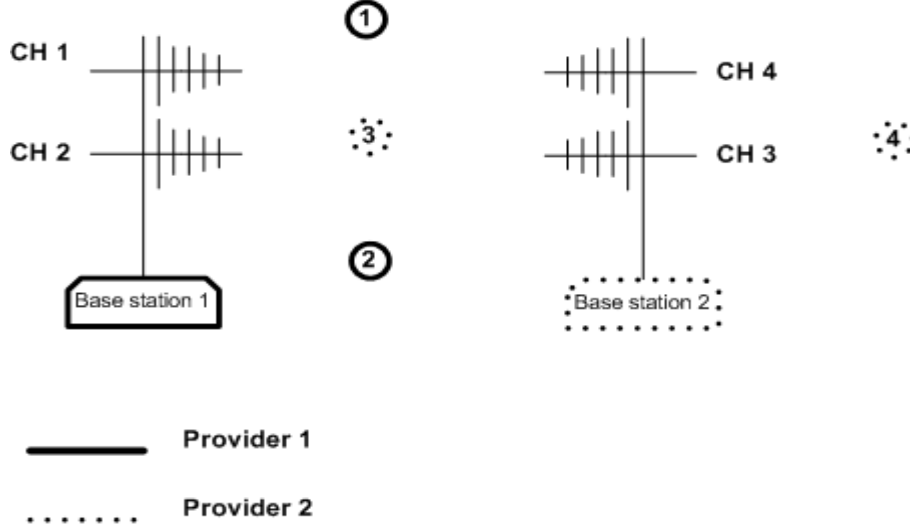


Figure 7.6 Cooperation between two different providers

In this section we assume the channels available to each provider are not identical in nature. If both providers (as in Figure 7.6) are not cooperating, there are two channels available to each provider to serve its mobile users. The bit rate received by mobile user 1 and 2 (belonging to provider 1) would be dependent on the state of the channels (channel '1' and channel '2') and their relative position. The bit rate received by mobile users '1' and '2' is shown below in (7.8) and (7.9) respectively.

$$b_1 = \alpha_{11} \times R_{11} + \alpha_{21} \times R_{21} \quad (7.8)$$

$$b_2 = \alpha_{12} \times R_{12} + \alpha_{22} \times R_{22} \quad (7.9)$$

Similarly the bit rate received by mobile users '3' and '4' (belonging to provider 2) is shown below in (7.10) and (7.11) respectively.

$$b_3 = \alpha_{33} \times R_{33} + \alpha_{43} \times R_{43} \quad (7.10)$$

$$b_4 = \alpha_{34} \times R_{34} + \alpha_{44} \times R_{44} \quad (7.11)$$

In general terms, the bit rate received by mobile user j in non-cooperative case would be as follows:

$$b_j = \sum_{l \in C_k, j \in M_N} \alpha_{lj} \times R_{lj} \quad (7.12)$$

When the provider associated with mobile user j is in coalition S , the rate received by j is given below in (7.13):

$$b_j = \sum_{l \in C_S} \alpha_{lj} \times R_{lj} \quad (7.13)$$

Example 7.5: Consider the network in Figure 7.6 with $N = \{1,2\}$ and $C_1 = \{\text{ch1}\}$ $C_2 = \{\text{ch3}\}$. Let $R_{12}=R_{31}=R_{32}= P$ and $R_{11}=R_{33}=Q$, where $Q < P$ and $R_{lj}=0$ otherwise. Let $m_j = \frac{Q}{2}$ for $j = 1,2,3,4$. The payoff is equal to the sum of the service rates.

Solution:

i. Non-cooperative

a. Provider 1

$$v(\{1\}) = \alpha_{11} \times R_{11} + \alpha_{13} \times R_{13} = \alpha_{11} \times Q + \alpha_{13} \times 0 = Q$$

b. Provider 2

$$v(\{2\}) = \alpha_{32} \times R_{32} + \alpha_{34} \times R_{34} = \alpha_{32} \times P + \alpha_{34} \times 0 = P$$

ii. Cooperative

$$\text{Let } \alpha_{11}=\alpha_{32}=0, \alpha_{12}=1 \text{ and } \alpha_{31}=\alpha_{33}=\frac{1}{2}$$

$$\begin{aligned} v(\{1,2\}) &= \alpha_{11} \times R_{11} + \alpha_{12} \times R_{12} + \alpha_{13} \times R_{13} + \alpha_{14} \times R_{14} + \alpha_{31} \times R_{31} + \alpha_{32} \\ &\quad \times R_{32} + \alpha_{33} \times R_{33} + \alpha_{34} \times R_{34} \\ &= R_{12} + \frac{1}{2} R_{31} + \frac{1}{2} R_{33} \\ &= P + \frac{1}{2} P + \frac{1}{2} Q = \frac{3P + Q}{2} \end{aligned}$$

Example 7.6: Consider the network $N = \{1,2,3\}$ with $C_1 = \{\text{ch1}\}$ $C_2 = \{\text{ch2}\}$ and $C_3 = \{\text{ch3}\}$ as shown in Figure 7.7. The number of mobile users belonging to a network 'N' is represented by M_N . Let $M_1 = \{\emptyset\}$ $M_2 = \{1\}$ $M_3 = \{2\}$ & $R_{lj} = P, j \in M_N$ and $R_{lj} = Q, l \in \{2,3\}, j \in M_N$ where $P > Q$. Let $m_j = 0$ for $j \in M_N$. The payoff is equal to the sum of the service rates.

Solution:

$$v(\{1\}) = 0$$

$$\begin{aligned} v(\{2\}) &= \alpha_{21} \times R_{21} = \alpha_{21} \times Q = Q \text{ Since the channel 2 is utilized by user '1' only so} \\ \alpha_{21} &= 1 \end{aligned}$$

$v(\{3\}) = \alpha_{32} \times R_{32} = \alpha_{32} \times Q = Q$ Since the channel 3 is utilized by user '2' only so $\alpha_{32} = 1$

$v(\{1,2\}) = \alpha_{11} \times R_{11} = P$ or $\alpha_{21} \times R_{21} = Q$ Since $P > Q$ the channel 1 is utilized by user '1'.

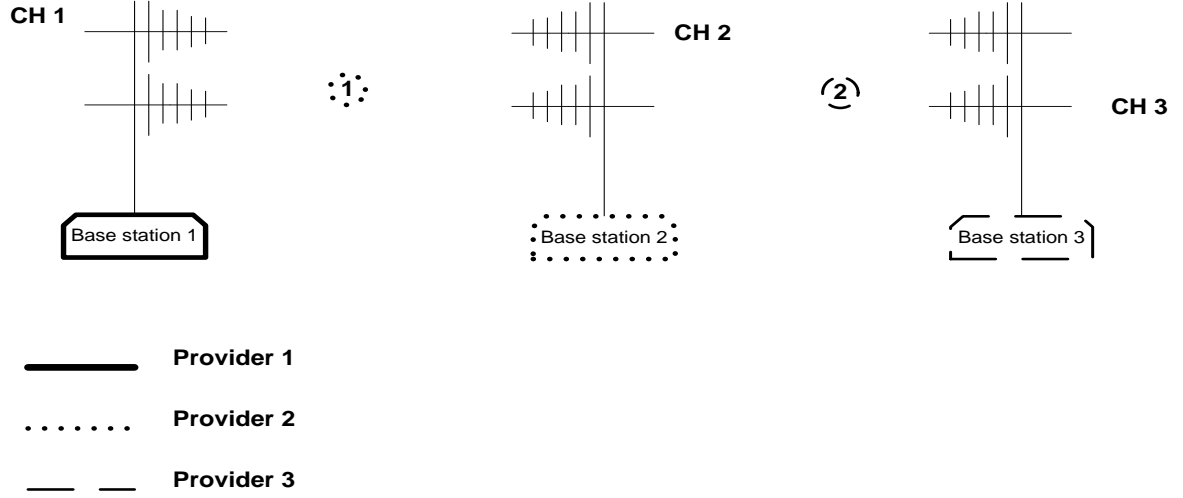


Figure 7.7 Cooperation between three different providers

$v(\{1,3\}) = \alpha_{12} \times R_{12} = P$ or $\alpha_{32} \times R_{32} = Q$ Since $P > Q$ the channel 1 is utilized by user '2'.

$$v(\{2,3\}) = \alpha_{21} \times R_{21} + \alpha_{32} \times R_{32} = 2Q$$

$$v(\{1,2,3\}) = \alpha_{11} \times R_{11} + \alpha_{32} \times R_{32} = P + Q$$

Let $S = \{1,2\}$ and $T = \{1,3\}$ Then

$$v(S) + v(T) = 2P$$

$$v(S \cup T) = v(\{1,2,3\}) = P + Q$$

$$v(S \cap T) = v(\{1\}) = 0$$

Thus $v(S) + v(T) > v(S \cup T) + v(S \cap T)$ which proves this game is not a convex one.

7.4 Summary

The coalition formation process includes three main activities: coalitional value calculation, coalition structure generation, and payoff distribution. In this chapter, the linear programming approach under resource specific constraints to calculate the coalitional values for a wireless network is discussed. This chapter also highlights the limitations of the state of the art algorithm for coalition structure generation. The

advantages and disadvantages of each of these classes have also been discussed, and examples from existing literature have been provided.

To conclude, this approach can be used to calculate the payoff value of all the possible coalition structures for a given number of players. This is a linear programming problem and so a solution can be found unless there is no feasible solution. This coalitional game approach is explained with the help of few examples and the linear programming technique is used to compute the solution (or core) of the game.

8 Conclusion and Discussion

8.1 Conclusion

This thesis describes examples of cooperative games theory supported by AHP to wireless resource management. Evolutionary games and the selection of optimal coalitions of users are the focus of the work. Users and networks decisions were modelled using AHP. The examples covered the choice of network where two technologies overlap and to modelling optimal frequency allocation between different networks in heterogeneous environment and between the base stations belonging to the same provider. AHP is systematically used to address the challenges in network selection and optimisation in heterogeneous environments. An AHP based network selection model considering four QoS related attribute as presented in Chapter 5 is applied to approximate the respective traffic load within the networks. This generally approximated traffic load can be used as a historical data in the next two phases.

Cooperative control mechanisms supported by evolutionary game theory are described in Chapter 5 and are used to balance the traffic load across the different networks. The mechanism was based an evolutionary game between the wireless networks and was illustrated in the context of shifting users from one network to another depending on the payoff within a particular service area. This gave a procedure to decide upon adjustments to the transmitted power in a non-congested network to offer better services (i.e. better SINR or bit rate) to a mobile user. This allowed the appropriate traffic to be diverted from the congested network to the uncongested network. The process involved hypothetical reasoning steps considering both networks with the actual selection is performed at the end. The network configuration mechanism was implemented for omni-directional antennas and with the ability to adjust transmit power at BSs. The evolutionary equilibrium is a fixed point at which payoff of each user in a population is equal to the average payoff. Notionally, an evolutionary equilibrium is a point at which no user is willing to shift from one network to another network. If the evolutionary equilibrium is able to divert the congestion between the networks efficiently, then this is considered as an appropriate solution. This mechanism could be extended for six sectors case in the

WiMAX network where the power configuration within a particular sector is enhanced depending on their respective traffic load.

Adjustment to the load in a network may require invocation of the cooperative control mechanism between the base stations belonging to the same provider. When a BS is heavily loaded, it has less potential to serve new mobile users and so call blocking increases. Overloaded BSs therefore need to seek help from neighbouring BSs. The cooperative control techniques like dynamic frequency allocation techniques and cooperative tilting can be applied. My research colleagues Haibo Mei and Peng Jiang are investigating cross layer optimisation to increase spectral efficiency using cooperative tilting and dynamic frequency allocation. They are investigating the benefits of one over the other, and the value of applying both techniques one after the other. Physically altering the coverage, such as by tilting is the only real resource when there is a physical BS or RS failure.

The change in network configuration (originally R) results in different power patterns (R^*) i.e. the network can cover more areas. The cooperation between the neighbouring base stations and the congested base station is modelled as a coalitional game. The players in the game include the neighbouring base stations are able to help the congested base station. The channel allocation between base stations is modelled as an optimisation problem and is solved using linear programming techniques. The set of coalitions are represented as a search space and is heuristically searched to provide Pareto-optimal solution using the stability concepts of coalitional game. Validation of the computational approach has not been possible, but a detailed description of the steps in the process of finding the optimal coalitions has been given

8.2 Future Directions

Firstly, the evolutionary game theory model mentioned in Chapter 5 can be extended for the Cognitive Radio networks. The cognitive radio system consists of M primary users, where primary user 'i' owns the frequency spectrum denoted by F_i with bandwidth of size B_i (Figure 8.1). A primary user can sell portions of the available spectrum (e.g., time slots in a time division multiple access (TDMA)-based wireless access system) to secondary users who are willing to buy the spectrum opportunities. The primary user broadcasts the

availability of spectrum along with the price to secondary users over a dedicated control channel to access the spectrum. If a secondary user wants to buy the spectrum from this primary user, it will send a request message to the primary user through the control channel. After receiving the request message, the primary user allocates time slot(s) to the secondary user.

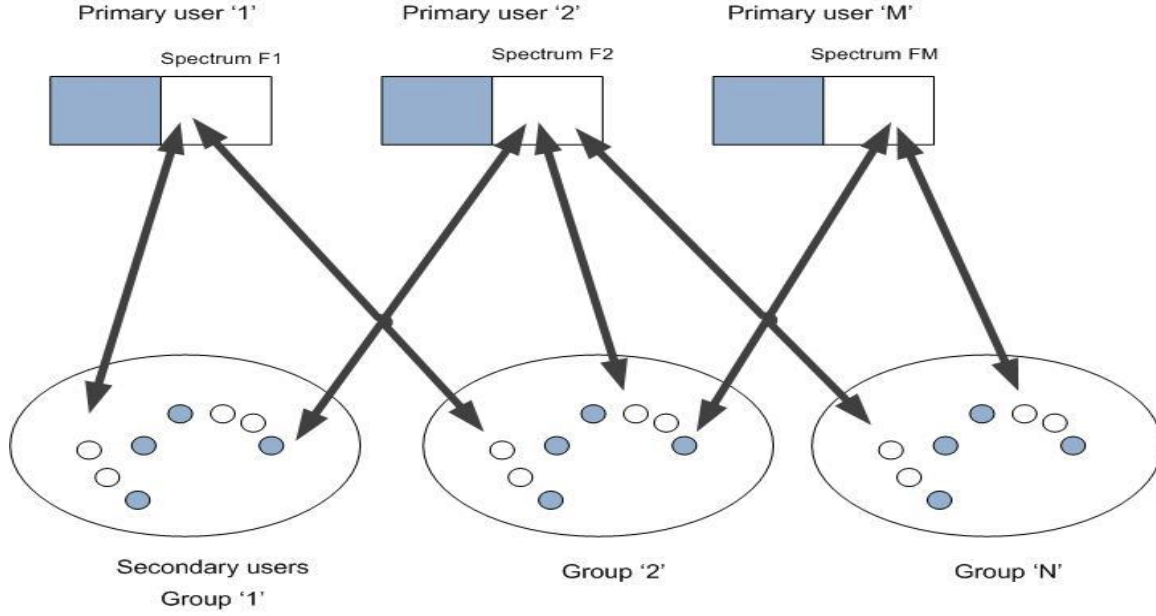


Figure 8.1 Evolutionary model for cognitive radio network

There are 'N' groups of secondary users, and $N^{(a)}$ denotes the number of secondary users in group 'a'. The number of users associated with secondary group 'a' served by primary user 'i' is denoted by $N_i^{(a)}$. The secondary groups may correspond to the sets of users in different geographical areas. The secondary users will make decisions on buying spectrum independently. The primary user 'i' sells spectrum opportunities of size b_i from the total available bandwidth of size B_i and charges price p_i (per user per unit time) to the secondary users. This available spectrum can be shared by secondary users from the same or from different groups. The secondary users dynamically choose and buy the spectrum from the primary user which maximizes its payoff in terms of performance and price. As a result, the secondary users will evolve to buy spectrum with lower price and/or better performance. A secondary user will stop evolving when the payoff becomes identical to the average payoff of the group in which that secondary user belongs to.

The game consists of a set of players i.e. group of secondary users. In an evolutionary game, the players are grouped into a population. The secondary users in group ‘1’ constitute one population whereas the secondary users in group ‘N’ constitute another population. The set of strategies associated with each player in a population is to select the primary user from whom to buy the spectrum. The net utility of secondary user ‘a’ buying spectrum from the primary user ‘i’ is denoted by $\pi_i^{(a)}$.

The deterministic model like replicator dynamics can be applied separately to each population (i.e. group of secondary users). The $n_i^{(a)}$ denotes the number of secondary users in group ‘a’ buying spectrum from primary user ‘i’, the total number of secondary users in group ‘a’ is shown below:

$$N^{(a)} = \sum_{i=1}^M n_i^{(a)}$$

The proportion of secondary users buying spectrum from primary user ‘i’ is $x_i^{(a)} = \frac{n_i^{(a)}}{N^{(a)}}$ and this is referred to as the population share. The population state can be denoted by the vector $x^{(a)} = \{x_1^{(a)}, \dots, x_i^{(a)}, \dots, x_M^{(a)}\}$. The replicator dynamics is defined as follows:

$$\dot{x}_i^{(a)} = x_i^{(a)} (\pi_i^{(a)} - \bar{\pi}^{(a)})$$

$$\bar{\pi}^{(a)} = \sum_{i=1}^M x_i^{(a)} \pi_i^{(a)}$$

According to this replicator dynamics of secondary users in group ‘a’, the number of secondary users buying spectrum from primary user i increases if their payoff is above the average payoff. The evolutionary equilibrium is considered as a solution to the game. The evolutionary equilibrium is defined as the stable fixed point of the replicator dynamics. When a population of players evolves over time (i.e., based on the replicator dynamics), it will converge to the evolutionary equilibrium. At this evolutionary equilibrium, none of the players wants to change the strategy since its payoff is equal to the average payoff of the population it belongs to. This evolutionary equilibrium can be obtained by solving:

$$\dot{x}_i^{(a)} = 0 \forall a, i$$

The more detail about the evolutionary equilibrium and their stability can be found in sections 5.6.3 and 5.6.4 respectively.

Secondly, network black holes are major concern, as increasing capacity in certain locations may adversely affect the coverage in other areas. When an antenna configuration is changed, it may not be able to cover a region or the received power cannot support link set up. They are particularly awkward network as the network provider cannot detect mobile users within a coverage black hole. Only when a mobile user cannot find service can the user determine that it is in an uncovered area. A reliable coverage prediction model to achieve collaboration between the cells and accommodate the complex propagation effects for optimization performance is required. When an antenna configuration is changed, the radio coverage is changed and some boundary MSs might be involved in handover processes. In case of a base station failure or RS failure a coverage black hole might be created.

Mobile users within the coverage black hole try to connect to the users connected to the base station. The connected users act as a relay for the users in the black hole. This interaction between the users in black hole and users connected to the base stations are modelled using a coalitional game theory. All the connected mobile users could detect those mobile users that are within their Bluetooth or Wi-Fi range. Because of this, all the connected mobile users would have a list of un-served MSs in the coverage hole. The connected mobile users would act as a Relay station (RS) for un-served users in the coverage hole. The RS have the option whether to connect to another RS or un-served MS. This is conceptually possible, but would require special software on the mobile handsets and also would incur battery usage on behalf of others- a persistent problem with ad-hoc and Delay Tolerant Networks (DTN). These practical implementations should be carefully considered in the coalitional game model.

The network formation game with the RSs as the players can be modelled. In this model, the players are the RSs who interact for forming a *directed* uplink tree structure (directed towards the BS). Every RS ‘i’ in the tree, acts as a source node, and transmits the packets that it receives from external mobile stations (MSs) to the BS, using multi-hop relaying.

Hence, when RS ‘ i ’ is transmitting its data to the BS, all the RSs that are parents of ‘ i ’ in the tree relay the data of ‘ i ’ using DTN. The RSs negotiate with other RS (or un-served MS) and choose whether to accept or reject a proposal to form a link between them. The BS accepts any connection from any RS. Through multi-hop relaying, the probability of error is reduced, and consequently the packet success rate (PSR) achieved by a RS can be improved. Essentially, the value function in this game is Non-Transferable Utility (NTU) as each RS optimizes its own utility. The utility of a RS ‘ i ’ is an increasing function of the effective number of packets received by the BS (effective throughput) while taking into account the PSR, as well as the number of packets received from other RS (the more a RS receives packet, the more it is rewarded by the network). The utility also reflects the cost of maintaining a link, hence, each RS ‘ i ’ has a maximum number of links that it can support. As the number of links on a RS ‘ i ’ increases, the rewards needed for *accepting* a link also increase, hence making it difficult for other RSs to form a link with ‘ i ’. The possible actions or strategies available to each RS is to select the link that it wants to form with available RSs or un-served MS (denoted by set B_i) and which already accepted links (A_i) should be maintained. The RS ‘ i ’ can only connect to all RSs that are not connected to ‘ i ’. If a RS wants to connect to another RS it needs to either have an available connection or drop the previously accepted link. The strategy of RS can be denoted by (a_i, b_i) where $a_i \in A_i$ and $b_i \in B_i$. The best response for the RSs is to select the link that maximizes its utility.

The RS are prioritized from the lowest to the highest Signal to Noise (SNR) ratio. The purpose is to allow the RS with low SNR more options to connect to other RSs or un-served MS. The dynamic algorithm for network formation game can be proposed with RS being myopic i.e. strategies are selected to maximize their payoff. Several models for myopic dynamics have been considered in the literature [SD00][RAY07] that proposes a myopic dynamics algorithm inspired from [JW02] and [AJM08] consisting of several rounds where each round mainly consists of two phases: a fair prioritization phase and a dynamics phase. The RSs could select their strategies sequentially. For any strategy (a_i, b_i) that RS i intends to choose, node b_i (another RS or un-served MS) approves to form link between RS i and node b_i (ib_i) only if it is able to improve its utility by either adding link ‘ ib_i ’ or replacing one or more of its already accepted links in A_{b_i} by ‘ ib_i ’.

Replacing implies that node b_i will break one or more of its already accepted links and replace them with ibi if this will improve its utility. This process continues until that no node ' i ' can improve its utility by a unilateral change in the strategy. The resulting graph G^* should be a local Nash tree and the stability of the tree can be checked according to conditions mentioned in [AJM08].

Finally, the AHP based network selection model can be used to select the best possible cognitive radio network for the secondary users depending on their preferences.

REFERENCES

- [AJK99] Y. Argyropoulos, S. Jordan, and S. Kumar, "Dynamic channel allocation in interference-limited cellular systems with uneven traffic distribution," Vehicular Technology, IEEE Transactions on, vol. 48, no. 1, pp. 224-232, 1999.
- [AJM08] E. Arcaute, R. Johari, and S. Mannor, "Local dynamics for network formation games," in Communication, Control, and Computing, 2008 46th Annual Allerton Conference on, pp. 937-938, 2008.
- [AKJPS09] J. Antoniou, I. Koukoutsidis, E. Jaho, A. Pitsillides, and I. Stavrakakis, "Access network synthesis game in next generation networks," Comput. Netw., vol. 53, no. 15, pp. 2716-2726, 2009.
- [AKL06] Ahmed, T.; Kyamakya, K.; Ludwig, M.; , "Architecture of a Context-Aware Vertical Handover Decision Model and Its Performance Analysis for GPRS - Wi-Fi Handover," Proceedings. 11th IEEE Symposium on Computers and Communications (ISCC '06), 2006, pp. 795- 801, 26-29 June 2006
- [APAPL05] T. Al-Gizawi, K. Peppas, D. Axiotis, E. Protonotarios, and F. Lazarakis, "Interoperability criteria, mechanisms, and evaluation of system performance for transparently interoperating WLAN and UMTS-HSDPA networks," Network, IEEE, vol. 19, no. 4, pp. 66-72, 2005.
- [AS09] A. Aram and C. Singh, Provider-customer coalitional games. USA: Dep. of Electr. & Syst. Eng., Univ. of Pennsylvania, Philadelphia, PA, USA, p. 19.
- [AS02] T. Arnold and U. Schwalbe, "Dynamic coalition formation and the core," Journal of Economic Behavior & Organization, vol. 49, no. 3, pp. 363-380, 2002.
- [ASSK09] A. Aram, C. Singh, S. Sarkar, and A. Kumar, "Cooperative Profit Sharing in Coalition Based Resource Allocation in Wireless Networks," in INFOCOM 2009, IEEE, pp. 2123-2131, 2009.
- [AW09] Krzysztof R. Apt and Andreas Witzel, "A Generic Approach To Coalition Formation," International Game Theory Review (IGTR), vol. 11, no. 03, pp. 347-367, 2009.
- [BCH99] J. Blogh, P. Cherriman, and L. Hanzo, "Dynamic channel allocation techniques using adaptive modulation and adaptive antennas," in Vehicular Technology Conference, 1999. VTC 1999 - Fall. IEEE VTS 50th, vol. 4, pp. 2348-2352 vol.4, 1999.
- [BD03] J. Bigham and L. Du, "Cooperative negotiation in a multi-agent system for real-time load balancing of a mobile cellular network," in Proceedings of the second international joint conference on Autonomous agents and multiagent systems, pp. 568-575, 2003.
- [BLE07] Farooq Bari and Victor C.M. Leung, "Automated network selection in a heterogeneous wireless network environment," Network, IEEE, vol. 21, no. 1, pp. 34-40, 2007.

- [BL07] F. Bari and V. Leung, "Application of ELECTRE to Network Selection in a Heterogeneous Wireless Network Environment," in *Wireless Communications and Networking Conference, 2007.WCNC 2007*. IEEE, pp. 3810-3815, 2007.
- [BLC07] F. Bari and V. Leung, "Multi-Attribute Network Selection by Iterative TOPSIS for Heterogeneous Wireless Access," in *Consumer Communications and Networking Conference, 2007. CCNC 2007*. 4th IEEE, pp. 808-812, 2007.
- [BR07] Y. Bachrach and J. S. Rosenschein, "Computing the Banzhaf power index in network flow games," in *Proceedings of the 6th international joint conference on Autonomous agents and multiagent systems*, pp. 1-7, 2007.
- [BRA07] A. Brandenburger, "Cooperative Game Theory," [Online]. Available: <http://pages.stern.nyu.edu/~abranden/coop-01-04-07.pdf>. [Accessed: 04-Nov-2008].
- [CLRS01] T. Cormen, C. Leiserson, R. Rivest, and C. Stein, *Introduction to Algorithms*, 2nd ed. MIT Press, 2001.
- [CSS07] P. Cramton, Y. Shoham, and P. Steinberg, *Combinatorial Auctions*. MIT Press, 2007.
- [DBC03] L. Du, J. Bigham, and L. Cuthbert, "Utility-based distributed geographic load balancing in mobile cellular networks," in *3G Mobile Communication Technologies, 2003. 3G 2003*. 4th International Conference on (Conf. Publ. No. 494), pp. 58-62, 2003.
- [DBC04] Lin Du, J. Bigham, and L. Cuthbert, "A bubble oscillation algorithm for distributed geographic load balancing in mobile networks," in *INFOCOM 2004. Twenty-third Annual Joint Conference of the IEEE Computer and Communications Societies*, vol. 1, p. 338, 2004.
- [DMPS97] F. Delli Priscoli, N. Magnani, V. Palestini, and F. Sestini, "Application of dynamic channel allocation strategies to the GSM cellular network," *Selected Areas in Communications, IEEE Journal on*, vol. 15, no. 8, pp. 1558-1567, 1997.
- [DSJ97] S. Das, S. Sen, and R. Jayaram, "A structured channel borrowing scheme for dynamic load balancing in cellular networks," in *Distributed Computing Systems, 1997, Proceedings of the 17th International Conference on*, pp. 116-123, 1997.
- [DYE90] J. S. Dyer, "Remarks on the Analytic Hierarchy Process," *Management Science*, vol. 36, no. 3, pp. 249-258, 1990.
- [FER] T. Ferguson, *Game Theory Text*. Mathematics Department: UCLA.
- [GAPS05] L. Giupponi, R. Agusti, J. Perez-Romero, and O. Sallent, "A novel joint radio resource management approach with reinforcement learning mechanisms," in *Performance, Computing, and Communications Conference, 2005. IPCCC 2005*. 24th IEEE International, pp. 621-626, 2005.
- [HN07] R. Haradau and S. Napel, "Holler-Packel value and index: a new characterization." *Homo Oeconomicus*, 24 2 (2007), pp. 255-268.

- [HS03] JOSEF HOFBAUER and KARL SIGMUND, "Evolutionary Game Dynamics," BULLETIN (New Series) OF THE AMERICAN MATHEMATICAL SOCIETY, vol. 40, no. 4, pp. 479-519, 2003.
- [HW81] C. Hwang, and K. Yoon, "Multiple attribute decision making: methods and applications," Springer, New York, no. 1981.
- [HWBS09] T. Harrold, L. Wang, M. Beach, G. Salami, A. Yarmohammad, and O. Holland, "Spectrum sharing and cognitive radio," in Ultra Modern Telecommunications & Workshops, 2009. ICUMT '09. International Conference on, pp. 1-8, 2009.
- [JBW08] Peng Jiang, J. Bigham, and Jiayi Wu, "Cooperative Geographic Load Balancing in Hybrid Cellular Networks," in Signal Processing, Communications and Networking, 2008. ICSCN '08. International Conference on, pp. 288-294, 2008.
- [JPW08] Libin Jiang, S. Parekh, and J. Walrand, "Base Station Association Game in Multi-Cell Wireless Networks (Special Paper)," in Wireless Communications and Networking Conference, 2008. WCNC 2008. IEEE, pp. 1616-1621, 2008.
- [JW02] M. O. Jackson and A. Watts, "The Evolution of Social and Economic Networks," Journal of Economic Theory, vol. 106, no. 2, pp. 265-295, 2002.
- [KCG09] H. Kamal, M. Coupechoux, and P. Godlewski, "Inter-operator spectrum sharing for cellular networks using game theory," in Personal, Indoor and Mobile Radio Communications, 2009 IEEE 20th International Symposium on, pp. 425-429, 2009.
- [KKGGM05] G. Karetsos, S. Kyriazakos, E. Groustiotis, F. Di Giandomenico, and I. Mura, "A hierarchical radio resource management framework for integrating WLANs in cellular networking environments," Wireless Communications, IEEE, vol. 12, no. 6, pp. 11-17, 2005.
- [KKP08] M. Kassar, B. Kervella, and G. Pujolle, "An Intelligent Handover Management System for Future Generation Wireless Networks," EURASIP Journal on Wireless Communications and Networking, vol. 2008, pp. 1-13, 2008.
- [KUY03] T. Kanazawa, T. Ushio, and T. Yamasaki, "Replicator dynamics of evolutionary hypergames," in Systems, Man and Cybernetics, 2003. IEEE International Conference on, vol. 4, pp. 3828-3833 vol.4, 2003.
- [LB07] W. Luo and E. Bondonese, "Intelligent Radio Access Network Selection System for Heterogeneous Wireless Network Environments," Networking and Electronic Commerce Research Conference, 2007.
- [LK00] J. Lee and S. Kim, "Using Analytic Network Process and Goal Programming for Interdependent Information System Project Selection," Computers & Operation Research, vol. 27, no. 4, pp. 367-382, 2000.
- [LSC99] Junyi Li, N. Shroff, and E. Chong, "The study of a channel sharing scheme in wireless cellular networks including handoffs," in INFOCOM '99. Eighteenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE, vol. 3, pp. 1179-1186 vol.3, 1999.

- [Lu07] N. Lu, "Utility-based Bandwidth Adaptation for QoS Provisioning in Multimedia Wireless Networks," Queen Mary University of London, 2007.
- [MAPP06] G. Mapp, D. Cottingham, F. Shaikh, P. Vidales, L. Patanapongpibul, J. Baliosian, and J. Crowcroft, "An Architectural Framework for Heterogeneous Networking," in Proceedings of the International Conference on Wireless Information Networks and Systems (WINSYS 2006), August 2006, pp. 5–10.
- [MAPP07] G. Mapp, F. Shaikh, J. Crowcroft, D. Cottingham, and J. Baliosian, "Y-Comm: A Global Architecture for Heterogeneous Networking (Invited Paper)," in 3rd Annual International Wireless Internet Conference (WICON), October 2007.
- [MAPP09] Glenford Mapp, Fatema Shaikh, Mahdi Aiash, Renata Porto Vanni, Mario Augusto, Edson Moreira, "Exploring Efficient Imperative Handover Mechanisms for Heterogeneous Wireless Networks," nbis, pp.286-291, 2009 International Conference on Network-Based Information Systems, 2009
- [MCN07] O. Markaki, D. Charilas, and D. Nikitopoulos, "Enhancing Quality of Experience in Next Generation Networks Through Network Selection Mechanisms," in Personal, Indoor and Mobile Radio Communications, 2007. PIMRC 2007. IEEE 18th International Symposium on, pp. 1-5, 2007.
- [MFS05] D. S. Menasché, D. R. Figueiredo, and E. D. S. E. Silva, "An evolutionary game-theoretic approach to congestion control," Perform. Eval., vol. 62, no. 1, pp. 295-312, 2005.
- [MJB10] Haibo Mei, Peng Jiang, and J. Bigham, "Cooperative pilot power control in relay based cellular network," in Information Management and Engineering (ICIME), 2010 The 2nd IEEE International Conference on, pp. 81-85, 2010.
- [MRN10] Martínez-Morales, J.D.; Pineda-Rico, U.; Stevens-Navarro, E.; , "Performance comparison between MADM algorithms for vertical handoff in 4G networks," *Electrical Engineering Computing Science and Automatic Control (CCE)*, 2010 7th International Conference on , vol., no., pp.309-314, 8-10 Sept. 2010
- [MYE91] R. Myerson, Game Theory, Analysis of Conflict. Cambridge,MA,USA: Harvard University Press, 1991.
- [NEI82] B. O'Neill, "A problem of rights arbitration from the Talmud," Mathematical Social Sciences, vol. 2, no. 4, pp. 345-371, 1982.
- [NH06] D. Niyato and E. Hossain, "A Cooperative Game Framework for Bandwidth Allocation in 4G Heterogeneous Wireless Networks," in Communications, 2006. ICC '06. IEEE International Conference on, vol. 9, pp. 4357-4362, 2006.
- [NH08] D. Niyato and E. Hossain, "Modeling User Churning Behavior in Wireless Networks Using Evolutionary Game Theory," in Wireless Communications and Networking Conference, 2008. WCNC 2008. IEEE, pp. 2793-2797, 2008.

- [NH09] D. Niyato and E. Hossain, "Dynamics of Network Selection in Heterogeneous Wireless Networks: An Evolutionary Game Approach," *Vehicular Technology, IEEE Transactions on*, vol. 58, no. 4, pp. 2008-2017, 2009.
- [NM44] J. V. Neuman and O. Morgenstern, *Theory of Games and Economic Behavior*. Princeton, NJ, USA: Princeton University Press, 1944.
- [NW06] Stevens-Navarro, E.; Wong, V.W.S.; , "Comparison between Vertical Handoff Decision Algorithms for Heterogeneous Wireless Networks," *Vehicular Technology Conference, 2006. VTC 2006-Spring. IEEE 63rd* , vol.2, no., pp.947-951, 7-10 May 2006
- [PBJC09] H. Pervaiz, J. Bigham, P. Jiang, and M. P. Chan, "A game theoretic based Call Admission Control scheme for competing WiMAX networks," in *2009 2nd International Conference on Computer, Control and Communication*, pp. 1-5, 2009.
- [PGALPA03] R. Pintenet, J. Gosteau, T. Al-Gizawi, F. Lazarakis, K. Peppas, and A. Alexiou, "Evaluation of interoperability mechanisms for coexisting HSDPA and WLAN enhanced with MTMR techniques," in *Vehicular Technology Conference, 2003. VTC 2003-Fall. 2003 IEEE 58th*, vol. 3, pp. 1807-1811 Vol.3, 2003.
- [PM60] Aumann, Peleg, "Aumann, Peleg: Von Neumann-Morgenstern solutions to cooperative games without side payments," vol. 66, no. 3, pp. 173-179, 1960.
- [PNB08] Yuwen Pan, A. Nix, and M. Beach, "A game theoretic approach to distributed resource allocation for OFDMA-based relaying networks," in *Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on*, pp. 1-5, 2008.
- [PSL02] Pulido M, Sanchez-Soriano J, and Llorca N, "Game Theory Techniques for University Management: An Extended Bankruptcy Model." [Online]. Available: <http://www.ingentaconnect.com/content/klu/anor/2002/00000109/F0040001/05088601>. [Accessed: 06-Sep-2010].
- [RAH07] T. Rahwan, "Algorithms for Coalition Formation in Multi-Agent Systems," Aug-2007. [Online]. Available: <http://eprints.ecs.soton.ac.uk/14894/>. [Accessed: 06-Sep-2010].
- [RAY07] D. Ray, *A Game-Theoretic Perspective on Coalition Formation*. New York, USA: Oxford University Press, 2007.
- [RFG95] E. Del Re, R. Fantacci, and G. Giambene, "Handover and dynamic channel allocation techniques in mobile cellular networks," *Vehicular Technology, IEEE Transactions on*, vol. 44, no. 2, pp. 229-237, 1995.
- [RJ07] T. Rahwan and N. R. Jennings, "An Algorithm for Distributing Coalitional Value Calculations among Cooperating Agents," 2007. [Online]. Available: <http://eprints.ecs.soton.ac.uk/13720/>. [Accessed: 06-Sep-2010].
- [RPH95] M. H. Rothkopf, A. Pekec, and R. M. Harstad, *Computationally Manageable Combinatorial Auctions*. Center for Discrete Mathematics & Theoretical Computer Science, 1995.

- [RRDGJ07] T. Rahwan, S. D. Ramchurn, V. D. Dang, A. Giovannucci, and N. R. Jennings, "Anytime Optimal Coalition Structure Generation," Feb-2007. [Online]. Available: <http://eprints.ecs.soton.ac.uk/13433/>. [Accessed: 06-Sep-2010].
- [RRJG09] T. Rahwan, S. D. Ramchurn, N. R. Jennings, and A. Giovannucci, "An anytime algorithm for optimal coalition structure generation," *J. Artif. Int. Res.*, vol. 34, no. 1, pp. 521-567, 2009.
- [SAA08] T. Saaty, "Consistency." [Online]. Available: <http://www.brahmatwinn.unijena.de/fileadmin/Geoinformatik/projekte/brahmatwinn/Workshops/FEEM/weights/consistency.pdf>. [Accessed: 06-Jun-2008].
- [SAA80] T. Saaty, "The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation", Mc-Graw Hill, 1980.
- [SAA90] T. L. Saaty, "How to make a decision: The Analytic Hierarchy Process", *European Journal of Operational Research*, 1990, Vol. 48, pp. 9-26.
- [SAGDB08] A. Subramanian, M. Al-Ayyoub, H. Gupta, S. Das, and M. Buddhikot, "Near-Optimal Dynamic Spectrum Allocation in Cellular Networks," in *New Frontiers in Dynamic Spectrum Access Networks*, 2008. DySPAN 2008. 3rd IEEE Symposium on, pp. 1-11, 2008.
- [SCSM08] E. M. Salgueiro, P. R. F. Cunha, R. J. P. B. Salgueiro, and J. A. S. Monteiro, "Fair bandwidth sharing using Shapley value," in *Proceedings of the 2008 Euro American Conference on Telematics and Information Systems*, pp. 1-8, 2008.
- [SD00] S. Sen and P. Dutta, "Searching for optimal coalition structures," in *MultiAgent Systems*, 2000. *Proceedings. Fourth International Conference on*, pp. 287-292, 2000.
- [SHAIKH06] F. Shaikh, A. Lasebae, G. Mapp, "Client-based SBM Layer for Predictive Management of Traffic Flows in Heterogeneous Networks," *2nd Information and Communication Technologies*, 2006. (ICTTA '06), vol.2, pp.3112-3117.
- [SHAIKH07] F. Shaikh, A. Lasebae, G. Mapp, "Proactive Policy Management using TBVH Mechanism in Heterogeneous Networks," *International Conference on Next Generation Mobile Applications, Services and Technologies*, (NGMAST 07), vol., no., pp.151-157, 12-14 September 2007
- [SHAIKH08] F. Shaikh, A. Lasebae, G. Mapp, "Proactive Policy Management for Heterogeneous Networks," *3rd International Conference on Information and Communication Technologies: From Theory to Applications*, (ICTTA 2008), vol., no., pp.1-6, 7-11 April 2008
- [SHAIKH10] Fatema Sabeen Shaikh, "Intelligent Proactive Handover and QoS Management using TBVH in Heterogeneous Networks", Middlesex University, 2010.
- [SHDH08] W. Saad, Zhu Han, M. Debbah, and A. Hjørungnes, "A Distributed Merge and Split Algorithm for Fair Cooperation in Wireless Networks," in *Communications Workshops*, 2008. ICC Workshops '08. IEEE International Conference on, pp. 311-315, 2008.

- [SJ04] Qingyang Song and A. Jamalipour, "Quality of service provisioning in wireless LAN/UMTS integrated systems using analytic hierarchy process and Grey relational analysis," in Global Telecommunications Conference Workshops, 2004. GlobeCom Workshops 2004. IEEE, pp. 220-224, 2004.
- [SJ05] Qingyang Song and A. Jamalipour, "A network selection mechanism for next generation networks," in Communications, 2005. ICC 2005. 2005 IEEE International Conference on, vol. 2, pp. 1418-1422 Vol. 2, 2005.
- [SJ07] Qingyang Song and A. Jamalipour, "Network selection in an integrated wireless LAN and UMTS environment using mathematical modeling and computing techniques," Wireless Communications, IEEE, vol. 12, no. 3, pp. 42-48, 2005.
- [SJZ07] W. Song, H. Jiang, and W. Zhuang, "Performance Analysis of the WLAN-First Scheme in Cellular/WLAN Interworking," Wireless Communications, IEEE Transactions on, vol. 6, no. 5, pp. 1932-1952, 2007.
- [SK95] O. Shehory and S. Kraus, "Task Allocation Via Coalition Formation Among Autonomous Agents," IN PROCEEDINGS OF THE FOURTEENTH INTERNATIONAL JOINT CONFERENCE ON ARTIFICIAL INTELLIGENCE, pp. 655--661, 1995.
- [SK96] O. Shehory and S. Kraus, "Formation of Overlapping Coalitions for Precedence-Ordered Task-Execution Among Autonomous Agents," 1996.
- [SK98] O. Shehory and S. Kraus, "Methods for task allocation via agent coalition formation," Artificial Intelligence, vol. 101, no. 1, pp. 165-200, May. 1998.
- [SL97] T. W. Sandholm and V. R. T. Lesser, "Coalitions among computationally bounded agents," Artificial Intelligence, vol. 94, no. 1, pp. 99-137, Jul. 1997.
- [SLAST99] T. Sandholm, K. Larson, M. Andersson, O. Shehory, and F. Tohmé, "Coalition structure generation with worst case guarantees," Artificial Intelligence, vol. 111, no. 1, pp. 209-238, Jul. 1999.
- [SLSX01] A. Lindsay-Stewart, W. Lee, M. Schulz, and C. Xu, "Incremental capacity gains for high blocking sites using dynamic channel sharing," IEEE Transactions on Vehicular Technology, vol. 50, no. 1, pp. 1-11, 2001.
- [SQT08] G. Salami, A. Quddus, D. Thilakawardana, and R. Tafazolli, "Nonpool based spectrum sharing for two UMTS operators in the UMTS extension band," in Personal, Indoor and Mobile Radio Communications, 2008. PIMRC 2008. IEEE 19th International Symposium on, pp. 1-5, 2008.
- [SZ08] Wei Shen and Qing-An Zeng, "Cost-Function-Based Network Selection Strategy in Integrated Wireless and Mobile Networks," Vehicular Technology, IEEE Transactions on, vol. 57, no. 6, pp. 3778-3788, 2008.
- [FV05] S. Fischer and B. Vöcking, "Evolutionary Game Theory with Applications to Adaptive Routing *.", 2005
- [SV06] T.L. Saaty and L. Vargas, "Decision Making with the Analytic Network Process: Economic, political, social and technological applications with benefits, opportunities, costs and risks," Springer, 2006.

- [TAKL06] Tansir Ahmed, Kyandoghere Kyamakya, Markus Ludwig , A Context-Aware Vertical Handover Decision Algorithm for Multimode Mobile Terminals and Its Performance in Proceedings of the IEEE/ACM Euro American Conference on Telematics and Information Systems (EATIS 2006), pp. 19-28, February 7-10, 2006, Santa Marta, Colombia.
- [TD97] P. Taylor and T. Day, "Evolutionary stability under the replicator and the gradient dynamics," in *Evolution Ecology*, SpringerLink, 1997.
- [WEI97] J. W. Weibull, *Evolutionary Game Theory*. MIT Press, 1997.
- [WLM05] A. Wilson, A. Lenaghan, and R. Malyan, "Optimising Wireless Access Network Selection to Maintain QoS in Heterogeneous Wireless Environments," in *WPMC 2005, 8th International Symposium on Wireless Personal Multimedia Communications*, pp. 1236-1240, 2005.
- [XY01] L. Xu and J. Yang, "Introduction to Multi-Criteria Decision Making and the Evidential Reasoning Approach," Working Paper Series, Paper 0106, pp. 1-21, 2001.
- [YW93] T. Yum and W. Wong, "Hot-spot traffic relief in cellular systems," *Selected Areas in Communications, IEEE Journal on*, vol. 11, no. 6, pp. 934-940, 1993.
- [Zan97] J. Zander, "Radio Resource Management in Future Wireless Networks-Requirements and Limitations," *IEEE COMMUNICATIONS MAGAZINE*, vol. 35, pp. 30-36, 1997.
- [ZCKN11] Zhichao Zhu, Guohong Cao, Ram Keralapura and Antonio Nucci, "Characterizing Data Services in a 3G Network: Usage, Mobility and Access Issues," *IEEE ICC 2011*.
- [ZHDHB09] W. Saad, Z. Han, M. Debbah, A. Hjørungnes, and T. Basar, "Coalitional Game Theory for Communication Networks: A Tutorial," 0905.4057, May. 2009.
- [ZM06] Fang Zhu , Janise McNair, Multiservice vertical handoff decision algorithms, *EURASIP Journal on Wireless Communications and Networking*, v.2006 n.2, p.52-52, April 2006
- [ZNW10] K. Zhu, D. Niyato, and P. Wang, "Network Selection in Heterogeneous Wireless Networks: Evolution with Incomplete Information," in *2010 IEEE Wireless Communication and Networking Conference*, pp. 1-6, 2010.
- [ZSWD98] S. H. Zanakakis, A. Solomon, N. Wishart, and S. Dublisch, "Multi-attribute decision making: A simulation comparison of select methods," *European Journal of Operational Research*, vol. 107, no. 3, pp. 507-529, Jun. 1998.
- [ZY89] M. Zhang and T. Yum, "Comparisons of channel assignment strategies in cellular mobile telephone systems," in *Communications, 1989. ICC '89, BOSTONICC/89. Conference record. 'World Prosperity Through Communications', IEEE International Conference on*, pp. 467-471 vol.1, 1989.

LIST OF PUBLICATIONS

- I. Haris Pervaiz, John Bigham, Peng Jiang and Mei Pou Chan. (2008) A Game Theoretic based Call Admission Control Scheme for Competing WiMAX networks. In Proceedings of 2nd IEEE International Conference on Computer, Control and Communication (IC-4), Feb 2009, Karachi, Pakistan. Pages 1-5.
- II. Haris Pervaiz and John Bigham. (2009) Game Theoretical Formulation of Network Selection in Competing Wireless Networks: An Analytic Hierarchy Process Model. In Proceedings of Third International Conference on Next Generation Mobile Applications, Services and Technologies (NGMAST09) in Cardiff, Wales. Pages 292-297.
- III. Haris Pervaiz and John Bigham. (2010) A Multi-Criteria Decision Making (MCDM) network selection model providing enhanced QoS differentiation to customers. In Proceedings of the International Conference of Multimedia Computing and Information Technology (MCIT) in Sharjah, UAE. Pages 49-52.
- IV. Haris Pervaiz, Haibo Mei, Peng Jiang and John Bigham. (2010) Enhanced cooperation in heterogeneous wireless networks using coverage adjustment. In Proceedings of the 6th International Wireless Communications and Mobile Computing Conference in session of Cognitive radio communications and networks (cooperative and cognitive networks) in Caen, France. Pages 241-245.

APPENDICES

APPENDIX A. Using lpsolve from MATLAB

Lpsolve is callable from MATLAB via an external interface or MEX-function. As such, it looks like lpsolve is fully integrated with MATLAB. Matrices can directly be transferred between MATLAB and lpsolve in both directions. The complete interface is written in C so it has maximum performance. The whole lpsolve API is implemented with some extra's specific for MATLAB (especially for matrix support). So you have full control to the complete lpsolve functionality via the mxlpsolve MATLAB driver. If you find that this involves too much work to solve an lp model then you can also work via higher-level M-files that can make things a lot easier.

MATLAB is ideally suited to handle linear programming problems. These are problems in which you have a quantity, depending linearly on several variables that you want to maximize or minimize subject to several constraints that are expressed as linear inequalities in the same variables. If the number of variables and the number of constraints are small, then there are numerous mathematical techniques for solving a linear programming problem. Indeed these techniques are often taught in high school or university level courses in finite mathematics. But sometimes these numbers are high, or even if low, the constants in the linear inequalities or the object expression for the quantity to be optimized may be numerically complicated in which case a software package like MATLAB is required to effect a solution.

A.1 Installation

To make this possible, a driver program is needed: mxlpsolve (mxlpsolve.dll under Windows). This driver must be put in a directory known to MATLAB (specified via File, Set Path or via the MATLAB path command) and MATLAB can call the mxlpsolve solver. This driver calls lpsolve via the lpsolve shared library (lpsolve51.dll under Windows and liblpsolve51.so under Unix/Linux). This has the advantage that the

mxlpsolve driver doesn't have to be recompiled when an update of lpsolve is provided. The shared library must be somewhere in the Windows path.

So note the difference between the MATLAB lpsolve driver that is called mxlpsolve and the lpsolve library that implements the API that is called lpsolve51. There are also some MATLAB script files (.m) as a quick start. To test if everything is installed correctly, enter mxlpsolve in the MATLAB command window. If it gives the following, then everything is ok:

```
mxlpsolve MATLAB Interface version 5.1.0.1
using lpsolve version 5.1.1.3
```

```
Usage: [ret1, ret2, ...] = mxlpsolve('functionname', arg1, arg2, ...)
```

However, if you get the following:

```
mxlpsolve driver not found!!!
Check if mxlpsolve.dll is on your system and in a directory known to
MATLAB.
Press enter to see the paths where MATLAB looks for the driver.
```

Then MATLAB can find the mxlpsolve.m file, but not the mxlpsolve.dll file. This dll should be in the same directory as the .m file.

If you get the following:

```
??? Undefined function or variable 'mxlpsolve'.
```

Then MATLAB cannot find the mxlpsolve.* files. Enter path in the command line to see the MATLAB search path for its files. You can modify this path via File, Set Path. Specify the path where the mxlpsolve.* files are located on your system.

If you get the following (Windows):

```
??? Failed to initialise lpsolve library. Error
in == > ...\mxlpsolve.dll
```

Or (Unix/Linux):

```
liblpsolve51.so: cannot open shared object file: No such file or
directory.
```

Then MATLAB can find the mxlpsolve driver program, but the driver program cannot find the lpsolve library that contains the lpsolve implementation. This library is called lpsolve51.dll under Windows and liblpsolve51. So under Unix/Linux. Under Windows, the lpsolve51.dll file must be in a directory that in the PATH environment variable. This path can be shown via the following command in MATLAB: !PATH.

It is common to place this in the WINDOWS\system32 folder. Under Unix/Linux, the liblpsolve51.so shared library must be either in the directories /lib or /usr/lib or in a directory specified by the LD_LIBRARY_PATH environment variable. Note that it may also be necessary to restart MATLAB after having put the files in the specified directory. It was noted that MATLAB sometimes doesn't see the newly added files in folders until it is restarted. All this is developed and tested with MATLAB version 6.0.0.88 Release 12.

A.2 Solve an lp model from MATLAB via mxlpsolve

In the following text, >> before the MATLAB commands is the MATLAB prompt. Only the text after >> must be entered.

To call an lpsolve function, the following syntax must be used:

```
>> [ret1, ret2, ...] = mxlpsolve('functionname', arg1, arg2, ...)
```

The return values are optional and depend on the function called. Function name must always be enclosed between single quotes to make it alphanumerical and it is case sensitive. The number and type of arguments depend on the function called. Some functions even have a variable number of arguments and a different behaviour occurs depending on the type of the argument. Function name can be (almost) any of the lpsolve API routines (see lp_solve API reference) plus some extra MATLAB specific functions. Most of the lpsolve API routines use or return an lprec structure. To make things more robust in MATLAB, this structure is replaced by a handle. This is an incrementing number starting from 0 and the lprec structures are maintained internally by the mxlpsolve driver. However you will see not much (if any) difference in the use of it. Almost all callable functions can be found in the lp_solve API reference.

APPENDIX B. Analytic Hierarchy Process related Material

B.1 Attribute scores of different application types per payment plan

Table B.1 Attribute scores per payment plan for video-interactive application

Score	Pay as you go	Pay Monthly	Business
1	Bit rate	Bit rate	Bit rate
3	Reputation	Reputation	Cost
5	Cost	Mobility support	Reputation
7	Mobility support	Cost	Mobility support

Table B.2 Attribute scores per payment plan for video-streaming application

Score	Pay as you go	Pay Monthly	Business
1	Bit rate	Bit rate	Bit rate
3	Cost	Reputation	Cost
5	Reputation	Mobility support	Mobility support
7	Mobility support	Cost	Reputation

Table B.3 Attribute scores per payment plan for data application

Score	Pay as you go	Pay Monthly	Business
1	Bit rate	Bit rate	Bit rate
3	Cost	Mobility support	Cost
5	Reputation	Reputation	Mobility support
7	Mobility support	Cost	Reputation

B.2 Weight calculation of different application types per payment plan

B.2.1 Voice

- i. pay monthly

Maximum Eigen Value =4.34826

C.I =0.116088

Weights (Eigen Vector)

0.0400948
0.691545
0.192264

0.0760971

Pair-wise Comparison Matrix

1	0.111111	0.166667	0.333333
9	1	7	8
6	0.142857	1	4
3	0.125	0.25	1

ii. business

Maximum Eigen Value =4.34826

C.I = 0.116088

Weights (Eigen Vector)

0.192264
0.0760971
0.691545
0.0400948

Pairwise Comparison Matrix

1	4	0.142857	6
0.25	1	0.125	3
7	8	1	9
0.166667	0.333333	0.111111	1

B.2.2 Video Streaming

i. pay monthly

Maximum Eigen Value =4.34826

C.I=0.116088

Weights (Eigen Vector)

0.0400948
0.192264
0.691545
0.0760971

Pairwise Comparison Matrix

1	0.166667	0.111111	0.333333
6	1	0.142857	4
9	7	1	8
3	0.25	0.125	1

ii. pay as you go

Maximum Eigen Value =4.34826
C.I =0.116088

Weights (Eigen Vector)

0.192264
0.0760971
0.691545
0.0400948

Pairwise Comparison Matrix

1	4	0.142857	6
0.25	1	0.125	3
7	8	1	9
0.166667	0.333333	0.111111	1

iii. business

Maximum Eigen Value =4.34826
C.I =0.116088

Weights (Eigen Vector)

0.192264
0.0400948
0.691545
0.0760971

Pairwise Comparison Matrix

1	6	0.142857	4
0.166667	1	0.111111	0.333333
7	9	1	8
0.25	3	0.125	1

B.2.3 Video Interactive

- i. pay as you go

Maximum Eigen Value =4.59739
C.I =0.199129

Weights (Eigen Vector)

0.0849364
0.537845
0.334111
0.0431081

Pairwise Comparison Matrix

1	0.25	0.125	3
4	1	4	6
8	0.25	1	9
0.333333	0.166667	0.111111	1

- ii. pay monthly

Maximum Eigen Value =5.39012
C.I =0.463375

Weights (Eigen Vector)

0.0465368
0.517157
0.31334
0.122967

Pairwise Comparison Matrix

1	0.166667	0.333333	0.111111
6	1	4	6
3	0.25	1	9
9	0.166667	0.111111	1

- iii. business

Maximum Eigen Value =4.34826
C.I =0.116088

Weights (Eigen Vector)

0.192264
0.0760971
0.691545
0.0400948

Pairwise Comparison Matrix

1	4	0.142857	6
0.25	1	0.125	3
7	8	1	9
0.166667	0.333333	0.111111	1

B.2.4 Data

- i. pay as you go

Maximum Eigen Value =4.34826
C.I =0.116088

Weights (Eigen Vector)

0.192264
0.0760971
0.691545
0.0400948

Pairwise Comparison Matrix

1	4	0.142857	6
0.25	1	0.125	3
7	8	1	9
0.166667	0.333333	0.111111	1

- ii. pay monthly

Maximum Eigen Value =4.34826
C.I =0.116088

Weights (Eigen Vector)

0.192264
0.0760971
0.691545
0.0400948

Pairwise Comparison Matrix

1	4	0.142857	6
0.25	1	0.125	3
7	8	1	9
0.166667	0.333333	0.111111	1

iii. business

Maximum Eigen Value =4.34826

C.I =0.116088

Weights (Eigen Vector)

0.0400948
0.0760971
0.691545
0.192264

Pairwise Comparison Matrix

1	0.333333	0.111111	0.166667
3	1	0.125	0.25
9	8	1	7
6	4	0.142857	1

APPENDIX C. cnlab Speed Test Collected data sample

This section shows a sample of download data rate, upload data rate and response time of Wi-Fi for different locations of scenario ‘1’ taken on 3rd August 2011 between 12.25 pm and 13.22 pm.

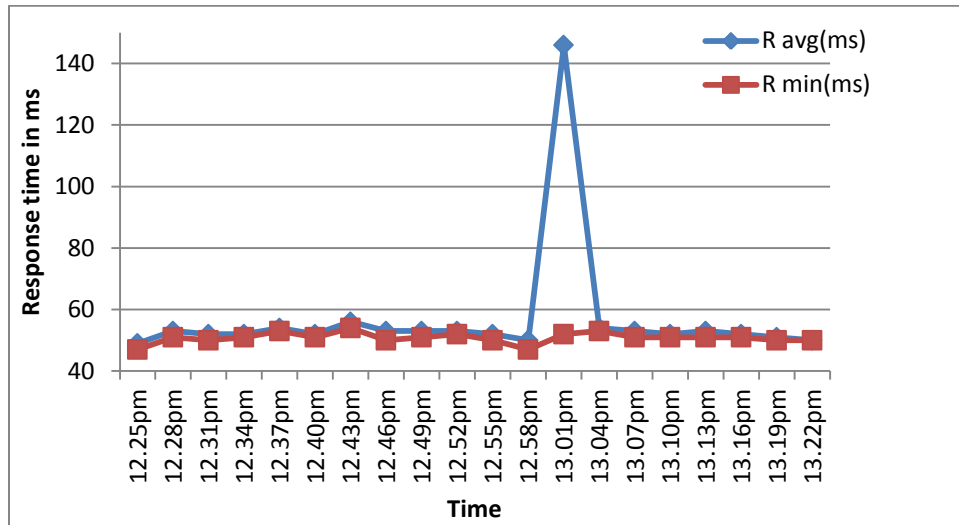


Figure C.0.1 Response time in milliseconds of Wi-Fi for scenario ‘1’ measured on 3rd August 2011 between 12:25 pm to 13:22 pm

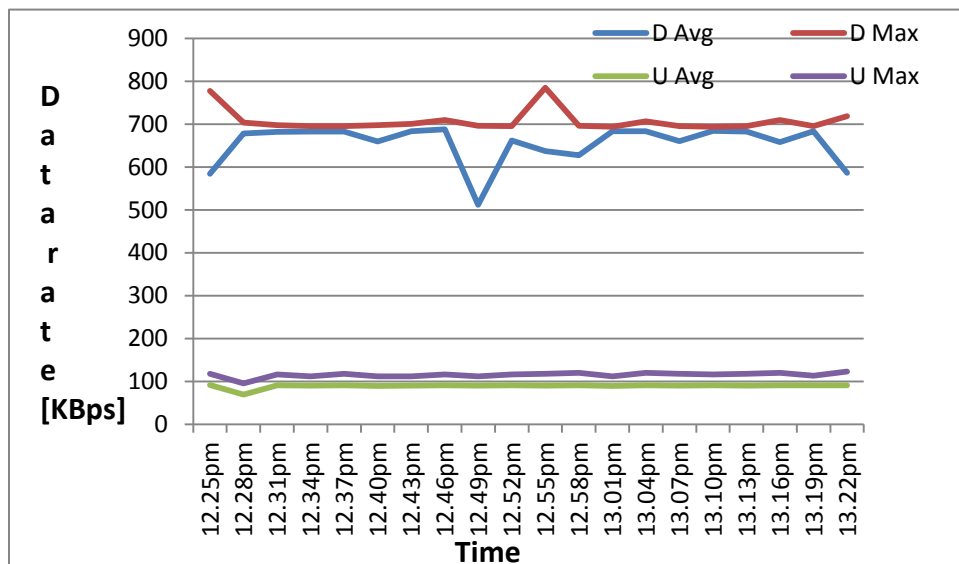


Figure C.2 Download and Upload data rates of Wi-Fi for scenario ‘1’ measured on 3rd August 2011 between 12:25 pm to 13:22 pm

APPENDIX D. Basics of Game Theory

In this section, background on relevant research fields is introduced. Topics covered include basics of game theory and non-cooperative game theory. Section D.1 gives an introduction to the basic principles of game theory.

D.1 Basics of Game theory

Game theory is a branch of mathematics that provides a suite of analytical tools to analyze the interactions of parties with conflicting interests. Each player has independent decision rights only over its own possible actions, which are confined to its strategy space. In general, game theory provides a formal modelling approach to situations in which decision makers interact with other players. It analyzes and represents such situations as games, where players choose different actions in an attempt to maximize their returns. In other words, game theory studies choice of optimal behaviour when costs and benefits of each option depend upon the choices of other individuals.

Game theory is divided into two branches, called the non-cooperative and cooperative branches. A game is considered to be a collection of players who play different moves aiming at maximizing their individual payoff obtain when the game is ended. The players have the option of different game strategies and following one strategy or more strategies dictates which move to make at each given turn in the game. In the wireless networking context, the players can be the *users* controlling their devices or the network providers. As we assume that the devices are bound to their users, we will refer to devices as players and the two terms are used interchangeably here. In compliance with the practice of game theory, we assume that the players are *rational*, which means that they try to maximize their *payoff* or alternatively to minimize their *costs*. In a static game, players make their moves simultaneously whereas in a dynamic game players make their moves in turn (the player can decide its action depending on other player's actions).

D.1.1 Static games

A static game is one in which all players make decisions (or select a strategy) simultaneously, without knowledge of the strategies that are being chosen by other players. Even though the decisions may actually be made at different points in time, the

game is simultaneous because each player has no information about the decisions of others; thus, it is as if the decisions are made simultaneously.

In a game G , a pure strategy for player E_i denoted by s_i provides a complete plan of action for whatever situation might arise; this fully determines the player's behaviour. The strategy of a player can be a single move or a set of moves during the game. Generally strategy is the set of possible actions. The strategy concept is sometimes confused with that of a move. A move is an action taken by a player at some point during the play of a game (e.g., in chess, moving white's Bishop a_2 to b_3). A strategy on the other hand is a complete algorithm for playing the game, telling a player what to do for every possible situation throughout the game.

A strategy profile is a vector of strategies (s_1, s_2, \dots, s_n) one for each player E_i of a game. The s_{-i} describes the strategies chosen by all other players except for a given player E_i . Any given strategy profile in a game may then be represented by the pair (s_i, s_{-i}) . The set of strategy profiles denoted by S is the Cartesian product of the strategy spaces over all players: $S = S_1 \times S_2 \times \dots \times S_n$. In a game G , a payoff function u_i is defined for each player E_i . The domain of u_i is the set of strategy profiles S and the range of the function is the set of real numbers, so that for each strategy profile $(s_i, s_{-i}) \in S$, $u_i(s_i, s_{-i})$ represents the player E_i 's payoff when E_i plays strategy s_i and the other players follow strategies s_{-i} .

A simultaneous game in strategic form is defined by the tuple: $G = \{E, S, U\}$ where

$E = \{E_i\}$ where $i \in \{1, 2, \dots, n\}$ is a set of n players

$S = S_1 \times S_2 \times \dots \times S_n$ is a set of strategy profiles

$U = [u_1(\quad), \dots, u_n(\quad)]$ is a vector of payoff functions

Note D.1: *A game with complete information is a game in which each player has full knowledge of all aspects of the game. In this context, complete information is used to describe a game in which all players know the type of all the other players, i.e. they know the payoffs and strategy spaces of the other players.*

Example D.1: Consider a forwarder's dilemma represented as a two player static game. The player p_1 and p_2 wants to send a packet to his or her destination denoted by B and A respectively, in each time step using the other player as a forwarder. We assume that the

communication between a player and the respective receiver is possible only if the other player forwards the packet. The Forwarder's Dilemma is illustrated in Figure D.1.

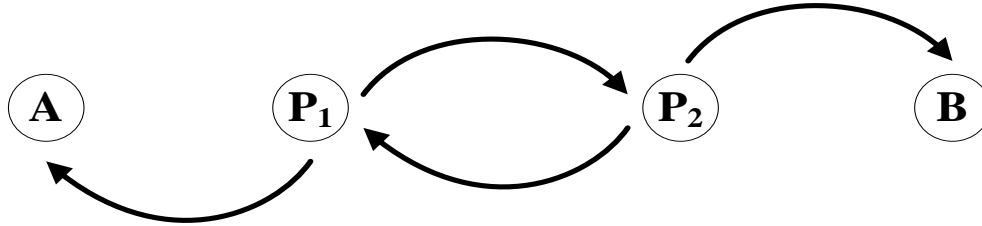


Figure D.1 Forwarder's Dilemma game

If player p_1 forwards the packet of p_2 , it costs player p_1 a fixed cost $0 < C \ll 1$, which represents the energy and computation spent for the forwarding action. This enables the communication between p_2 and A, which gives p_2 a benefit of 1. The payoff is the difference of the benefit and the cost. If player p_2 forwards the packet of p_1 , it costs player p_2 a fixed cost $0 < C \ll 1$, which represents the energy and computation spent for the forwarding action. This enables the communication between p_1 and B, which gives p_1 a benefit of 1.

The player p_1 and p_2 can decide to forward (F) the packet to the other player or to drop it (D); this decision represents the strategy of the player. In this game p_1 is the row player and p_2 is the column player. Each cell of the matrix corresponds to a possible combination of the strategies of the players and contains a pair of values representing the payoffs of player p_1 and p_2 , respectively. The 'c' is the cost of forwarding a packet by a player.

Table D.1. Forwarder's Dilemma game in strategic form

$p_1 \backslash p_2$	Forward	Drop
Forward	$(1-c, 1-c)$	$(-c, 1)$
Drop	$(1, -c)$	$(0, 0)$

In the rewards represented in the table, the first element is the reward to p_1 and the second the reward to p_2 . This is a symmetric non zero sum game, because the players can mutually increase their payoffs by cooperating (i.e. from zero to $1-c$). By helping each

other to forward, they can achieve an outcome that is better for both players than mutual dropping.

D.1.2 Iterated Dominance

A game expressed in normal (or strategic form) can be solved in many ways. The simplest way to solve a game is by using the concept of iterative strict dominance.

Note D.2: *Strategy s'_i of player 'i' is said to be strictly dominated by his or her strategy s_i if,*

$$u_i(s'_i, s_{-i}) < u_i(s_i, s_{-i}), \forall s_{-i} \in S_{-i}$$

The $u_i(s'_i, s_{-i})$ is the utility or payoff of player 'i' given the strategy s'_i , when the remaining players select strategy s_{-i} . In example D.1 from the point of view of player 1, the Forward (F) strategy is strictly dominated by the Drop (D) strategy. This means we can eliminate the first row of the matrix since the rational player p_1 will never choose this strategy. From the point of view of player 2, the same argument leads to the elimination of the first column of the matrix. Thus the solution of the game is (D, D) and the payoff is (0, 0). You can observe that strategy pair (F, F) would lead to better payoff for both the players (not selected because of lack of trust between the players). It is worth to mention that iterated strict dominance cannot be used to solve every game.

Example D.2: Consider a Joint Packet Forwarding *Game*, in which a source *src* wants to send a packet to its destination *dst* in each time step. To this end, it needs both devices p_1 and p_2 to forward. Similar to the previous example D.1, there is a forwarding cost $0 < C \ll 1$ if a player forwards the packet of the sender. If both players forward the packet, then they each receive a benefit of 1 (e.g, from the sender or the receiver. This packet forwarding scenario is shown in Figure D.2.



Figure D.2 Joint Packet Forwarding game

The two players have to decide whether to forward the packet simultaneously, before the source actually sends it.

Table D.2. Joint Packet forwarding game in strategic form

$p_1 \backslash p_2$	Forward	Drop
Forward	$(1-c, 1-c)$	$(-c, 0)$
Drop	$(0, 0)$	$(0, 0)$

In the Joint Packet Forwarding Game, none of the strategies of a player strictly dominates the other. If player p_1 drops the packet, then p_1 is indifferent to the move of player p_2 and thus we cannot eliminate his strategy D based on strict dominance.

D.1.3 Nash Equilibrium

A Nash equilibrium is a strategy profile $s^* = (s_1^*, s_i^*)$ in which no player has an incentive to unilaterally modify his or her strategy. Given the other players' strategies s_{-i}^* , player E_i cannot increase his or her payoff by choosing a strategy different from s_i^* . The current set of strategies s^* and the corresponding payoff values constitute a Nash equilibrium. Nash equilibrium is said to represent a solution for a given game.

Note D.3: Given a game $G = \{E, S, U\}$, a strategy profile $s^* \in S$ represents Nash equilibrium if and only if for every player E_i , $i \in \{1, 2, \dots, n\}$:

$$u_i(s_i^*, s_{-i}^*) \geq u_i(s_i, s_{-i}^*) \quad \forall s_i \in S_i$$

According to the Nash equilibrium concept, the solution of the game mentioned in Example D.1 is (D, D) which is same as conceived by iterative dominance. The Nash equilibrium for Example D.2 would be (F, F) or (D, D).

D.1.4 Pareto Optimality

One method for identifying the desired Nash equilibrium point in a game is to compare strategy profiles using the concept of Pareto-optimality. Let's define the key concepts of Pareto-optimality as follows:

Note D.4: The strategy profile s is Pareto-superior to strategy profile s' if for any player $i \in N$:

$$u_i(s_i, s_{-i}) \geq u_i(s'_i, s'_{-i})$$

with strict inequality for at least one player

The strategy profile s is Pareto-superior to strategy profile s' , if the payoff of the player 'i' is increased by switching from strategy profile s to s' without decreasing the payoff of other players. The strategy profile s' is Pareto-inferior to strategy profile s .

Note D.5: The strategy profile s^{po} is Pareto-optimal (or efficient) if there exists no other strategy profile that is Pareto-superior to s^{po} .

In Pareto-optimal strategy profile, one cannot increase the payoff of player 'i' without decreasing the payoff of at least one other player.

In Example D.1, the Nash equilibrium (D, D) is not Pareto-optimal. The strategy profiles like (F, F), (F, D) and (D, F) are Pareto-optimal but are not Nash equilibrium. In Example D.2, the strategy profiles (F, F) and (D, D) are Nash equilibrium but only (F, F) is Pareto-optimal.

D.1.5 Repeated Games

In repeated games, the players interact several times. Each interaction is called a *stage*. We assume that the players make their moves simultaneously in each stage. The set of players is defined similarly to the static game. Repeated games can be expressed in both strategic and extensive forms. The two player prisoner's dilemma game is represented as below:

Table D.3. Two player Prisoner's dilemma

	C	D
C	2,2	-1,3
D	3,-1	0,0

In this game there are two players—a row player and a column player—each of whom has two possible actions: to “cooperate” (C) or to “defect” (D). Notice that if the game is played just once, then regardless of what the other player does, it is optimal (i.e., a

In extensive form the game is represented as a tree. The root of the tree is the start of the game and represented with an empty circle. Each of the levels of the tree below the root node is called stage. In a two player game, a stage represents the sequence relation of the moves of the players. The sequence of moves defines a *path* on the tree and is referred to as the *history* h of the game. The leaf (or terminal node) of the tree defines the potential end of the game called *outcome* and it is assigned the corresponding payoff. The game can be either *finite-horizon* (finite number of stages) or *infinite-horizon* (infinite number of stages).

210

The set of the past moves at stage t is referred to as the history $h(t)$ of the game. If the move of the player i in stage t is denoted by $m_i(t)$. Then the history $h(t)$ can be formally written for number of players 'N' as follows:

$$h(t) = \left\{ \left(m_i(t), \dots, m_{|N|}(t) \right), \dots, \left(m_1(0), \dots, m_{|N|}(0) \right) \right\}$$

For example, the history of twice repeated prisoner's dilemma, if both players have defected so far is as follows:

$$h(2) = \{(D, D), (D, D)\}$$

The strategy s_i defines a move for player i in the next stage $t+1$ for a given history $h(t)$ of the game. Initially history $h(0)$ is an empty set and the strategy s_i of the players i must define a move $m_i(0)$ which is referred as initial move.

For example: In the Two stage repeated prisoner's dilemma, the one example strategy of each player is DDDDD where the entries define the defecting behaviour if the following conditions hold as follows:

- i. Initial move $h(0) = D$
- ii. If the history $h(1) = \{(D, D)\}$ or $h(1) = \{(D, F)\}$

It is infeasible to make an exhaustive search in repeated games for the best strategy and hence for Nash equilibrium. The objectives of the players in the repeated games can be either to

- i. Maximize their payoffs only for the next stage and is referred as myopic games as the players are short-sighted optimizers.
- ii. Maximize their total payoffs during the game is called as long-sighted optimizers

APPENDIX E. Multi-Network System Level Simulator

The comprehensive WiMAX network simulator developed by the research colleague Peng Jiang is extended to cater multi-networks namely as WiMAX and WLAN.

In network setting module, the WLAN access point is located within the coverage area of WiMAX BS. The operating modes of WLAN are initialized in the simulation network initialization module.

In the traffic initialization module, the users in traffic snapshots are classified into different payment plans. Each payment plan has different preferences for the considered attributes. The scores of attributes for each application type per payment plan, scores of application preferences and the network preference scores are computed and assigned to each traffic unit in traffic initialization module.

In MCDM module, two MCDM methods Analytic Hierarchy Process (AHP) and Simple Additive Weighting (SAW) are implemented. In AHP, the pair-wise comparison matrix and geometric mean method are implemented to compute the weight of the considered attributes. This module takes user preferences for the considered attributes as an input and outputs the weight of each attribute. In SAW, the network values offered by available networks for the considered attributes are compared with each other and assigned a score. This module also computes the utility value of each traffic unit for the WiMAX and WLAN networks. The traffic unit is connected to the network with the highest utility value.

In Game theory module, the evolutionary game theory concepts are implemented. This module also consists of random and inverse rank sub-modules to select a traffic unit to be moved. This module also stores the current subscription of each traffic unit.

In network simulation module, the transmission power of WiMAX BS is dynamically re-configured to extend the coverage area. At each re-configuration step, the SAW sub-module recalculates the utility values of each traffic unit. The game theory sub-modules are initiated to check whether any traffic unit needs to be moved. This re-configuration step is repeated until the maximum transmission power of WiMAX BS is reached.

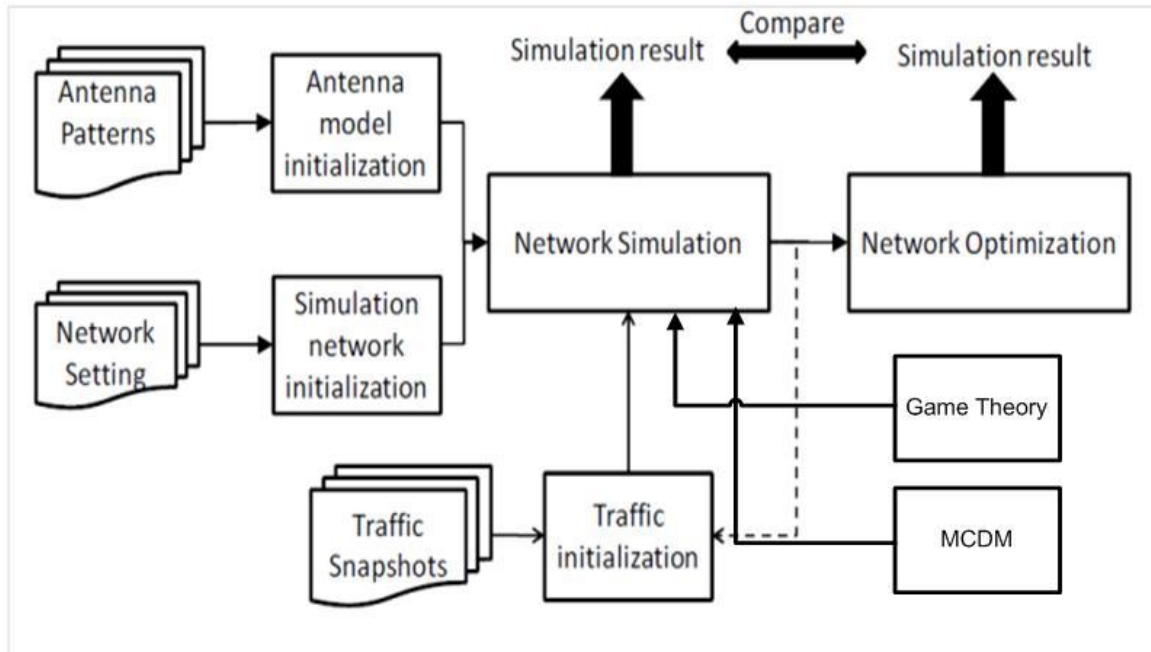


Figure E.1 Multi-network System Level Simulator