BRUNEL UNIVERSITY, WEST LONDON

# Game Theory for Dynamic Spectrum Sharing Cognitive Radio

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy (Ph.D.) to:
Electronic and Computer Engineering,
School of Engineering and Design,
Brunel University,
United Kingdom.

by:
**Omar Raoof**

**May 2010**

Supervised By:
**Professor Hamed Al-Raweshidy**

# Abstract

'Game Theory' is the formal study of conflict and cooperation. The theory is based on a set of tools that have been developed in order to assist with the modelling and analysis of individual, independent decision makers. These actions potentially affect any decisions, which are made by other competitors. Therefore, it is well suited and capable of addressing the various issues linked to wireless communications.

This work presents a Green Game-Based Hybrid Vertical Handover Model. The model is used for heterogeneous wireless networks, which combines both dynamic (Received Signal Strength and Node Mobility) and static (Cost, Power Consumption and Bandwidth) factors. These factors control the handover decision process; whereby the mechanism successfully eliminates any unnecessary handovers, reduces delay and overall number of handovers to 50% less and 70% less dropped packets and saves 50% more energy in comparison to other mechanisms.

A novel Game-Based Multi-Interface Fast-Handover MIPv6 protocol is introduced in this thesis as an extension to the Multi-Interface Fast-handover MIPv6 protocol. The protocol works when the mobile node has more than one wireless interface. The protocol controls the handover decision process by deciding whether a handover is necessary and helps the node to choose the right access point at the right time. In addition, the protocol switches the mobile nodes interfaces 'ON' and 'OFF' when needed to control the mobile node's energy consumption and eliminate power lost of adding another interface. The protocol successfully reduces the number of handovers to 70%, 90% less dropped packets, 40% more received packets and acknowledgments and 85% less end-to-end delay in comparison to other Protocols.

Furthermore, the thesis adapts a novel combination of both game and auction theory in dynamic resource allocation and price-power-based routing in wireless Ad-Hoc networks. Under auction schemes, destinations nodes bid the information data to access to the data stored in the server node. The server will allocate the data to the winner who values it most. Once the data has been allocated to the winner, another mechanism for dynamic routing is adopted. The routing mechanism is based on the source-destination cooperation, power consumption and source-compensation to the intermediate nodes. The mechanism dramatically increases the seller's revenue to 50% more when compared to random allocation scheme and briefly evaluates the reliability of predefined route with respect to data prices, source and destination cooperation for different network settings.

Last but not least, this thesis adjusts an adaptive competitive second-price pay-to-bid sealed auction game and a reputation-based game. This solves the fairness problems associated with spectrum sharing amongst one primary user and a large number of secondary users in a cognitive radio environment. The proposed games create a competition between the bidders and offers better revenue to the players in terms of fairness to more than 60% in certain scenarios. The proposed game could reach the maximum total profit for both primary and secondary users with better fairness; this is illustrated through numerical results.

## Acknowledgments

I am grateful to the creator who taught the names to Adam and gave human being authority to pass beyond the zones of heavens and earth, without his blessing and mercy, this thesis would not have been possible.

I owe my deepest gratitude to my parents and my sisters without whom I would not have made it through my master and PhD degrees. Their tremendous help and prayers showed me the way and always guided me to the end of the tunnel.

It is my pleasure to thank all those who made this thesis possible. I am heartily thankful to my supervisor, Professor Hamed Al-Raweshidy, whose encouragement, guidance and support from the initial to the final level enabled me to develop an understanding of this work. I appreciate all his help and support. I am indebted to my many of my colleagues at the WNCC and friends at Brunel University. I would like to show my gratitude to all staff at Brunel University, especially RCCS staff and Isambard Complex, I would like to thank their encouraging and supportive attitude.

I would like to express gratitude to those who helped me to finalize my thesis; without them, I could not have written this thesis.

Lastly, I offer my regards to all of those who supported me in any respect during the completion of the project.

# Table of Contents

# List of Figures

## List of Tables

## List of Abbreviations

| | |
|---|---|
| AMC | Adaptive Modulation and Coding |
| AP | Access Point |
| AR | Access Routers |
| BID | Binding Unique Identifier |
| CN | Corresponding Node |
| CoA | Care-of-Address |
| CT2 | Cordless Telephone-second generation |
| CR | Cognitive Radio |
| DNS | Domain Name System |
| DVH | Dynamic Vertical Handover |
| DSP | Digital Signal Processing |
| FACoA | Foreign Agent CoA |
| FBU | Fast Binding Update |
| FBack | Fast Binding Acknowledgment |
| FCC | Federal Communications Commission |
| FIFO | First-in-First-out |
| FMIPv6 | Fast-handover Mobile IP version 6 |
| FNA | Fast Network Attachment |
| FNA | Fast Neighbour Advertisement |
| FSA | Fixed Spectrum Access |
| GC | Game-based Controller |
| GPRS | General Packets Radio Service |
| GHVHM | Green Hybrid Vertical Handover Model |
| GMFMIPv6 | Game-based Multi-interface Fast-handover Mobile IPv6 |
| HACK | Handover Acknowledge |
| HI | Handover Initiate |
| HCC | Handoff Control Centre |
| HE | Handoff Executor |
| HHD | Hybrid Handoff decision |
| HO | Handover |
| HHO | Horizontal Handover |
| IANA | Internet Assigned Number Authority |
| IEEE | Institute of Electrical and Electronic Engineering |
| IETF | Internet Engineering Task Force |
| IP | Internet Protocol |
| LAN | Local Area Network |
| MIPv4 | Mobile IP version 4 |
| MI | Moving Into the preferred network |
| MIPv6 | Mobile IP version 6 |
| MFBU | Multi-interface Fast Binding Update |

| | |
|---|---|
| MFMIPv6 | Multi-interface Fast-handover Mobile IP version 6 |
| MN | Mobile Node |
| MO | Moving Out of the preferred network |
| NAR | New Access Router |
| NA | Network Analysis |
| NC | Network Capacity |
| NCoA | New Care-of-Address |
| ND | Network Discovery |
| NE | Network Efficiency |
| NUD | Neighbour Unreachability Detection |
| NP | Network Preference |
| NPP | Negative Payoff Path |
| NS-2 | Network Simulator-2 |
| PAR | Present Access Router |
| PCoA | Previous Care-of-Address |
| PDA | Personal Digital Assistants |
| PrRtAdv | Proxy Router Advertisement |
| PU | Primary User |
| PPP | Positive Payoff Path |
| QoS | Quality of Service |
| RF | Radio Frequency |
| RCC | Radio Common Carriers |
| RSS | Received Signal Strength |
| RFC | Request for Comment |
| RtSolPr | Router Solicitation for Proxy |
| SDR | Software Defined Radio |
| SU | Secondary User |
| SINR | Signal-to-Interference Noise Ratio |
| SVH | Static Vertical Handover |
| SM | System Monitor |
| TCL | Tool Command Language |
| TCP/IP | Transmission Control Protocol/Internet Protocol |
| UMTS | Universal Mobile Telecommunications System |
| USHA | Universal Seamless Handoff Architecture |
| VHO | Vertical Handover |
| WLAN | Wireless Local Area Network |

# CHAPTER 1

## *Introduction*

### 1.1 Motivations

Recent advances in Access Networks have made voice, data and multimedia communications ubiquitous and have knowingly/unknowingly changed our life styles. However, important challenges still stand in the way of widespread use of wireless applications; power consumption, lack of spectrum, end user acceptance and interoperability. In fact, the complexity of mobility and traffic models, together with the dynamic topology and the unpredictability of link quality that characterize wireless networks made the application of mathematical analysis to such networks an extremely useful tool for determining the performance bottlenecks [1]. Game theory [2-4], and its application for qualitative decision making in such scenarios is of tremendous importance. Its ability to model individual, independent decision makers whose actions potentially affect all other decision makers makes it particularly attractive for analyzing the performance of wireless networks. It actually consists of a set of analytical tools that predict the outcome of complex interactions among rational entities, where rationality demands a strict adherence to a strategy based on perceived or measured results.

Looking around us we can easily see that wireless networks are growing increasingly less structured. However, the dynamic interactions arising in these networks make it difficult to analyze and predict performance, inhibiting the development of wireless technologies. Thus, in order to deal with such challenging demands, a constant and thorough research is required for improving the existing protocols, developing new standards and technologies.

The research presented in this thesis is motivated by the following issues:

1. Portable devices with multiple wireless interfaces, switching between interfaces, handover latency and power consumption turns to be the most important issues in heterogeneous wireless networks which are the focus of current research [5]. The research presented in this thesis addresses solutions for enhancing user and/or the application ability to choose the right interface at the right time, eliminating the handover latency and reducing energy consumption in heterogeneous wireless networks.
2. Recent extensions to Mobile IPv6 [6] such as the Fast-handover MIPv6 Protocol [7-8], which aims at improving the handover latency by redirecting traffic to the new access point when the handoff occurs and the Multi-Interface Fast Handover MIPv6 Protocol [9], which works when the mobile node has multiple wireless interfaces; aims to reduce the number of lost packets, reducing handover latency and improving overall throughput. Yet, neither Fast-handover MIPv6 Protocol nor Multi-interface Fast-handover MIPv6 Protocol offer the user and/or the application the ability to choose when a handoff is needed or not and which access point to choose in terms of Quality of Service (QoS) and how to cut power consumption.

The above two points are linked to each other, as when we look to the problem we can see that a game-based model/mechanism can be used to control the handover process and decide when to switch between interfaces and which interface to go with.

3. Because of increasing demand for wireless services and rising cost to provide these services, we must choose how to allocate these services in a fair manner. Future wireless networks will be integrated into every aspect of daily life, and therefore could affect our life in a magnitude similar to that of the Internet and cellular phones. Thus, there is a fundamental need to understand how to design and control wireless applications that lies beyond what the currently theory can provide [10-11].
4. One of the main reasons which limit our ability to introduce new wireless services and improve the current ones such as providing ubiquitous internet access or make the current services less expensive or even increase the data rate of current systems is, according to conventional wisdom, we currently suffer from a shortage of

spectrum. In reality, much of the spectrum sits idle at any given time, this is because system designers usually give each system exclusive access to a block of spectrum in order to prevent interference between adjacent systems. Therefore, a model that allows different wireless systems share spectrum without causing excessive harmful interference to other neighbors is needed. Such system would increase the amount of communications that can take place in a given amount of spectrum, which would defiantly lead to a revolution in the world of wireless services and applications.

## 1.2 Aims and Objectives

The aims of the research presented in this thesis can be summarized by the following points:

1. The research aims to design a game theory based vertical handover model for mobile nodes with multiple interfaces.
2. The research aims to use game theory in Multi-interface Fast-handover MIPv6 (MFMIPv6), works when the mobile node has more than one wireless interface.
3. The research aims to adopt both game and auction theory to fairly allocate resources and improve traffic routing in ad hoc wireless networks.
4. The research also aims to propose a solution to fairly share the spectrum in Cognitive Radio networks [12-13], by adopting both auction and game theory tools.

The research primarily focuses on achieving the following objectives:

1. In the case of heterogeneous multihomed wireless portable devices, the introduced mechanism must give the user and/or the application the ability to manage the handover decision process and select an appropriate interface when a handover is needed. The model should reduce the node's power consumption problem by controlling the state of the interfaces, when to switch the interfaces 'ON' and 'OFF'.
2. The Green Game-based MFMIPv6 protocol should allow the mobile node to control the handover decision process by deciding whether a handover is needed or not and should help the mobile node to choose the 'best' access point when more than one available. This protocol should control the device power expenditure throughout controlling when to switch the second interface 'ON' and 'OFF'.

3. A mechanism that insures a fair allocation of resources in Ad-Hoc networks, which should take into account the competitive behavior between players in the game in order to make sure that the user who values the resources more will have a better chance in gaining access to it. The dynamic game-based routing mechanism the research aiming to achieve should insure a reliable path between the source and destination and should give the intermediate node the chance to decide whether to participate in any route or not based on power consumption and source compensation.
4. The competitive Auction game-based spectrum sharing mechanism the research aiming to achieve should provide a dynamic ability to assign spectrum between secondary users in different scenarios. The mechanism should provide a fair share between secondary users when the number of users increases dynamically. It should adapt itself to the changes occurred during the sharing time, such as changes in the channel quality and when users retreat from their share.

## 1.3 Contribution to Knowledge

This thesis contributes to knowledge by designing two game theory based interface selection and handover models for mobile nodes with multiple wireless interfaces, aiming at reducing the unnecessary handovers and reduces the handover latency by controlling the handover decision process and insuring that the mobile node will choose the access point, which offers better QoS if handover is needed.

Furthermore, the thesis presents a novel auction and game-based mechanism for both resource allocation and price and power based routing in Ad-Hoc networks. Beside, a similar combination of both auction and game theory is proposed to fairly assign free spectrum to a group of secondary users in Cognitive Radio networks.

The key contributions are summarized as follows:

1. Hybrid vertical handover model for heterogeneous wireless networks, which aims at reducing the number of unnecessary handovers mobile nodes with multiple interfaces of different technologies experience in real scenarios. The model consists of a game-controller that aims to control the handover decision process.

   a. Dynamic and Static handover controller to reduce the number of unnecessary handovers and insure the continuity of node communications' links.
   b. A game-decision model to choose the right interface and when a handover is needed.
   c. A game-controller to choose the right access point when multiple access points operate in the same area.
   d. A game-controller to keep the unused interfaces 'OFF' until a handover is needed, in order to reduce the overall power consumption generated by the nodes' interfaces.

2. Game-based Multi-Interface Fast-handover Mobile IPv6 protocol as an extension to the Multi-Interface fast-handover mobile IPv6 protocol works when the mobile node has more than one wireless interface.
   a. Green game-based interface selection mechanism to control the handover decision process by deciding a handover is needed or not and choosing the right access point when more than one access point can offer an acceptable service to the mobile node.
   b. Similar to (1.d.), the mechanism decides to turn 'ON' the second interface when the received signal strength received from the serving access point goes just below a predefined threshold value.

3. Auction and game based dynamic resource allocation and price and power routing mechanisms in Ad-Hoc wireless networks. Under auction schemes, end-users bid the information data to access the data stored in the server. The server allocates the data to the user who values it the most. The routing mechanism is based on the source-destination cooperation, how much the source will compensate the intermediate nodes to define a more reliable path and how much will cost (in terms of transmission power) intermediate nodes to forward packets to the end-user.
   a. Both first and second-price sealed-auctions are examined to ensure higher source revenue and fairer allocation of resources.

   b. A power and price based routing mechanism; where the intermediate nodes decide whether it is appropriate to participate in any route or not based on how much the source compensates each intermediate node and how much energy the node has before participating in the named route.

4. Dynamic game-based reputation model and auction and game-based dynamic spectrum sharing mechanism in Cognitive Radio networks. Auctions are used to improve primary users' revenue and a game-model is used to insure a fair share is allocated between secondary users.
   a. Both first and second-price sealed auctions are tested to ensure acceptable revenue to the primary user.
   b. Defining the pros and cons of three main spectrum sharing game models, namely; optimum, competitive and cooperative spectrum sharing games.
   c. A combination of both auction and competitive game models are used to shape a novel spectrum sharing mechanism. Users with high priority traffic and value the offered spectrum more than others will get better chance to get more of the offered spectrum.
   d. A game-based reputation mechanism between secondary users to arrange access to the offered spectrum. A secondary-primary user is defined between secondary users who will be responsible of arranging fair share between secondary users.

## 1.4 Research Methodology

The initial phase of my research focused on literature review; relevant research articles, books, research papers which includes conference proceedings and journal papers, IEEE standards, progress and proposals of IEEE task groups, and different white papers on Game Theory and its applications on Mobile IPv6, heterogeneous wireless networks, resource allocation and routing in Ad-Hoc networks and Spectrum sharing in Cognitive Radio were studied. During this stage, basic definitions, types and classifications of games were examined and issues related to mobile IPv6 and its recent extinctions, routing and resource allocations in Ad-Hoc networks and spectrum sharing in Cognitive Radio networks were identified.

Literature review was followed by mathematical study of different parameters and scenarios for each case was carried out using different variables and strategies according to the needs and settings of each individual case. Not only the performance of each proposed solution was tested but it also helped in developing a different perspective. Such as, looking at the issues of interface selection when the mobile device has more than one interface, fair allocation of resources, power-price-based routing in ad hoc networks and fair spectrum sharing in Cognitive Radio networks.

In the final stage, development of simulation models of different interface selection mechanisms based on static or dynamic factors have been implemented in order to compare them with the solutions introduced through this research. Apart from implementing the proposed protocols, Fast-handover Mobile IPv6 and Multi-interface Fast-handover Mobile IPv6 protocols were also implemented for comparison. Furthermore, game-based routing mechanisms and spectrum sharing models were implemented for the same reasons. The proposed models and various components were designed and tested in NS-2 and MATLAB. NS-2 [14] is an open source simulator and new models can be easily implemented using either C++ or Tool Command Language (TCL). However, applying matrices and mathematical equation into TCL is relatively difficult, and requires multiple header files and classes to be included. On the other hand, MATLAB provides easy, interactive environment and fast numerical algorithms. It allows matrix manipulation, plotting of functions and data, Implementation of algorithms, creation of user interfaces and interfacing with programs in other languages.

## 1.5 Thesis Structure

This thesis consists of seven chapters. Chapter two gives an introduction to the basic concepts of Game Theory. The aim is to supply sufficient information to understand the applications of game theory in this thesis. A brief history of the game, previous work and the most common types of games are discussed in details; the reasons behind applying game theory in telecommunications systems are examined.

In chapter three, a novel Vertical Handover model for heterogeneous wireless networks is explained in details, which aims to reduce the number of unnecessary handovers and reduce the energy consumption in mobile node. A Game Theory-based decision model is introduced, which controls the handover decision process and insures that the mobile node will choose the right access point at the right time.

Based on that model, chapter four describes the main applications of game theory in mobile IPv6 networks. In a few words, details about previous researches and the reasons behind them are explained throughout the chapter. Throughout it sections, a novel game-based green interface/network selection mechanism is proposed, which is an extension to the multi-Interface Fast-handover Mobile IPv6 Protocol, works when the mobile node has more than one wireless interface. The mechanism controls the handover decision process by deciding whether a handover is needed or not and helps the node to choose the right access point at the right time. What's more, the mechanism switches the mobile nodes interfaces 'ON' and 'OFF' when needed to control the mobile node's energy consumption and improves the handover latency.

Chapter five focuses on adopting a novel combination of both game and auction theories in dynamic resource allocation and routing in wireless Ad-Hoc networks. Under auction schemes, destinations nodes bid the information data to access to the data stored in the server node. Their bids are based on either the first or second-price sealed bids auctions, which accumulate throughout the repeated bidding process over time. The server will allocate the data to the winner user who values it the most. Throughout this chapter, both mechanisms have been investigated to prove that they yield to similar utilities in terms of seller's revenue and overall system efficiency. Once the data been allocated to the winner node, another mechanism for dynamic routing in Ad-Hoc wireless networks is adopted in this chapter, based on Game Theory. The routing mechanism is based on the source-destination cooperation and how much the source will compensate the intermediate nodes to define a more reliable path. The simulation results prove that the introduced auction mechanism dramatically increases the seller's revenue whether he decide to choose the first or second-price auction. Moreover, the results briefly evaluate the reliability of predefined route with respect to the data prices and source and destination cooperation for different network settings.

Chapter six explains an adaptive competitive second-price pay-to-bid sealed auction game as solution to the fairness problem of spectrum sharing among one primary user and a large number of secondary users in cognitive radio environment. Throughout the chapter, three main spectrum sharing game models are compared, namely; optimal, cooperative and competitive game models introduced as a solution to the named problem. Also, this chapter proves that the cooperative game model is built based on achieving Nash equilibrium between players and provides better revenue to the sellers and bidders in the game. Furthermore, the cooperative game is the best model to choose when the number of secondary users changes dynamically, but only when the number of competitors is low. As in practical situations, the number of secondary users might increase dramatically and the cooperative game will lose its powerful advantage once that number increases. As a result, the proposed mechanism creates a competition between the bidders and offers better revenue to the players in terms of fairness. Combining both; second-price pay-to-bid sealed auction and competitive game model will insure that the user with the better channel quality, a higher traffic priority and a fair bid will get a better chance to share the offered spectrum. It is shown by numerical results the proposed mechanism could reach the maximum total profit for secondary users with better fairness. The other solution introduced in chapter six is done by a reputation-based game between secondary users. The game aims to elect one of the secondary users to be a secondary-Primary user and arrange the access to other secondary users. It is shown by numerical results that the proposed game managed to give a better chance to secondary users to use the spectrum more efficiently and improve the primary user revenue.

Finally, this thesis is summarized in chapter seven and some ideas for future proposals are included based on the research carried out in this work.

## 1.6 References

[1] M. Guizani (Ed.), “Wireless Communications Systems and Networks”, Western Michigan University, Michigan, 2004.

[2] D. Fudenberg, and J. Tirole, “Game Theory”, Cambridge, MA: MIT Press, 1991.

[3] M. J. Osborne, and A. Rubinstein, “A Course in Game Theory”, Cambridge, MA: MIT Press, 1994.

[4] A.B. MacKenzia, and L.A. DaSilva, “Game Theory for Wireless Engineers”, Morgan&Claypool Publisher, 2006.

[5] E. Hossain (Ed.), “Heterogeneous Wireless Access Networks”, Springer, Architectures and Protocols, 2009.

[6] D. Johnson, C. Perkins and J. Arkko, “Mobility Support in IPv6”, Network working group, RFC 3775, June 2004.

[7] R. Koodli (Ed.), “Fast Handover for Mobile IPv6”, Network working group, RFC 4068, July 2005.

[8] R. Wakikawa, T. Ernst, and K. Nagami, "Multiple Care-of Addresses Registration", draft-ietf-monami6-multiplecoa-05.txt (work in progress), January 2008.

[9] M.K. Park, J.Y. Lee, B.C. Kim and D.Y. Kim. “Design of Fast Handover Mechanism for Multiple Interfaces Mobile IPv6”, IEEE INFOCOM, pp. 697-701, 2008.

[10] M.S. Gast, “802.11 Wireless Network, the Definitive Guide”, O’Reilly, Second Edition, 2005.

[11] S. Tekinay (Ed.), “Next Generation Wireless Networks”, Springer Netherlands, 2001.

[12] B. Fette, “Cognitive Radio Technologies”, Communications Engineering Series, 2006.

[13] Y. Xiao and F. Hu (Ed.), “Cognitive Radio Networks”, CRC Press, First edition, 2009.

[14] The Network Simulator – NS-2, available online at; http://www.isi.edu/nsnam/ns/ [Accessed 01st February 2010].

# CHAPTER 2

# *Game Theory: An Introduction*

## 2.1 Game Theory: A Brief History

'Game Theory' is a mathematical concept, which deals with the formulation of the correct strategy that will enable an individual or entity (i.e., player), when confronted by a complex challenge, to succeed in addressing that challenge. It was developed based on the premise that for whatever circumstance, or for whatever 'game', there exists a strategy that will allow one player to 'win'. Any business can be considered as a game played against competitors, or even against customers. Economists have long used it as a tool for examining the actions of economic agents such as firms in a market.

The ideas behind game theory have appeared through-out history [1], apparent in the bible, the Talmud, the works of Descartes and Tzu, and the writings of Darwin [2]. However, some argue that the first actual study of game theory started with the work of Bernoulli, a mathematician born in 1700 [3]. Although his work the “Bernoulli’s Principles” formed the basis of jet engine production and operations, he is credited with introducing the concepts of expected utility and diminishing returns. Others argue that the first mathematical tool was presented in England in the 18th century, by Bayes, known as “Bayes’ Theorem”; his work involved using probabilities as a basis for logical conclusion [3]. Nevertheless, the basis of modern game theory can be considered as an outgrowth of a three seminal works; a “Researches into the Mathematical Principles of the Theory of Wealth” in 1838 by Cournot, gives an intuitive explanation of what would eventually be formalized as *Nash equilibrium* and gives a dynamic idea of players best-response to the actions of others in the game. In 1881, Francis Edgeworth expressed the idea of competitive equilibrium in a two-person economy. Finally, Borel, suggested the existence of *mixed* *strategies*, or probability distributions over one's actions that may lead to stable play. It is also widely accepted that modern analysis of game theory and its modern methodological framework began with John Von Neumann and Oskar Morgenstern book [4].

We can say now that “Game Theory” is relatively not a new concept, having been invented by *John von Neumann* and *Oskar Morgenstern* in 1944 [4]. At that time, the mathematical framework behind the concept has not yet been fully established, limiting the concept's application to special circumstances only [5]. Over the past 60 years, however, the framework has gradually been strengthened and solidified, with refinements ongoing until today [6]. Game Theory is now an important tool in any strategist's toolbox, especially when dealing with a situation that involves several entities whose decisions are influenced by what decisions they expect from other entities.

In [4], von Neumann and Morgenstern conceived a groundbreaking mathematical theory of economic and social organization, based on a theory of games of strategy. Not only would this reform economics, but the entirely new field of scientific inquiry it yielded has since been widely used to analyze a host of real-world phenomena from arms races to optimal policy choices of presidential candidates, from vaccination policy to major league baseball salary negotiations [6]. In addition, it is today established throughout both the social sciences and a wide range of other sciences.

Game Theory can be also defined as the study of how the final outcome of a competitive situation is dictated by interactions among the people involved in the game (also referred to as 'players' or 'agents'), based on the goals and preferences of these players, and on the strategy that each player employs. A *strategy* is simply a predetermined 'way of play' that guides an agent as to what actions to take in response to past and expected actions from other agents (i.e., players in the game).

In any game, several important elements exists, some of which are; *the agent*, which represents a person or an entity having their own goals and preferences. The second element, the *utility* (also called *agent payoff)* is a concept that refers to the amount of satisfaction that an agent derives from an object or an event. *The Game*, which is a formal description of a strategic situation, *Nash equilibrium*, also called *strategic equilibrium*, which is a list of strategies, one for each agent, which has the property that no agent can change his strategy and get a better *payoff*.

Normally, any game $G$ has three components: a set of players, a set of possible actions for each player, and a set of utility functions mapping action profiles into the real numbers. In this chapter, the set of players are denoted as $I$, where $I$ is finite with, $i = \{1, 2, 3, \dots\dots.., I\}$. For each player $i \in \mathrm{I}$ the set of possible actions that player $i$ can take is denoted by $A_i$, and $A$, which is denoted as the space of all action profiles is equal to:

$$A = A_1 \times A_2 \times A_3 \times \dots \times A_I \qquad (2\text{-}1)$$

Finally, for each $i \in \mathrm{I}$, we have $U_i : A \rightarrow R$, which denotes $i$'s player utility function. Another notation to be defined before carrying on; suppose that $a \in A$ is a strategy profile and $i \in I$ is a player; and then $a_i \in A_i$ denote player $i's$ action in $a_i$ and $a_{-i}$ denote the actions of the other $I - 1$ players.

In this chapter, some famous examples of games, some important definitions used in games and classifications of games are presented. Throughout this chapter, a mathematical proof is presented to show when mixed strategy games can be valid and invalid in different scenarios.

## 2.2 Examples of Games

### 2.2.1 Prisoners' Dilemma

In 1950, Professor Tucker of Princeton University invented the Prisoner's Dilemma [7-8], an imaginary scenario that is without doubt one of the most famous representations of Game Theory. In this game, two prisoners were arrested and accused of a crime; the police do not have enough evidence to convict any of them, unless at least one suspect confesses. The police keep the criminals in separate cells, thus they are not able to communicate during the process. Eventually, each suspect is given three possible outcomes:

1) If one confesses and the other does not, the confessor will be released and the other will stay behind bars for ten years (i.e. -10);
2) If neither admits, both will be jailed for a short period of time (i.e. -2,-2); and
3) If both confess, both will be jailed for an intermediate period of time (i.e. six years in prison, -6).

The possible actions and corresponding sentences of the criminals are given in Table 2-1.

**Table 2-1: Prisoners'' Dilemma game.**

| | | ***2nd Criminal*** | |
|---|---|---|---|
| | | *Cooperate* | *Defect* |
| ***1st Criminal*** | *Cooperate* | ***-2, -2*** | ***-10, 0*** |
| | *Defect* | ***0, -10*** | ***-6, -6*** |

To solve this game, the dominating strategy of each player must be found, which is the best response of each player regardless of what the other player will play. From player one's point of view, if player two cooperates (i.e. not admitting), then he is better off with the defect (i.e. blaming his partner). If player two defects, then he will choose defect as well. The same will work with player two. In the end, both prisoners conclude that the best decision is to defect, and are both sent to intermediate imprisonment.

### 2.2.2 Battle of the Sexes

Another well know game is the battle of the sexes [4-6], in which two couple argues where to spend the night out. In this example, she would rather attend an audition of Swan Lake in the opera and he would rather a football match. However, none of them would prefer to spend the night alone. The possible actions and corresponding sentences of the couple are given in Table 2-2.

**Table 2-2: Battle of the Sexes game.**

| | | ***Female*** | |
|---|---|---|---|
| | | *Ballet* | *Football* |
| ***Male*** | *Ballet* | ***2, 4*** | ***0, 0*** |
| | *Football* | ***0, 0*** | ***4, 2*** |

It is easy to see that both of them will either decide to go to the ballet or to the football match, as they are much better off spending the evening alone.

## 2.3 Nash Equilibrium

***Definition:*** Nash Equilibrium exists in any game if there is a set of strategies with the property that no player can increase her payoff by changing her strategy while the other players keep their strategies unchanged [1-3]. These sets of strategies and the corresponding payoffs represent the Nash Equilibrium. More formally, a Nash equilibrium is a strategy profile $a$ such that for all $a_i \in A_i$,

$$U(a_i, a_{-i}) \geq U(\tilde{a}_i, a_{-i}) \qquad (2\text{-}2)$$

where ã, denotes another action for the player $i's$ [1-3]. We can simply see that the action profile (defect, defect) is the Nash Equilibrium in the prisoners dilemma game and the actions profile (ballet, ballet) and (football, football) are the ones for the battle of the sexes game.

## 2.4 Pareto Efficiency

***Definition:*** Pareto efficiency is another important concept of game theory. This term is named after Pareto, an Italian economist, who used this concept in his studies and defined it as; “A situation is said to be Pareto efficient if there is no way to rearrange things to make at least one person better off without making anyone worse off” [9].

More Formally, an action profile $a \in A$ is said to be Pareto if there is no action profile $\tilde{a} \in A$ such that for all $i$,

$$U(a_i) \geq U(\tilde{a}_i) \qquad (2\text{-}3)$$

In another word, an action profile is said to be Pareto efficient if and only if it is impossible to improve the utility of any player without harming another player.

In order to see the importance of Pareto efficiency, assume that someone was walking along the shore on an isolated beach finds a £20 bill on the sand. If bill is picked up and kept, then that person is better off and no one else is harmed. Leaving the bill on the sand to be washed out would be an unwise decision. However, someone might argue the fact that the original owner of the bill is worse off. This is not true, because once the owner loses the bill he is defiantly worse off. On the other hand, once the bill is gone he will be the same whether someone found it or it was washed out to the sea. This will lead us to another argument; assume there are two people walking on the beach and they saw the bill on the sand. Whether one of them will pick up the bill and the other will not get anything or they decide to split the bill between themselves. Who gains from finding the bill is quite different in those scenarios but they all avoid the inefficiency of leaving it sitting on the beach.

## 2.5 Pure and Mixed Strategy Nash Equilibrium

In any game, someone will find pure and mixed strategies; a pure strategy has a probability of one, and will be always played. On the other hand, a mixed strategy has multiple purse strategies with probabilities connected to them. A player would only use a mixed strategy when she is indifferent between several pure strategies, and when keeping the challenger guessing is desirable, that is when the opponent can benefit from knowing the next move. Another reason why a player might decide to play a mixed strategy is when a pure strategy is not dominated by other pure strategies, but dominated by a mixed strategy. Finally, in a game without a pure strategy Nash Equilibrium, a mixed strategy may result in a Nash Equilibrium.

From the battle of the sexes game, we can see the mixed strategy Nash equilibria are the action profile (ballet, ballet) and (football, football). In order to drive that, we will assume first that the women will go to the ballet and the man will play some mixed strategy σ. Then the utility of playing this action will be $U_F = f(\sigma)$.

Then, $U_B = \sigma_B(4) + (1 - \sigma_B)(0)$, therefore in another word, the women gets '4' some percentage of the time and '0' for the rest of the time. Assuming the women will be going with her partner to the football match, then $U_F = \sigma_B(0) + (1 - \sigma_B)(2)$, she will get '0' some percentage of the time and '2' for the rest of the time. Setting the two equations equal to each other and solving for σ, this will $\sigma_B = 1/3$. This means that in this mixed strategy Nash equilibrium, the man is going to the ballet third of the time and to going to the football match two-third of the time. Taking another look to the Table 2-2 , we can see that the game is symmetrical against the strategies, which means that the women will decide to go the ballet two-third of the time and third of the time to go to the football match.

In order to calculate the utility of each player in this game, we need to multiply the probability distribution of each action by the user strategy, as shown in Table 2-3. We can simply see that the utility of both players is '4/3', which means that if they will not communicate with each other to decide where to go, they are both better-off to use mix strategies.

Table 2-3: Pure and Mixed Strategies, Battle of the Sexes example.

| | | ***Female*** | |
|---|---|---|---|
| | | *Ballet (2/3)* | *Football (1/3)* |
| ***Male*** | *Ballet (1/3)* | 2/9 ***2, 4*** | 1/9 ***0, 0*** |
| | *Football (2/3)* | 4/9 ***0, 0*** | ***4, 2*** 2/9 |

## 2.6 Valid and Invalid Mixed Strategy Nash Equilibrium

This section shows how mixed strategies can be invalid with games in general forms. Recalling the prisoner's dilemma game from the previous section, where we going to solve the general class of the game by removing the numbers from the table and use the following variables;

Table 2-4: Valid and Invalid Mixed Strategy Nash Equilibrium, Prisoners' Dilemma example.

| | | ***$2^{nd}$ Criminal*** | |
|---|---|---|---|
| | | *Cooperate* | *Defect* |
| ***$1^{st}$ Criminal*** | *Cooperate* | ***B, b*** | ***D, a*** |
| | *Defect* | ***A, d*** | ***C, c*** |

Where we have, $A > B > C > D$ and $a > b > c > d$. We will simply start to solve this game the same way we did before, we will start looking for the dominate strategies. From the player one point of view, if player two cooperate then player one will not as $A > B$. If player two defect, then player one will defect as well as $C > D$. Doing the same thing for player two; if player one confess, then player two will defect as $a > b$. If player one defect, then player two will defect as well as $c > d$. Then, the only sensible equilibrium will be (Don't confess, Don't confess).

To make sure that there are no mixed strategy Nash equilibrium in this scenario, we need to find the utility of player two confessing as a function of some mixed strategy of player one. That is, some percentage of the time player two will get $b$ and for the rest of the time will get $d$. Mathematically this will be; $U_C = \sigma_C(b) + (1 - \sigma_C)(d)$. Then, we do the same to find what the utility of player two will be as function of player one mixed strategy. This can be shown as; $U_D = \sigma_C(a) + (1 - \sigma_C)(c)$. To find the mixed strategy, $U_C$ must be equal to $U_D$, and that will lead us to the following equation;

$$\sigma_C = \frac{c-d}{b-d-a+c} \qquad (2\text{-}4)$$

In order to proof that this is a valid mixed strategy Nash equilibrium, the following condition must be satisfied; $Pr(i) \epsilon [0,1]$ (i.e. no event can occur with negative probability and no event can occur with probability greater than one). That is the probability that this strategy will happen is grater than zero and not less than one. For the first case, when $\sigma_C \geq 0$, the nominator and the denominator must be both positive or negative, otherwise, this mixed strategy will be invalid. Recalling our assumption, $a > b > c > d$, then the nominator must be grater than zero, the denominator must be grater than zero as well. That is $b + c - a - d > 0$, which can be re-arranged as $b + c > a + d$, at this point we cannot be sure whether this will give us the right answer of whether this is a valid mixed strategy or not as there will be some times where $b + c$ is grater than $a + d$ and some times where it is not. So, for the mixed strategy Nash equilibrium for this game does exist, $\sigma_C$ must be less than or equal to one. This will lead us to the following equation:

$$\frac{c-d}{b-d-a+c} \leq 1 \qquad (2\text{-}5)$$

That is $c - d \leq b - d - a + c$, which can be solved to $a \leq b$, which is not right as this violate or rule that $a > b$, so this is an invalid mixed strategy. Thus, we proved that there is no mixed strategy Nash equilibrium in this game and the two players will defect.

On the other hand, if we work for the example of the Battle of the Sexes game. Table (2-5) shows the game in general format, were we removed the numbers again and used the following variables; $A \geq B \geq C \geq 0$ and $a \geq b \geq c \geq 0$. Following the same procedure we used in the previous example, we can solve for the man mixed strategy when his partner goes to watch the match, which will lead us to the following equality: $U_F = \sigma_F(b) + (1 - \sigma_F)(c)$, as the women get $b$ some percentage of the time and get c the rest of the time. If she decides to go to the ballet, the equality becomes; $U_B = \sigma_F(c) + (1 - \sigma_F)(a)$. Now, taking these two equations to solve for the man mixed strategy, we can finally get:

$$\sigma_F = (a - c)/(a + b - 2c) \qquad (2\text{-}6)$$

Table 2-5: Valid and Invalid Mixed Strategy Nash Equilibrium, Battle of the Sexes example.

| | | ***Female*** | |
|---|---|---|---|
| | | *Ballet* | *Football* |
| ***Male*** | *Ballet* | ***A, b*** | ***C, c*** |
| | *Football* | ***C, c*** | ***B, a*** |

In order to prove that this mixed strategy is valid, the same condition used before must be satisfied, $Pr(i) \epsilon [0,1]$. That is, $\sigma_F \geq 0$, we already have $a > c$, then the numerator is positive and greater than zero. For the denominator to be positive, $(a + b - 2c)$ must be positive. That is $a + b - 2c \geq 0$, which can be arranged as $a - c \geq c - b$, which proves that the denominator is positive as this is always true.

We must prove that $\sigma_F \leq 1$ to prove the validity of such mixed strategy. That means we must prove the following; $a - c \leq a + b - 2c$, which can be arranged to the following $c \leq b$, which is true as we already mentioned that $b \geq c \geq 0$.

Thus, we have proved that there exist three equilibriums in this game, the two players can go the Ballet or to the match together or each one of them can go to their preferred show with a probability of $(a - c)/(a + b - 2c)$.

## 2.7 Classification of Game theory

Games can be classified into different categories according to certain significant features. The terminology used in game theory is inconsistent, thus different terms can be used for the same concept in different sources. A game can be classified according to the number of players in the game, it can be designated as a one-player game, two-player game or *n*-players game (where *n* is greater than ‘2’). In addition, a player need not be an individual person; it may be a nation, a corporation, or a team comprising many people with shared interests.

### 2.7.1 Non-Cooperative and Cooperative (Coalition) Games

A game is called non-cooperative when each agent (player) in the game, who acts in her self interest, is the unit of the analysis. While the cooperative (Coalition) game treats groups or subgroups of players as the unit of analysis and assumes that they can achieve certain payoffs among themselves through necessary cooperative agreements [10].

In non-cooperative games, the actions of each individual player are considered and each player is assumed to be selfish, looking to improve its own payoff and not taken into account others involved in the game. So, non-cooperative game theory studies the strategic choices resulting from the interactions among competing players, where each player chooses its strategy independently for improving its own performance (utility) or reducing its losses (costs). On the other hand, Cooperative game theory was developed as a tool for assessing the allocation of costs or benefits in a situation where the individual or group contribution depends on other agents actions in the game [11]. The main branch of cooperative games describes the formation of cooperating groups of players, referred to as coalitions, which can strengthen the players’ positions in a game.

In Telecommunications systems, most game theoretic research has been conducted using non-cooperative games, but there are also approaches using coalition games [12]. Studying the selfishness level of wireless node in heterogeneous ad-hoc networks is one of the applications of coalition games. It may be beneficial to exclude the very selfish nodes from the network if the remaining nodes get better QoS that way [13].

### 2.7.2 Strategic and Extensive Games

One way of presenting a game is called the strategic, sometimes called static or normal, form. In this form the players make their own decisions simultaneously at the beginning of the game, the players have no information about the actions of the other players in the game. The prisoner’s dilemma and the battle of the sexes are both strategic games.

Alternatively, if players have some information about the choices of other players, the game is usually presented in extensive, sometimes called as a game tree, form. In this case, the players can make decisions during the game and they can react to other players’ actions. Such form of games can be finite (one-shot) games or infinite (repeated) games [14]. In repeated games, the game is played several times and the players can observe the actions and payoffs of the previous game before proceeding to the next stage.

### 2.7.3 Zero-Sum and Non-Zero Sum Games

Another way to categorize games is according to their payoff structure. Generally speaking, a game is called zero-sum game (sometimes called if one gains, another losses game, or strictly competitive games) if the player’s gain or loss is exactly balanced those of other players in the game [14]. For example, if two are playing chess, one person will lose (with payoff ‘-1’) and the other will win (with payoff ’+1’). The win added to the loss equals zero. Given that sometimes a loss can be a gain, real life examples of zero-sum game can be very difficult to find. Going back to the chess example, a loser in such game may gain as much from his losses as he would gain if he won. The player may become better player and gain experience as a result of loosing at the first place.

In telecommunications systems, it is quite hard to describe a scenario as a zero-sum game. However, in a bandwidth usage scenario of a single link, the game may be described as a zero-sum game.

### 2.7.4 Games with Perfect and Imperfect Information

A game is said to be a perfect information game if each player, when it is her turn to choose an action, knows exactly all the previous decisions of other players in the game. Then again, if a player has no information about other players’ actions when it is her turn to decide, this game is called imperfect information game. As it is hardly ever any user of a network knows the exact actions of the other users in the network, the imperfect information game is a very good framework in telecommunications systems. Nevertheless, assuming a perfect information game in such scenarios is more suitable to deal with.

### 2.7.5 Games with Complete and Incomplete Information

In games with “complete information”, all factors of the game are common knowledge to all players [6, 14]. That is, each individual player is fully aware of other players in the game, their strategies and decisions and the payoff of each player. As a result, a complete information game can be represented as an efficient perfectly competitive game. On the other hand, in the “incomplete information” games, the player’s dose not has all the information about other players in the game, which made them not able to predict the effect of their actions on others.

One of the very well known types of such games is the sealed-bid auctions, in which a player knows his own valuation of the good but does not knows the other bidders’ valuation. A combination of incomplete but perfect information game can exist in a chess game, if one player knows that the other player will be paid some amount of money if a particular event happened, but the first player does not know what the event is. They both know the actions of each other, perfect information game, but does not know the payoff function of the other player, incomplete information game.

### 2.7.6 Rationality in Games

The most fundamental assumption in game theory is rationality [15]. It implies that every player is motivated by increasing his own payoff, i.e. every player is looking to maximize his own utility. von Neumann and Morgenstern justified the idea of maximizing the expected payoff in their work in 1944 [4]. However, previous studies have shown that humans do not always act rationally [16]. In fact, humans use a propositional calculus in reasoning; the propositional calculus concerns truth functions of propositions, which are logical truths (statements that are true in virtue of their form) [17]. For this reason, the assumption of rational behaviour of players in telecommunications systems is more justified, as the players are usually devices programmed to operate in certain ways.

### 2.7.7 Evolutionary Games

Evolutionary game theory started its development slightly after other games have been developed [18]. This type of game was originated by Smith formalization of evolutionary stable strategies as an application of the mathematical theory of games in the context of biology in 1973 [19]. The objective of evolutionary games is to apply the concepts of non-cooperative games to explain such phenomena which are often thought to be the result of cooperation or human design, for example; market information, social rules of conduct and money and credit. Recently, this type of games has become of increased interest to scientist of different background, economists, sociologists, anthropologists and also philosophers. One of the main reasons behind the interest among social scientists in the evolutionary games rather than the traditional games is that the rationality assumptions underlying evolutionary game theory are, in many cases, more appropriate for the modelling of social systems than those assumptions underlying the traditional theory of games [20].

## 2.8 Applications of Game Theory in Telecommunications

Communications systems are often built around standard, mostly open ones, such as the TCP/IP (Transmission Control Protocol/Internet Protocol [21]) standard in which the internet is based. Devices that we use to access these systems are being designed and built by a diversity of different manufactures. In many cases, these manufacturers may have an incentive to develop products, which behave “selfishly” by seeking a performance advantage over other network users at the cost of overall network performance [22]. On the other hand, end users may have the ability to force these devices in order to work in a selfish manner. Generally speaking, the maximizing of a player’s payoff is often referred to as selfishness in a game. This is true in the sense that all the players try to gain the highest possible utility of their actions. However, a player gaining a high utility does not necessarily mean that the player acts selfishly. As a result, systems that are prepared to cope with users who behave selfishly need to be designed. If the designs of such systems are possible, designers should make sure that selfish behaviour within the system is unprofitable for individuals. When designing such system is not possible, they should be at least aware of the impact of such behaviour on the operation of the specified system.

One important thrust in these efforts focuses on designing high-level protocols that prevent users from misbehaving and/or provide incentives for cooperation. To prevent misbehaviour, several protocols based on reputation propagation have been proposed in the literature, e.g., [23], [24]. The mainstream of existing research in telecommunications networks focused on using non-cooperative games in various applications such as distributed resource allocation [25], congestion control [26], power control [27], and spectrum sharing in cognitive radio, among others. This need for non-cooperative games led to numerous tutorials and books outlining its concepts and usage in communication, such as [28], [29]. Another thrust of research analyzes the impact of user selfishness from a game theoretic perspective, e.g., [22], [30]. Since the problem is typically too involved, several simplifications to the network model are usually made to facilitate analysis and allow for extracting insights. For example, in [22], the wireless nodes are assumed to be interested in maximizing energy efficiency. At each time slot, a certain number of nodes are randomly chosen and assigned to serve as relay nodes on the source- destination route. The authors derive a Pareto optimal operating point and show that a certain variant of the well known TIT-FOR-TAT algorithm converges to this point. In [22], the authors assume that the transmission of each packet costs the same energy and each session uses the same number of relay nodes. Another example is [30], which studies the Nash equilibrium of packet forwarding in a static network by taking the network topology into consideration. More specifically, the authors assume that the transmitter/receiver pairs in the network are always fixed and derive the equilibrium conditions for both cooperative and non-cooperative strategies. Similar to [22], the cost of transmitting each packet is assumed fixed. It is worth noting that most, if not all of, the works in this thrust utilize the repeated game formulation, where cooperation among users is sustainable by credible punishment for deviating from the cooperation point.

Cooperative games have also been widely explored in different disciplines such as economics or political science. Recently, cooperation has emerged as a new networking concept that has a dramatic effect of improving the performance from the physical layer [23], [24] up to the networking layers [25]. However, implementing cooperation in large scale communication networks faces several challenges such as adequate modelling, efficiency, complexity, and fairness, among others. In fact, several recent works have shown that user cooperation plays a fundamental role in wireless networks. From an information theoretic perspective, the idea of cooperative communications can be traced back to the relay channel [31]. More recent works have generalized the proposed cooperation strategies and established the utility of cooperative communications in many relevant practical scenarios, such as [25], [26] and [32]. In another line of work, in [27], the authors have shown that the simplest form of physical layer cooperation, namely multi hop forwarding, is an indispensable element in achieving the optimal capacity scaling law in networks with asymptotically large numbers of nodes. Multi-hop forwarding has also been shown to offer significant gains in the efficiency of energy limited wireless networks [28], [29]. These physical layer studies assume that each user is willing to expend energy in forwarding packets for other users. This assumption is reasonable in a network with a central controller with the ability to enforce the optimal cooperation strategy on the different wireless users. The popularity of ad-hoc networks and the increased programmability of wireless devices, however, raise serious doubts on the validity of this assumption, and hence, motivate investigations on the impact of user selfishness on the performance of wireless networks. The following chapters will be full of more details about the applications of game theory in wireless telecommunications systems, including applications of game theory in interface selections mechanisms, Mobile IPv6 protocol extensions, resource allocations and routing in Ad-Hoc wireless network and spectrum sharing in Cognitive Radio networks.

## 2.9 Summary

This chapter gives a detailed insight in the game theory definition, classifications and applications of games in telecommunications. Prisoners Dilemma and the Battle of the Sexes games have been discussed in details, showing different strategies from the players and discussing the expected outcome of such games. Nash Equilibrium and Pareto Efficient terms are discussed in details with detailed examples. Moreover, we have discussed mixed strategies in games and mathematically proved that a mixed strategy in Prisoners' Dilemma example does not exist. We have also proved that a mixed strategy exists in the battle of the sexes game. Finally, after classifying games into different categories, an introduction to the applications of game theory in Telecommunications is given.

## 2.10 References:

[1] E.R. Weintraub, “Toward a History of Game Theory”, Duke University Press, 1992.

[2] M. Shor, “Brief Game Theory History”, available online at; http://www. gametheory.net/Dictionary/Game_theory_history.html [Accessed 14th February 2010].

[3] P. Dittmar, “Practical Poker Math”, ECW Press, November 2008.

[4] J. von Neumann and O. Morgenstern, “Theory of Games and Economic Behavior”, Princeton University Press, 1944.

[5] Game Theory, SiliconFarEast.com, available online at http://www.siliconfareast.com/ game-theory.htm [Accessed 20th February 2010].

[6] J. von Neumann and O. Morgenstern, “Theory of Games and Economic Behavior (Commemorative Edition, 60th-Anniversary Edition)”, With an introduction by Harold Kuhn and Ariel Rubinstein., 2007.

[7] Prisoner's Dilemma, Stanford encyclopaedia of Philosophy, Available online at; http://plato.stanford.edu/entries/prisoner-dilemma/ [Accessed 20 February 2010].

[8] A. Rapoport and M. Chammah, “Prisoner’s dilemma: a study in conflict and cooperation”, The University of Michigan Press, Second edition 1970.

[9] D. Fudenberg and J. Tirole, “Game Theory”, MIT Press, 1983.

[10] J. Nash, “Non-Cooperative Games”, Second series, vol. 54, No. 2, pp. 286-295, 1951.

[11] W. David, K. Yeung, and L. A. Petrosyan, “Cooperative Stochastic Differential Games”, Springer Series in Operations Research and Financial Engineering, 2004.

[12] A.B. MacKenzie, S.B. Wicker, “Game Theory in Communications: Motivation, Explanation, and Application to Power Control”, IEEE GLOBECOM 2001, vol. 2, pp. 821-826, 2001.

[13] J. Leino, “Applications of Game Theory in Ad Hoc Networks”, Helsinki University of Technology, Master Thesis, October 30, 2003.

[14] J. Ratliff, “Repeated Games”, University of Arizona Press, Graduate-level course in Game Theory, Chapter 5, 1996.

[15] American Mathematical Society, “Rationality and Game Theory”, Available online at; http://www.ams.org/featurecolumn/archive/rationality.html [Accessed 1st March 2010].

[16] J. Friedman (Ed.), “The Rational Choice Controversy”, Yale University Press, 1996.

[17] A. Lacey, “A Dictionary of Philosophy”, London: Rout ledge, 3rd ed, 1996.

[18] J.W. Weibull, “Evolutionary Game Theory”, MIT Press, First edition 1997.

[19] J.M. Smith, “Evolution and the Theory of Games”, Cambridge University Press, 1982.

[20] Evolutionary Game Theory, Stanford encyclopaedia of Philosophy, available online at; http://plato.stanford.edu/entries/game-evolutionary/ [Accessed 26th February 2010].

[21] T. Socolofsky, and C. Kale, “TCP/IP tutorial”, RFC1180, Network Working Group, January 1991. Available online at: http://www.faqs.org/rfcs/rfc1180.html [Accessed 14th March 2010].

[22] R.J. Aumann, and B. Peleg, “Von neumann-morgenstern solutions to cooperative games without side payments”, Bulletin of American Mathematical Society, vol. 6, pp. 173–179, 1960.

[23] R. La and V. Anantharam, “A game-theoretic look at the Gaussian multiaccess channel”, in Proceeding of the DIMACS Workshop on Network Information Theory, New Jersey, NY, USA, Mar. 2003.

[24] S. Mathur, L. Sankaranarayanan, and N. Mandayam, “Coalitions in cooperative wireless networks”, IEEE Journal in Selected Areas in Communications, vol. 26, pp. 1104–1115, Sep. 2008.

[25] Z. Han and K.J. Liu, “Resource Allocation for Wireless Networks: Basics, Techniques, and Applications”, New York, USA: Cambridge University Press, 2008.

[26] T. Alpcan and T. Basar, “A Globally Stable Adaptive Congestion Control Scheme for Internet-Style Networks with Delay”, IEEE/ACM Trans. On Networking, vol. 13, pp. 1261–1274, Dec. 2005.

[27] T. Alpcan, T. Basar, R. Srikant, and E. Altman, “CDMA Uplink Power Control as A Noncooperative Game”, Wireless Networks, vol. 8, pp. 659–670, 2002.

[28] A. MacKenzie, L. DaSilva, and W. Tranter, “Game Theory for Wireless Engineers”, Morgan&Claypool Publishers, March 2006.

[29] T. Basar, “Control and Game Theoretic Tools for Communication Networks (overview)”, Application of Computer and Mathematics, vol. 6, pp. 104–125, 2007.

[30] R. Thrall, and W. Lucas, “N-person Games in Partition Function Form”, Naval Research Logistics Quarterly, vol. 10, pp. 281–298, 1963.

[31] T. Basar and G. J. Olsder, “Dynamic Noncooperative Game Theory”, Philadelphia, PA, USA: SIAM Series in Classics in Applied Mathematics, Jan. 1999.

[32] G. Owen, “Game Theory”, London, UK: Academic Press, 3rd edition, October1995.

# CHAPTER 3

# *Design of Game-Based Green Hybrid Vertical Handover Model for Heterogeneous Multihomed Wireless Portable Devices*

## 3.1 Introduction and Motivation

Nowadays, wireless network access is increasingly popular since wireless communication offers interesting advantages: it allows movements during communications and network access at a fair rate among nodes. Generally speaking, Mobile IPv6 [1-2] is designed to manage Mobile Nodes (MNs') movements between wireless IPv6 networks. The protocol provides unbroken connectivity to IPv6 MNs when they move from one wireless point to another in a different subnet, an operation known as layer three handover. However, a MN cannot receive IP packets on its new point of attachment until the handover ends. This time includes the new prefix discovery on the new subnet, the new care-of address establishment, and the time needed to notify the correspondents and home agent about the new locality of the MN. This time is called handover latency [3-5].

Already, mobile Internet hosts are often equipped with several network interfaces or are at least able to connect to such interfaces. These interfaces may use different access technologies such as Bluetooth, WLAN and 3G cellular. For this purpose, a few mobile host multihoming protocols supporting handovers between interfaces have been proposed. The most advanced protocols are able to move single traffic flows independently of each other. However, the current solutions do not propose any means for the user to be able to dynamically influence the interface selection during operation. Different access technologies and access operators offer several types of price and quality. Therefore, a mobile user must be able to affect on the interface selection so that the most suitable of the available interfaces is used. Changes in the availability or characteristics of an access network may result in a situation, where the user wants to move already established traffic flows from one interface to another.

## 3.2 Multihoming: Definition and Services

There are many examples of Multihoming cases but not real formal definition. We can see two basic scenarios: The first is a node with a single network interface, which has been assigned multiple IP addresses, and the second is multiple network interfaces on a same network node [6]. We can add a third case in higher scale Site Multihoming: When "a network site has more than one connection to the public Internet". Multihoming can provide us with numerous services:

1. Redundancy/Fault-tolerance: When an address is not any more reachable, when a link goes down or a router has a failure, the reachability to the Internet can be provided by the use of other addresses, links or routes. The continuity of the connectivity should be transparent for the applications.
2. Load Sharing: The multihomed host/site should be able to distribute upstream and downstream traffic between his interfaces/border routers.
3. Traffic Policy: The multihomed host/site should be able to define some policy to manage the network traffic for reasons of costs, traffic requirements, uses conditions, social policy, etc...

Nevertheless, depending on the service offered, there are many problems to resolve:

1) Routing scalability: Multi-homing heavily increases the size of routing tables. Actually, it is a problem mainly for router located in the backbone of the Internet. Theses routers have no default route and must know every route for all top-providers. For many people it is one of the most important points because it is essential to other benefits.

2) Transport-Layer Transparency: Change of address/link/router after a multi-homing decision should be transparency for transport-layer session. Otherwise, the benefits of the Redundancy/Fault-Tolerance are less.
3) DNS Issues, It is a client host issue: How to deal with multiple addresses for one single host.
4) Packet Filtering/Ingress Filtering: In general, a provider filters his customer’s traffic and permit only transient to the Internet packets with addresses that it provided to them.
5) Address selection: For provide benefits of load sharing and policy behaviour, the network node must make source and destination address selection for each packet or stream of packets.

## 3.3 Horizontal and Vertical Handoffs in Heterogynous Wireless Networks

At present, researchers consider the Heterogeneous networks to become the main focus in the development toward the next generation wireless networks. In the heterogeneous or sometimes called converged networks [6-7], both Horizontal Handoff (HHO) (known as intra-technology handoff) and Vertical Handoff (VHO) (known as inter-technology handoff) [8-9] might take place as illustrated in Figure 3.1. HHO, Occurs when the mobile user switches between different networks Accesses Points (AP) of the same kind (e.g., handoff among 802.11 APs). VHO, Involves two different network interfaces that usually represent different technologies (e.g. Handoff from 802.11 to Bluetooth). One of the main features that distinguish between VHO and HHO is symmetry. While, HHO is a symmetric process, VHO is an asymmetric process in which the MN moves across two different networks with different characteristics. That is where the concept of ‘preferred network’ came from, which is the network that offers a better QoS to the MN as compared to the around networks. One of the main problems that every MN equipped with multiple interfaces of different technologies faces is the ping-pong effect [8-9], which occurs when the MN moves around the edges of the AP’s coverage areas as the MN will face multiple signals from different APs of different technologies. The MN will be in favour to switch to the AP that offers the highest Received Signal Strength (RSS), which might be any of the surrounding ones and that's will lead to increase the number of unnecessary handovers. We can say that HHO can reduce such a problem, as the MN will switch from one AP to another of the same technology and in some cases of the same service provider. The ping-pong effect often leads to reduce the overall system throughput by causing repeated interruption to the service, which leads to increase the overall end-to-end delay, number of lost packets and number of retransmissions.

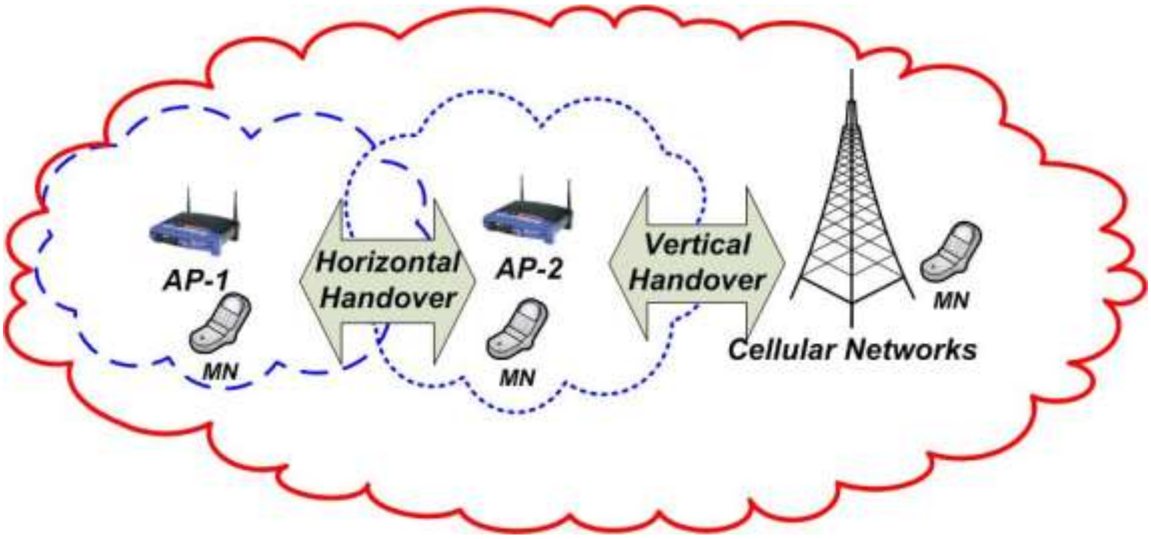


Figure 3-1: Horizontal and Vertical Handovers example.

The process of VHO consists of two main scenarios; moving out of the preferred network (MO) and moving into the preferred network (MI). It is highly desirable to keep the MN within the coverage of the preferred network, as long as the named network satisfies the user requirements. This can improve both, the resource utilization of access networks as well as the user perceived QoS. What's more, the handoff mechanism should be seamless, minimizing user involvement, while dynamically adapting to the wireless channel state, network layer characteristics and application requirements.

Typically, the process of handover can be divided into three main steps [10], System Discovery, Handoff Decision and Handoff Execution. The system discovery phase helps the MN to determine which network can be accessed and the services available in each network. On the other hand, during the handoff decision phase, the MN decides which network to connect. The decision may be based on various QoS parameters such as, the available bandwidth, service cost, transmit power, current battery life of the mobile device, and the user's/application's preferences. Finally, during the handoff decision phase, the connection needs to be moved from the previous AP and a new connection to be created with the new AP in a seamless manner. This phase also includes the authentication and authorization, re-routing all users' traffic through the new route, and the transfer of user's context information.

A seamless handoff can be defined as a handoff scheme that guarantees an ongoing connectivity to all the mobile device applications when the handoff occurs; it aims to maintain end-to-end data service to overcome any link failure or handoff events. A range of seamless handoff techniques have been proposed [12-24], they can be classified into two classes; network layer and upper layer approaches (i.e. transport and session layers).

Seamless handoff solutions, whether network layer or upper layer approaches, are often complex to implement and operate. The network layer approach needs upgrading every existing router without mobile IP capabilities. Furthermore, the upper layer solution requires an update to all existing applications and servers not supporting it. The high cost behind implementing these two solutions reduces the chances of implementing them in reality. Although, these solutions managed to reduce both handover latency and packet loss, they are often considered impartial by the majority of service providers and are still rarely deployed in real life.

A Universal Seamless Handoff Architecture (USHA) was proposed in [14] to deal with both horizontal and vertical handoff scenarios with minimal changes in infrastructure, which requires deployment of handoff servers only in the Internet. USHA is an upper layer solution; yet, instead of introducing a new session layer or a new transport protocol as in the upper layer handoff approach, it achieves seamless handoff by following the middleware design philosophy, integrating the middleware with existing Internet services and applications. USHA is based on the fundamental assumption that handoff, either vertical or horizontal, only occurs on overlaid networks with multiple Internet access methods (i.e. seamless handoff), which translates to zero waiting time in bringing up the target network interface when the handoff event occurs. If coverage from different access methods fails to overlap, it is possible for USHA to lose connectivity to the upper layer applications.

In multiple network environments (i.e., different AP's from different technologies), the problem of VHO is one of the main challenges for seamless mobility as it is not possible to define a single parameter by which the mobile device will decide whether the handoff is needed or not. Some of the most important factors are:

1. Service Cost in $£/min$: one of the major issues that influence the customer's choice is the cost of accessing the network. The network providers may well provide a variety of billing plans and options that will probably influence the customer's choice of network and thus handoff decision.
2. Power Consumption in $mW$: generally speaking, wireless devices often operate on limited battery life. When the battery level decreases, leaving a network with low power consumption might alter the user/mobile device from handing off to another network.
3. Channel Capacity in $Mbits/sec$: a user/mobile device will defiantly be interested in staying with a network with a higher offered bandwidth as this will ensure lower call dropping and call blocking probabilities, hence higher throughput.
4. Mobility in $meters/sec$: when a mobile device crosses a network having small coverage area at high speed, the chances are very low to support a handoff process as there is a big chance of a back hand off to the original network.
5. RSS in $dB$: The signal strength has a great role in the HHO decisions due to its comparability between the current attachment point RSS and that of the candidate attachment points. However, In VHO, the RSSs are incomparable due to VHO's asymmetrical nature. However, they can be used to determine the availability as well as the condition of different networks. If more than one candidate networks are available, the MN should associate itself with the one having the strongest RSS as it does in HHO.

## 3.4 Hybrid Vertical Handover Model (HVHM) for Multihomed Portable Devices

***Definition***: HVHM is a game-based handoff scheme that maintains the connectivity of all applications on the wireless mobile device when the handoff occurs. It aims to provide continuous end-to-end data service in the face of any link break or handoff events, which should provide low latency and minimum packet loss.

In order to design such a model, the decision by which the best network is to be chosen may be based on fixed factors such as the bandwidth offered by the visited network (i.e., channel capacity), the cost of using the service, power consumption of the active interface, and battery life of the mobile device. On the other hand, other dynamic factors must be considered in any handoff decision to improve the effectiveness of the network usage. Dynamic factors include the RSS from the access point, which would help in deciding whether a handoff is needed or not, and the speed of the MN, as some network might not support mobility, especially if the node is moving with relatively high speed.

Game Theory [25] can be a great help in deciding when to choose the best AP, as explained earlier, it is a mathematical concept that deals with the formulation of the correct strategy that will enable an individual or entity (i.e., player), when confronted by a complex challenge, to succeed in addressing that challenge. The MN interfaces will act as players and their individual strategies will be able to choose the AP that offers a better QoS (i.e. payoff to the node). Table 3-1 below shows the matrix format of this game, each column represents the QoS parameters of each AP, while the rows show the compatible interfaces. The results of each interface (i.e. player in the game) actions are represented as A, B and C, which can be taken as the payoff of the MN when choosing the named interface.

**Table 3-1: Matrix format of the game selection process.**

| | ***QoS Parameters*** | | |
|---|---|---|---|
| | *AP#1* | *AP#2* | *AP#3* |
| ***Interface#1*** | *A,-,-* | -,-,- | -,-,- |
| ***Interface#2*** | -,-,- | *-,B,-* | -,-,- |
| ***Interface#3*** | -,-,- | -,-,- | *-,-,C* |

Since each interface will be compatible with at least one AP, the mechanism will not be complicated. The winner will be calculated easily throughout a game-based score function. In fact, if the MN moves across multiple AP of the same technology, the mechanism will only check the compatible interface and choose the winning AP. Nash equilibrium can be achieved easily when the MN reach to the decision of which AP to choose. Once the QoS received from this AP is acceptable, the mechanism will force the MN to stay with the named AP until a handoff is needed.

Previous works dealing with VHO, which to the author's knowledge are very few and include simple extensions to the common HHO techniques. Throughout this literature, we have recorded three main approaches for VHO algorithms. The first approach combines the RSS with other parameters such as network loading [7-10]. In the second approach, artificial intelligence techniques are used, where several parameters are combined in the handoff decision such as network conditions and MN's mobility [11]. Finally, the third approach combines service cost, power consumption, and available bandwidth in a cost function estimated for the available access networks, which is then used in the MN handoff decision [13-14]. Several papers followed the same approach of the one introduced in [12]; the authors introduced a policy enabled handoff. This system separates the decision making from the handoff mechanism. The introduced system allows users to express policies on what is the "best" wireless system at any moment and make tradeoffs among network characteristics and dynamics such as cost, performance and power consumption. In [15] a generic vertical handoff decision function is proposed, which gives an indication of whether or not a handoff is needed based on different weighted factors and metric qualities such as financial cost, quality of service, power requirements, and user preferences. The performance of the whole system is considered by taking VHO decisions by providing users' needs in a decision strategy model introduced in [16]. The introduced strategy selects the best network based on the highest RSS and lowest Variation of received signal strength (VRSS), thus it reduce the number of unnecessary handoffs, which ensures a better system performance. In [17], the handoff decision is based on a time adaptive scheme by adjusting interface activating intervals based on the user's movement and the actual network performance. In [27], the authors defined a system-wise entity that is activated when a user is in an area with over-lapping access technologies and needs to decide what is the best technology to be used in order to optimize the overall system performance metric in terms of throughput and capacity limitations. In [28], the authors proposes a dynamic decision model to deicide "best" network at "best" time moment to handoffs. The proposed DVH decision model based on dynamic factors, such as RSS values and velocity of the mobile node. On the other hand, in [29], the authors proposed an Autonomic Handover Manager (AHM) based on the autonomic computing concept to decide the best network interface to handover in 4G networks. The proposed model decides the appropriate policy for the specific service or application without the user's intervention using the context information from the mobile terminal (i.e. type of application and its requirement and device power status), the network (i.e. reachability of access points) and the user (i.e. user settings, application settings and willingness to pay).

Previous models that used either static parameters (cost, power consumption, bandwidth, etc…) or only one dynamic parameter (RSS and node mobility), intended to improve the system performance, except the work of [29]. However, none of these systems combined game theory with the two types of parameters in one model (i.e. static and dynamic factors) to use the advantages of learning ability and dominate strategies in games. In the following sections a game-based hybrid handoff mechanism is introduced, which uses both RSS and MN velocity as dynamic factors all together with static factors including service cost, Link capacity, and power consumption to improve the system performance. Although, in [30], the authors introduced a game-theoretic model to help the node to select a better AP in terms of load and distance, they did not take into account user and/or application requirement, the mobility of the node and they consider the case of HHO only.

Figure 3-2 shows the proposed HVHM decision model, a handoff control centre (HCC), monitors the various inputs collected from the network interfaces and their APs, analyze this information and took handoff decisions. The HCC also provides the connection between the network interface and the upper layer applications. HCC consist of six components; Network Analysis (NA), Network Discovery (ND), Hybrid Handoff decision (HHD), Game-based Controller (GC), system monitor(SM) and Handoff executor (HE). NA is in charge of monitoring the status of each network interface in the MN (i.e. network offered bandwidth, user charges to access the service, and energy consumption of network interface) and analyzing these information based on the calculated score function. SM monitors and reports system information (i.e. battery life, application needs and user preferences) to NA module. ND module discovers all the available networks at fixed time intervals. It monitors the mobility of MN, the RSS of the AP, selects the candidate networks and assigns them priorities.

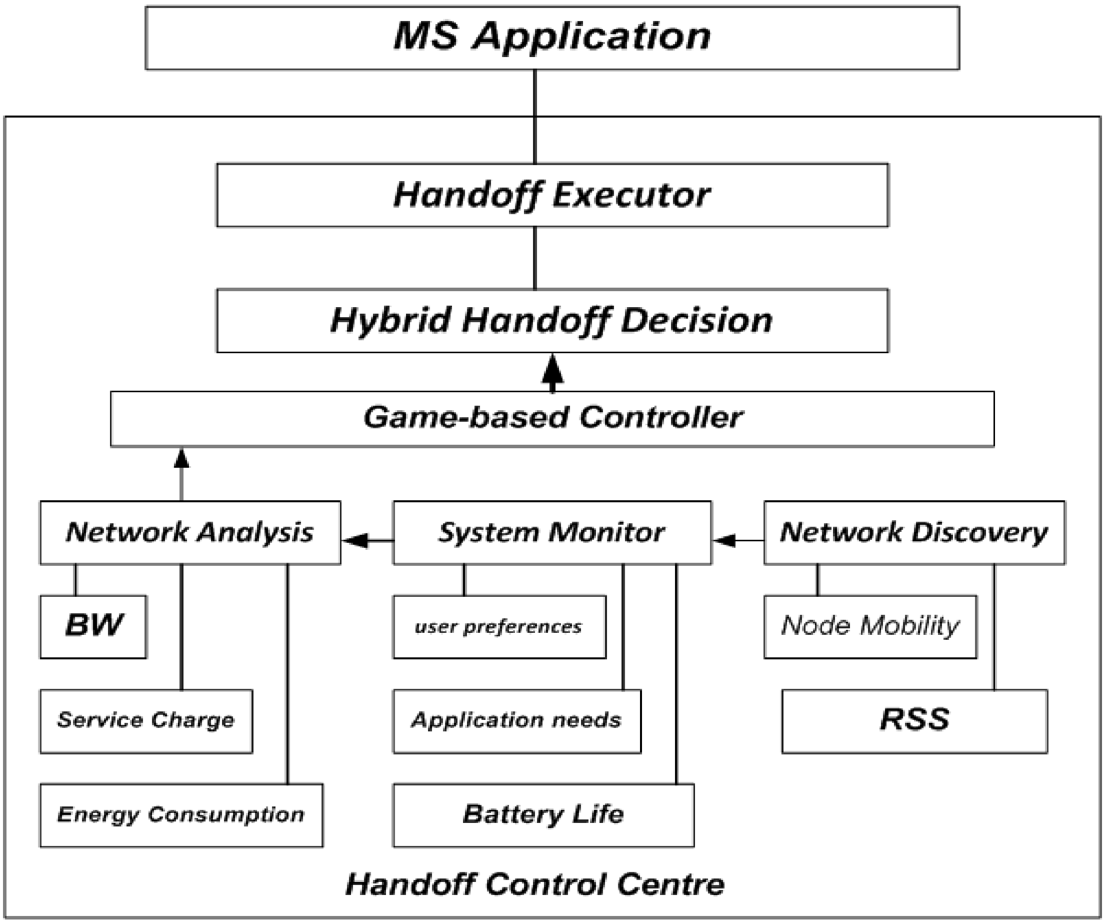


Figure 3-2: HVHM decision model.

Finally, the HHD module takes the decision based on the results received from GC, for selecting the "best" network to handoff, based on the inputs from NA and ND modules to GC. Each component is explained in more details below:

i. Network Discovery (ND): this model's objective is to identify all available networks and assign priorities to them. This process is divided into two parts;
    1) The network will be added to the candidate list if the RSS is higher than its threshold value and its mobility threshold is greater than the velocity of the MN. We assume that $N = \{n_1, n_2, n_3, \dots.., n_k\}$ is the set of available network interfaces in our MN, and $k$ is the total number of available networks. $MT = \{mt_1, mt_2, mt_3, \dots.., mt_k\}$, is the set of threshold values of velocities for a MN for the respective networks. $RssT = \{rt_1, rt_2, rt_3, \dots.., rt_k\}$ is the set of threshold values of RSS of respective networks. The set of values of differences between the RSS and its threshold value is represented by

$RssDiff = \{rd_1, rd_2, \ldots, rd_k\}$. The set of eligible candidate networks into which the handoff can take place is represented by CN. $P = \left\{0, \frac{1}{k}, \frac{2}{k}, \frac{3}{k}, \ldots., \frac{j}{k}, \ldots., 1\right\}$, is the set of priorities of the $j^{th}$ network, and $j = 1,2, \ldots k$. The mechanism scans all networks and compares the MN velocity with, if it satisfies the condition, the mechanism scans the AP's RSS value, and assign higher priority to APs with higher RSS. The network AP and MN is observed for the RSS and mobility respectively at the specified time intervals and the decisions are taken as the algorithm below to select the candidate networks, assuming that the MN is currently in network $n_i$:

```
If $RSS_j > rt_i$ then
For all $n_j$ where $j \neq i$
If ($RSS_j > rt_i$ and $m_j < mt_i$) then
$\{CN\} = \{CN\} \cup \{n_i\}$
$RssDiff_j = RSS_j - rd_i$
```

2) Network Assignment part: the network with the higher RssDiff will be assigned with a high priority. This is because a higher RssDiff means the MN is nearer to the AP of the named network and hence the MN can stay in that cell for longer before looking to handoff to another network. This will reduce the number of unnecessary handoffs and improve the overall performance of the system. The priorities are assigned according to the following algorithm, assuming that $n$ networks are available in the list;

```
While $j \leq k$ Do
if $j$ is not in the candidate list then
$P_j = 0$
            else if $j$ is the only network in the candidate list then
$P_j = 1$
else if $j$ is at the $i^{th}$ posotion, the list will be ordered in an ascending order then
$P_j = \frac{i}{k}$
```

ii. System Monitor (SM): the objectives of this model is to monitor the current battery level of the MN and record the user preferences for various networks based on the current battery life, network offered bandwidth, service charges and energy consumption by their interface card.

iii. Network Analysis (NA): this module is to keep a record of the network characteristics, the offered bandwidth by the network ($BW_n$), energy consumption of using network access device ($P_n$), and the service charge of the network ($C_n$). After that, it will forward all these information along with the data received from the previous stages to the game controller.

iv. Game-based Controller (GC): this module is based on a static score function *S*, which is a static-based function of the following parameters;

$$SC_n = f(BW_n, P_n, C_n) \tag{3-1}$$

Where, $SC_n$ is the static score function of network *n*. Normalization is needed to ensure that the sum of the values in different units is meaningful. Generally, if there are *k* factors to consider the score function, the score function of the interface *i* will be a sum of *k* weighted factors.

$$SC_i = \sum_{i=1}^{k} w_i(nf_i) \qquad 0 < SC_i < 1, \quad \sum_{i=1}^{k} w_i \tag{3-2}$$

In the equation, $w_i$ represent the weight of factor $j$ of interface $i$ defined according to user and/or application needs, and $nf_i$ is the normalized score value of factor $j$ for interface $i$. For our model;

$$SC_i = \; w_{bw} f_{bw,i} + w_c f_{c,i} + w_p f_{p,i} \tag{3-3}$$

Where $w_{bw}$, $w_c$, and $w_p$ are the weight factors for the offered bandwidth, service cost, and the power consumption by the network interface respectively, these parameters can be defined from the user or the application preferences. $nf_{bw,i}$, $nf_{c,i}$, and $nf_{p,i}$ are the normalized values of interface i's offered bandwidth, power consumption and service cost respectively. Whereas;

$$nf_{bw,i} = \frac{e^{\delta_i}}{e^{bw_i}} \qquad\qquad \delta_i \geq 0$$

$$nf_{c,i} = \frac{1}{e^{\frac{c_i}{\beta_i}}} \qquad\qquad \beta_i = \frac{1}{pk_i}\;, pk_i\ is\ the\ packets\ to\ be\ sent$$

$$nf_{p,i} = \frac{1}{e^{\frac{p_i}{\gamma_i}}} \qquad\qquad \gamma_i = \frac{1}{t_i}\;, t_i = time\ in\ hours \tag{3-4}$$

The coefficients $\delta_i$, $\beta_i$, and $\gamma_i$ are assumed to be greater than or equal to zero and less than one. The exponential functions have been used to increase the sensitivity of the functions to the respective parameters they are related to. Finally, they are inversed in order to bind the functions to a value between zero and one. It can be observed from these equations that high bandwidth value contributes proportionately to the $SC$ function, whereas cost and power consumption contribute inversely to $SC$. This is because, an interface having a better bandwidth is a better choice to the MN, while an interface costing more or a link consuming more power is a poor choice to the MN.

v. Hybrid Handover Decision: the final decision of selecting a particular network from the candidate list is the responsibility of this module. A dynamic score function is calculated in this phase for each network $i$ as below; $DS_i = S_i \times P_i$. Where $S_i$ is calculated by the GC module and $P_i$ is calculated in the ND module. The network with the highest value of $DS$ is selected as the best network to handoff to.

It is very important to mention that, the network selection process will depend on a size 20 First-In-First-Out (FIFO) list, as shown in Figure 3-3. The Model checks a maximum of 20 AP's at a time, and compares the new comers with the ones saved in the list, only if the preferred AP exist. Introducing such a list will reduce the chances of increasing the size of any temporary file, which might be used to save the details of any AP the MN visits. What's more, such list will reduce the chances of complexity in the introduced model, as it will make the computation process easier to the GC and improves the ability to get the preferred AP using our model. Any new comer is to be added to the top of the list and all entries after the 20th entry will be deleted, which will insure a better chance to the newcomers and never leave any old APs behind.

Finally, we can summarize the algorithm of the HVHM to four main phases: network discovery, network analysis, Game Controller and network selection and execution. The network discovery phase is used to remove all the unwanted and ineligible networks from the prospective candidate networks. This is done by adding all available networks into candidate list, scanning them and recording each network RSS. This will be followed by recording the speed of the MN and removing networks which do not satisfy cretin RSS and mobility. The network with higher RSS will be assigned with higher priority as compared to other networks in the list, and the list will be forwarded to the next phase. The network analysis phase is used to accommodate user-specific preferences, which is expressed in terms of weight factors, regarding the usage of network interfaces. First, current system status are collected from SM component and the weight factor determined, then these information to be collect from every wireless interface in the candidate list collected in the previous phase. Before continuing to the final phase, the game-based cost function is calculated for every network. Finally, the network selection and execution phase is used to select the "best" network and executing the handoff to the selected network.

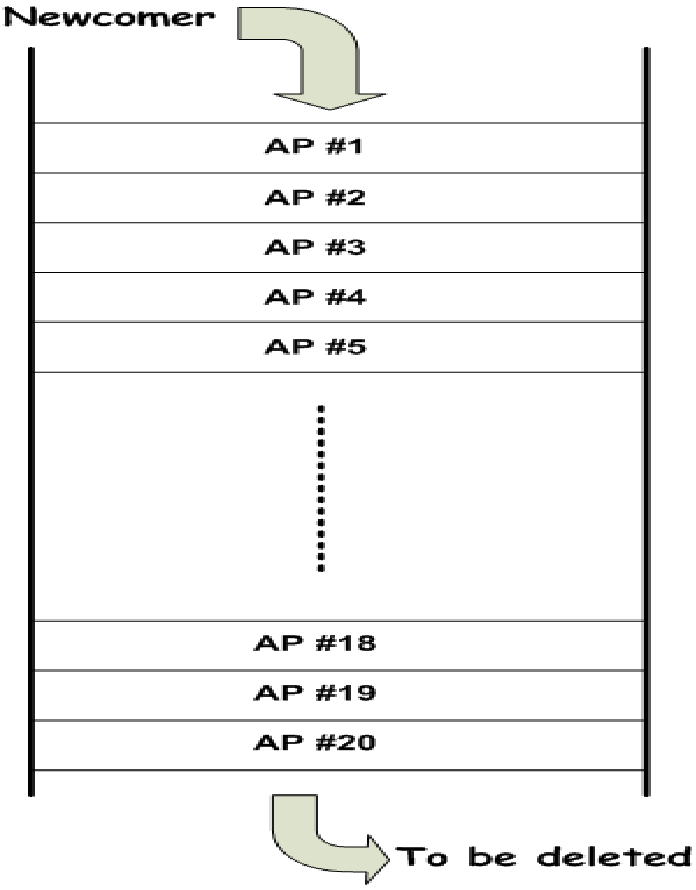


Figure 3-3: FIFO Access Points table.

## 3.5 Simulation Scenario

In order to evaluate the proposed HVHM, several application scenarios are written in MATLAB. A heterogeneous network systems where two cellular systems GPRS and UMTS and WLAN and Bluetooth form an overlay structure, as shown in Figure 3-4. A MN with four network interfaces can move around the shown structure through any network during simulation.

Throughout our scenarios, the MN can be in any of the regions shown in Figure 3-4, A, B, C, D, E or F and can access the networks according to their coverage area as follow;

1. Access to UMTS network only when the MN in region A.
2. Access both UMTS and GPRS networks when the MN in region B.
3. Access UMTS, GPRS and 802.11b networks when the MN in region C.
4. Access all networks when the MN in region D.
5. Access UMTS, GPRS and Bluetooth networks when the MN in region E.
6. Finally, access GPRS network only when the MN in region F.

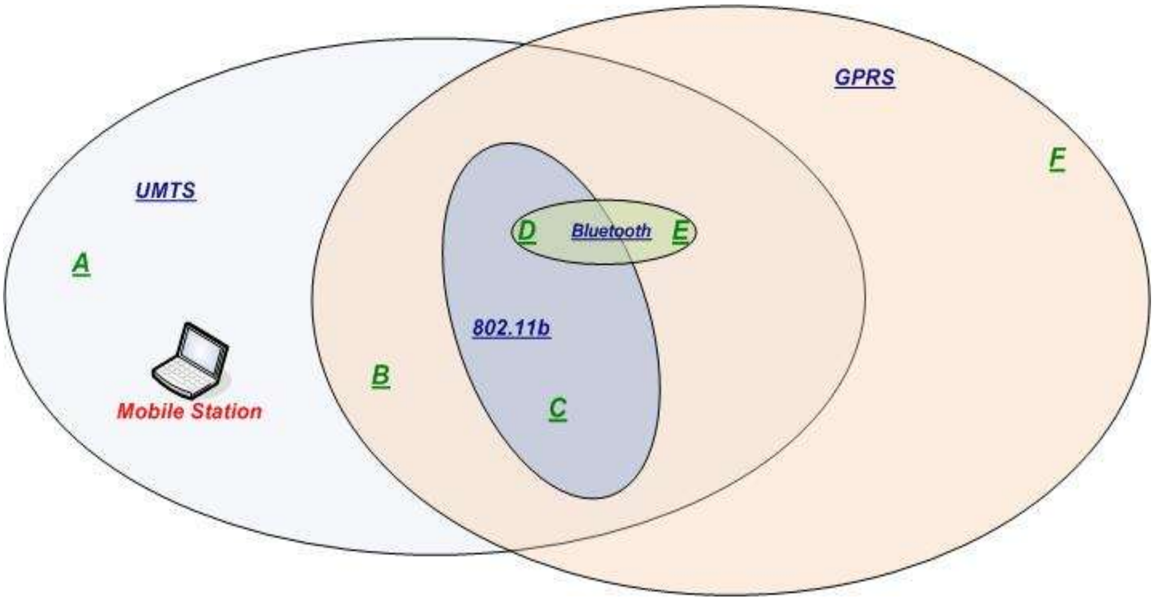


Figure 3-4: Simulation scenario.

The simulation results are based on different scenarios, the MN is assumed moving around all networks with different speed, different weight values of service cost, available bandwidth and energy consumption varies as well. The simulation start with 10000 packets transmitted with the assumed parameters shown in Table 3-2, where we assume that the battery life varied from one access technology to another [26]. Based on the fact that the MN will require more time to communicate using the Bluetooth interface as compared to other networks because of its low data rate, thus it will consume its power faster. The same assumption works for the rest, keeping in mind that this factor is based on the assumption that the whole MN (i.e. its interfaces and applications) uses the battery not only the interface to access different services.

The simulations are repeated for four models; standard VHO model (with two cases, one when the VHO decision model is based on static factors, and when the decision model is based on the dynamic factors) [16-17 and 28-29], UVSH [14] and our HVHM. The results are carried out for the number of handoffs in each scenario and the number of lost packets over the simulation time.

Table 3-2: Simulation Assumption.

| | ***UMTS*** | ***802.11b*** | ***Bluetooth*** | ***GPRS*** |
|---|---|---|---|---|
| ***Battery Consumption*** | 4 $hours$ | 3 $hours$ | 2 $hours$ | 3.5 $hours$ |
| ***Power to Transmit one bit*** | 300 $mW$ | 200 $mW$ | 140 $mW$ | 260 $mW$ |
| ***Power to Receive one bit*** | 300 $mW$ | 200 $mW$ | 140 $mW$ | 260 $mW$ |
| ***Service Cost*** | 0.8 $\pounds/min$ | $FREE$ | $FREE$ | 0.5 $\pounds/min$ |
| ***Bandwidth*** | 2 $Mbps$ | 5 $Mbps$ | 0.8 $Mbps$ | 150 $kbps$ |
| ***RSS Threshold*** | 130 $dBm$ | 60 $dBm$ | 20 $dBm$ | 120 $dBm$ |
| ***Mobility Threshold*** | 20 $m/sec$ | 10 $m/sec$ | 2 $m/sec$ | 16 $m/sec$ |
| ***Delay*** | 2 μ$sec$ | 11 μ$sec$ | 16 μ$sec$ | 4 μ$sec$ |

## 3.6 Simulation Results

The results presented in this section, are compared to highlight the advantages of using the proposed mechanism all the way through reducing the number of handoffs, end-to-end delay and number of packets lost/dropped during the simulation time. We assume that the MN always starts from the 802.11b coverage and moves around all coverage areas. Moreover, the weights of the factors mentioned in Table 3-2 are changed with different speeds for the MN (i.e. starting from 1 m/sec, 5 m/sec and 10 m/sec.). These results are to be compared with the USHA, introduced in [3] and two vertical handoff schemes, one using static factors to decide whether a handoff is needed or not and the other using dynamic factors only. The radius of each coverage area as follows; UMTS radius of 2600m, GPRS coverage radius of 1400m, 802.11b radius of 120m and Bluetooth coverage radius of 15m.

Firstly, it is assumed that both the power and service cost weights are equal and the bandwidth requirement is changing during the simulation time. Secondly, we set both the power and bandwidth weights to be equal and assume that the service cost needs are changing over simulation time. Finally, the bandwidth and service cost weights are set to be equal and the power weight is to be changed. Keeping in mind that the simulation results are examined based on three different speeds, as we mentioned earlier, and the simulation is tested over 10 minutes for each case. Results are shown in Figures 3-5, 3-6 and 3-7:

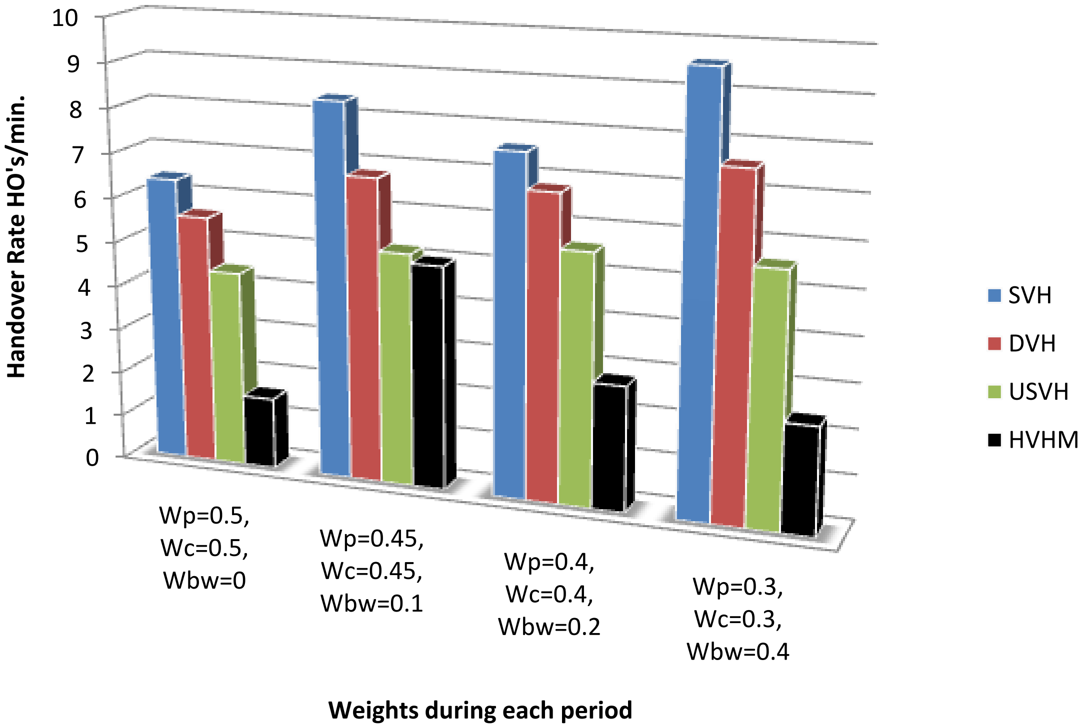


Figure 3-5: Handover rate, when Wc=Wp, MN's velocity=1m/sec.

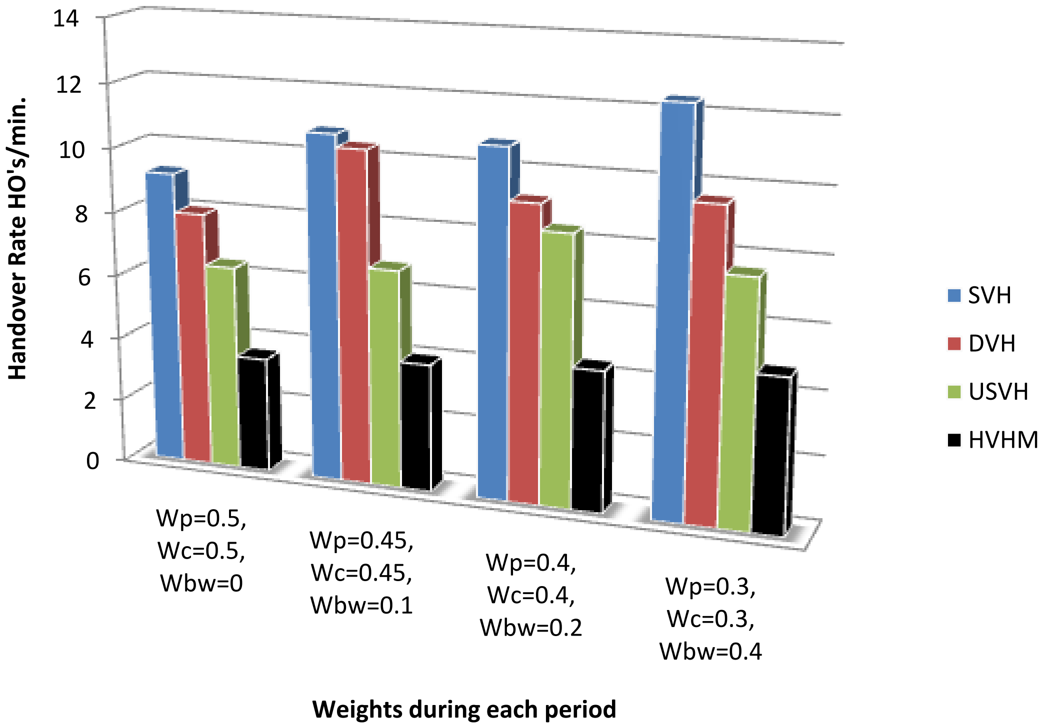


Figure 3-6: Handover rate, when Wc=Wp, MN's velocity=5m/sec.

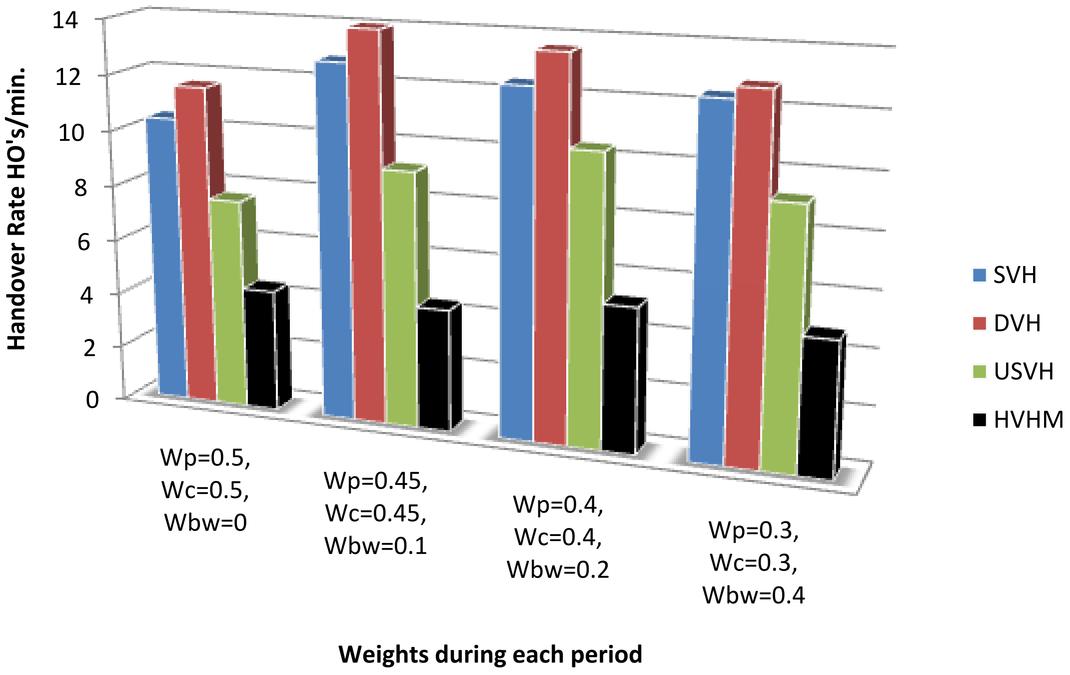


Figure 3-7: Handover rate, when Wc=Wp, MN's velocity=10m/sec.

From Figures 3-5, 3-6 and 3-7, we can see that the handover rates (i.e. number of handovers per minute during simulation time) increases as the velocity of the MN increases. However, using HVHM, the number of handoffs reduced to less than 50% in some cases. This is because we have introduced a decision model where the MN will decide whether a handoff is needed or not. Moreover, we can see that the number of handoffs increases as the weights of different factors increases, and as the number of factors taking into account increases as well. Interestingly, DVH mechanism shows a slight increase in the number of VHO's as compared to the SVH when the mobile speed goes up to 10 m/sec. This is due to the fact that the handover decision in the case of DVH is based on dynamic factors and the RSS from the around AP's plays a major role in deciding whether a handover is needed or not. When the MN moves in a fast speed, the probability of handing over to the surrounding AP's will increase thus increasing the chance of facing the ping-pong effect.

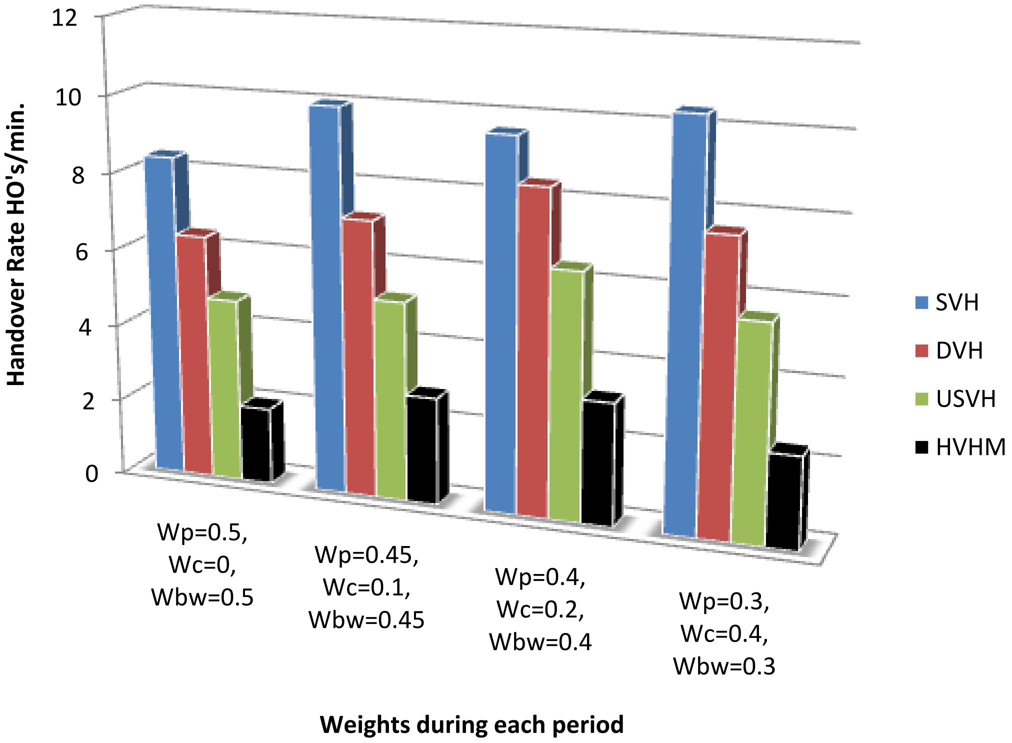


Figure 3-8: Handover rate, when Wbw=Wp, MN's velocity=1m/sec.

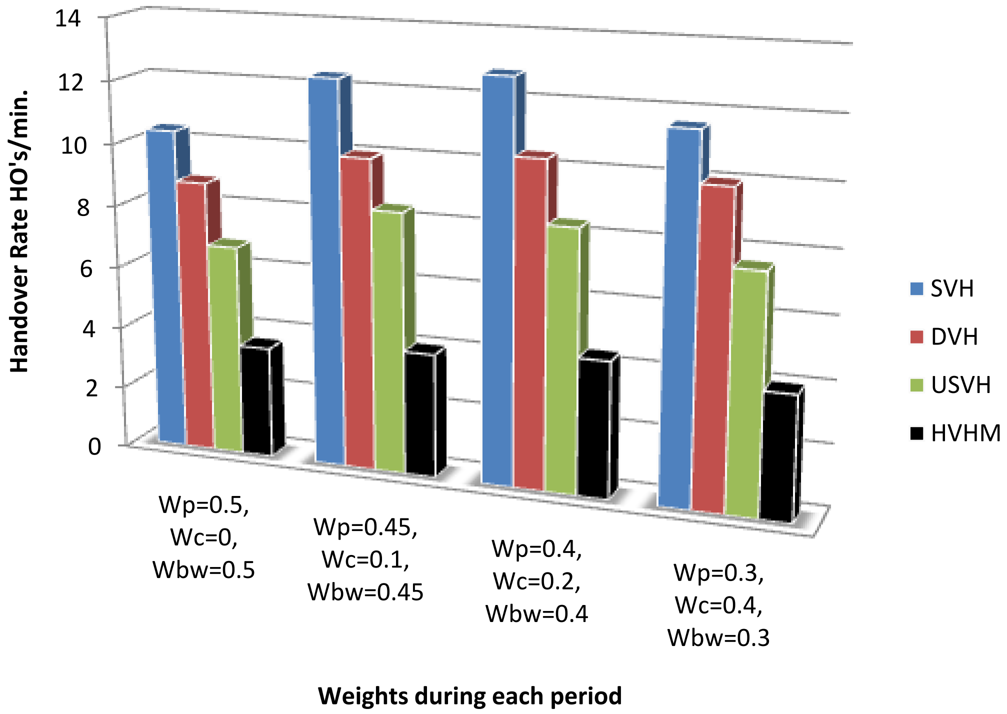


Figure 3-9: Handover rate, when Wbw=Wp, MN's velocity=5m/sec.

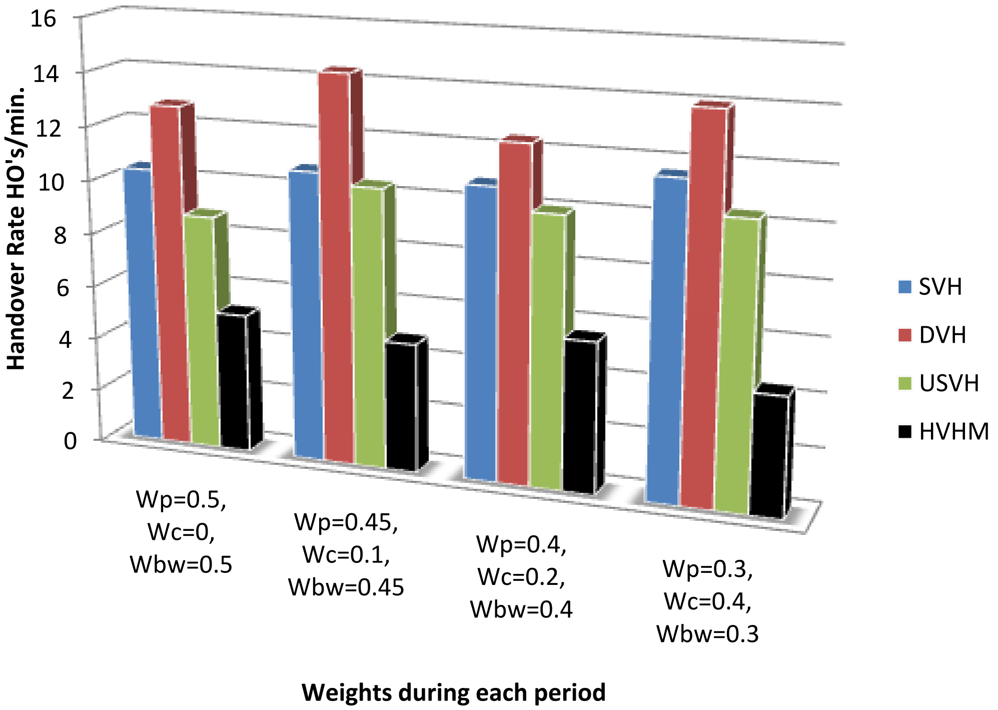


Figure 3-10: Handover rate, when Wbw=Wp, MN's velocity=10m/sec.

Once again, looking to Figures 3-8, 3-9 and 3-10, we can see very clearly that the handoffs rate increases as the speed of the MN increases and once the number of factors increases. It can be seen that there is a slight increase in the number of VHO's compared to the previous scenario as the MN will be much interested in handing over to an AP which offers a better bandwidth and it will not be worried about the service costs at some points. Again, our HVHM provide a massive reduction in the number of handoffs as compared to the other models for the same reasons mentioned earlier.

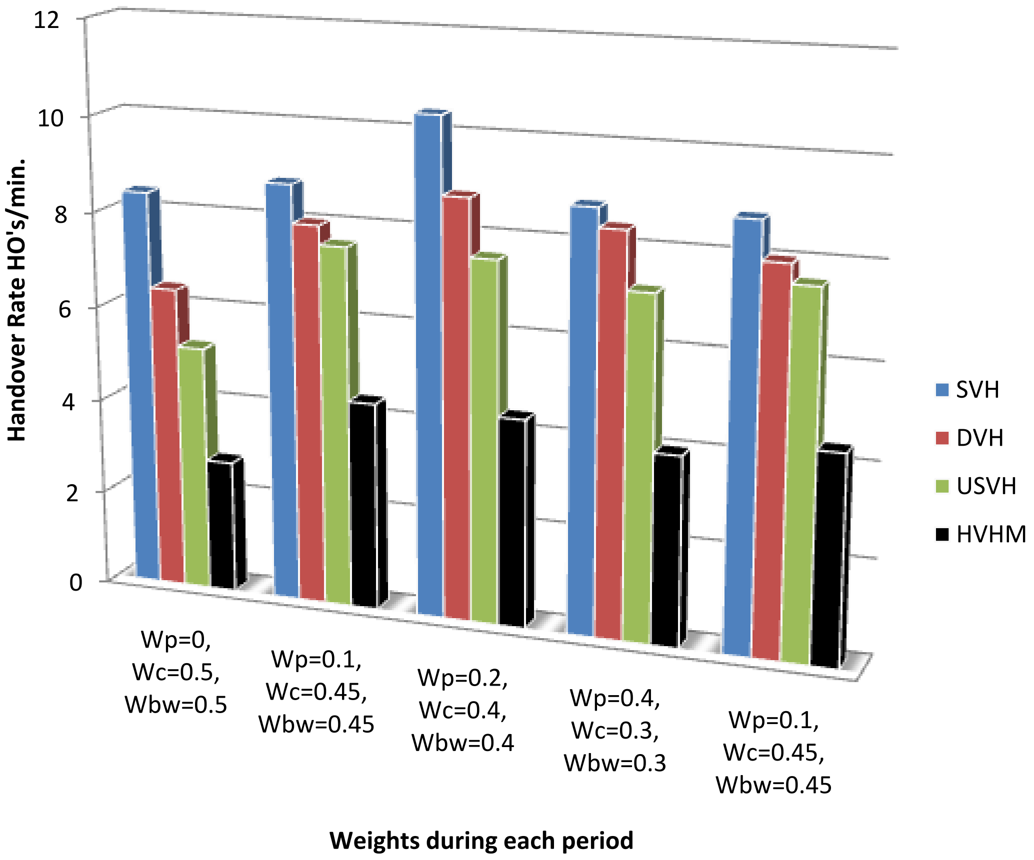


Figure 3-11: Handover rate, when Wbw=Wc, MN's velocity=1m/sec.

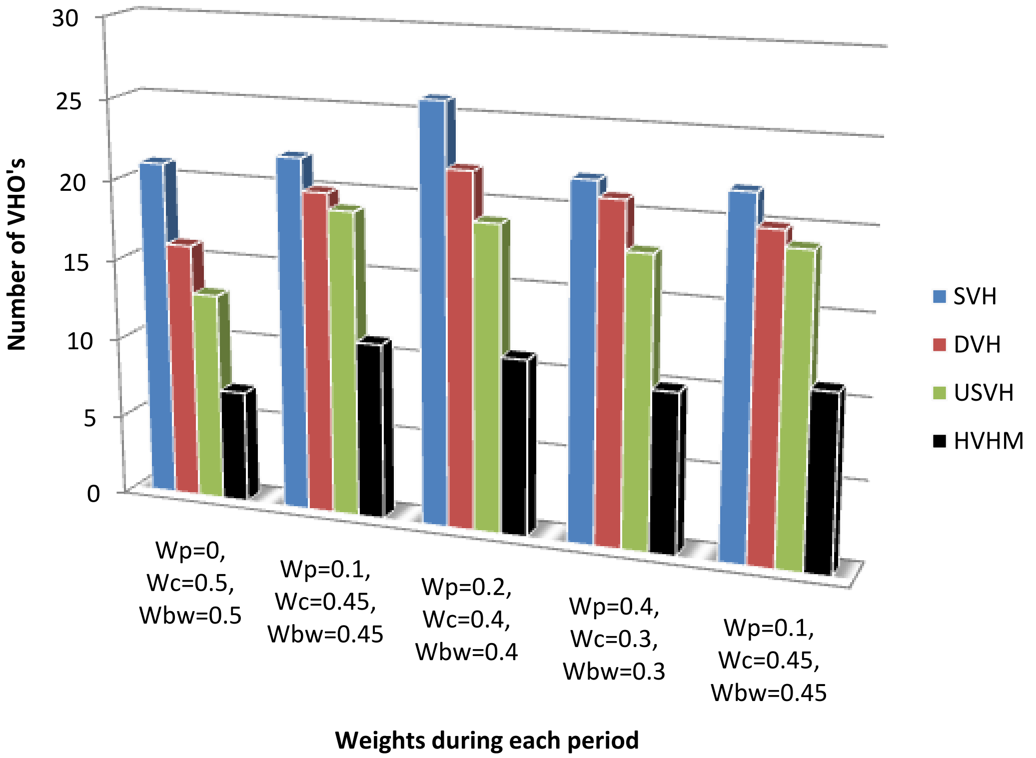


Figure 3-12: Number of handoffs when Wbw=Wc, MN's velocity=1m/sec.

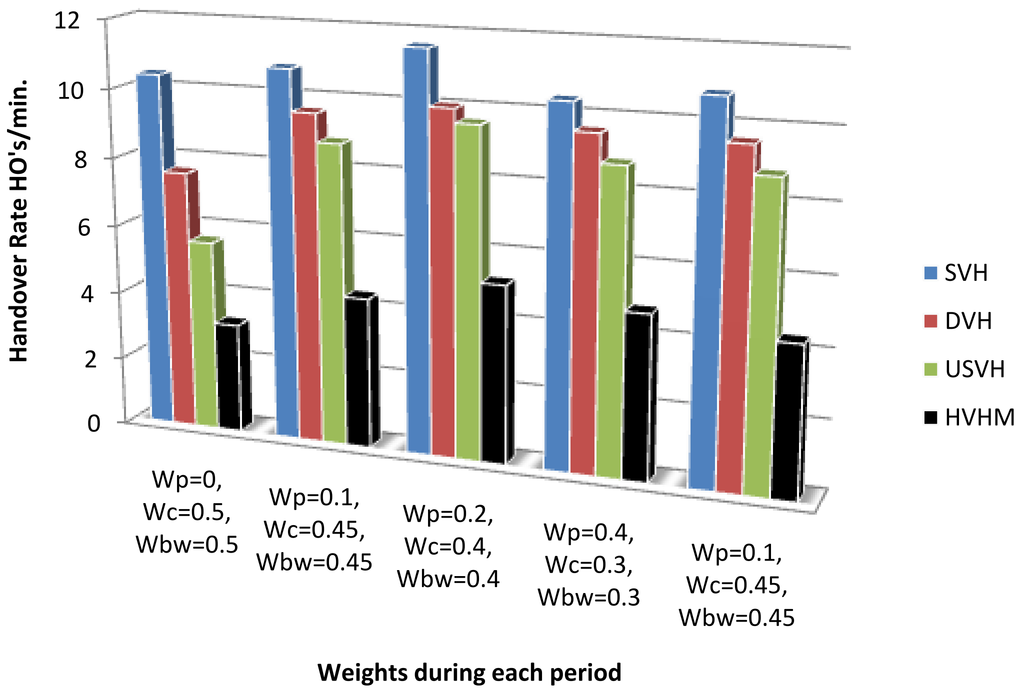


Figure 3-13: Handover rate, when Wbw=Wc, MN's velocity=5m/sec.

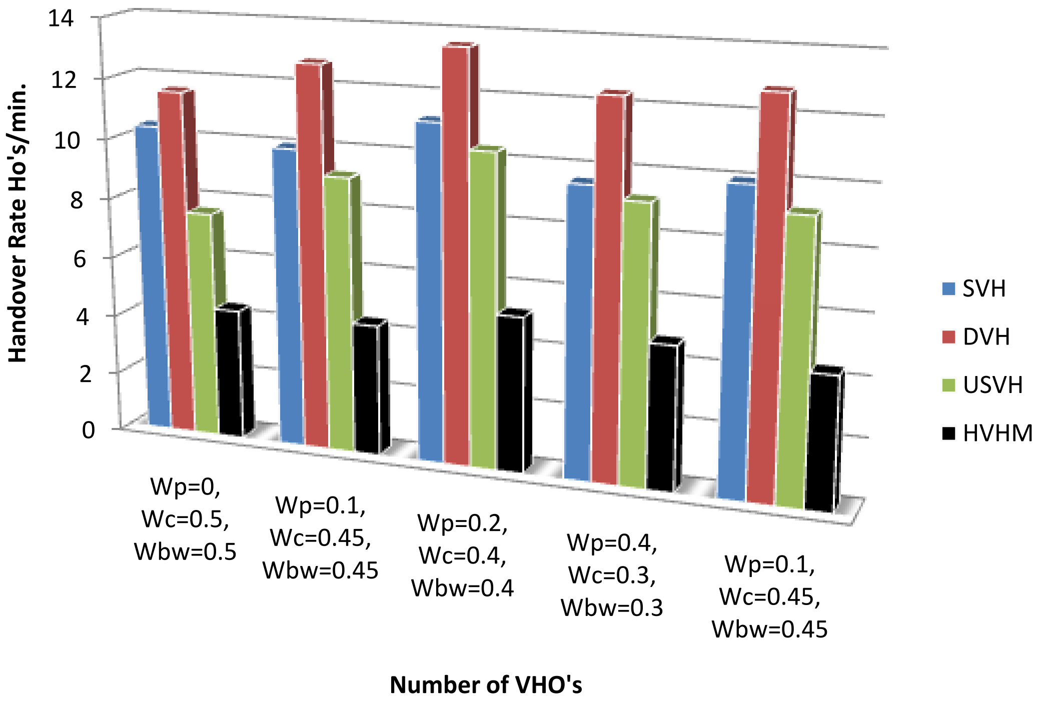


Figure 3-14: Handover rate, when Wbw=Wc, MN's velocity=10m/sec.

Finally, using different settings over the same scenario, Figures 3-11, 3-12 and 3-13, shows how the HVHM managed to reduce the handoffs rate to less than half as compared to the other mechanisms. Although, if for instance a VHO occurred the MN needs to divert the traffic to another interface through another AP using different technology, which might lead to undesirable amount of delay, packet loss and interrupt real time application. VHO's are still needed to maintain ongoing communications for the MN. Once the number of unnecessary VHO's has been reduced, for sure we will reduce the overall delay the node will face to deliver/receive a certain packet to/from the destination. Moreover, this will achieve more successfully delivered/received packets (i.e. reduce the packet loss factor and the number of retransmissions) and improve real-time negotiation matter. The following figures prove this point, Figure 3-14 shows the overall end-to-end delay when we applied the same statistics with the four VHO's mechanisms mentioned earlier to our scenario. The end-to-end delay is the time needed for a packet to be transmitted from the source to the destination over the network. The result shows how the delay increases as the speed of the MN increases obviously because the number of VHO's increase. However, HVHM shows more than 50% improvements as compared to the rest of the mechanisms. DVH mechanism shows better results as compared to the SVH, however, when the MN velocity increases the number of handovers increases as the handoff decision is based on RSS values received from the AP's which would increase the unnecessary handoffs. Finally, our HVHM shows the minimum end-to-end delay as compared to the other mechanisms, because of its ability to use both static and dynamic factors in order to decide whether a handoff is needed or not and to chose the right AP if the handoff is needed.

Finally, Figure 3-15 shows the rate of lost packets during the simulation time. Similarly, the number of packets lost over the simulation time increases as the number of HO's increase, which considered as one of the major reasons behind the lost of transmitted/received packets and number of retransmissions during communication time. For the same reasons discussed in previous sections, HVHM shows much better results as compared to other mechanisms, which will improve the overall communication experience of the MN over the entire simulation time. Furthermore, DVH mechanism shows better results as compared to SVH when the MN speed is low and the opposite is true when the velocity of the node increases.

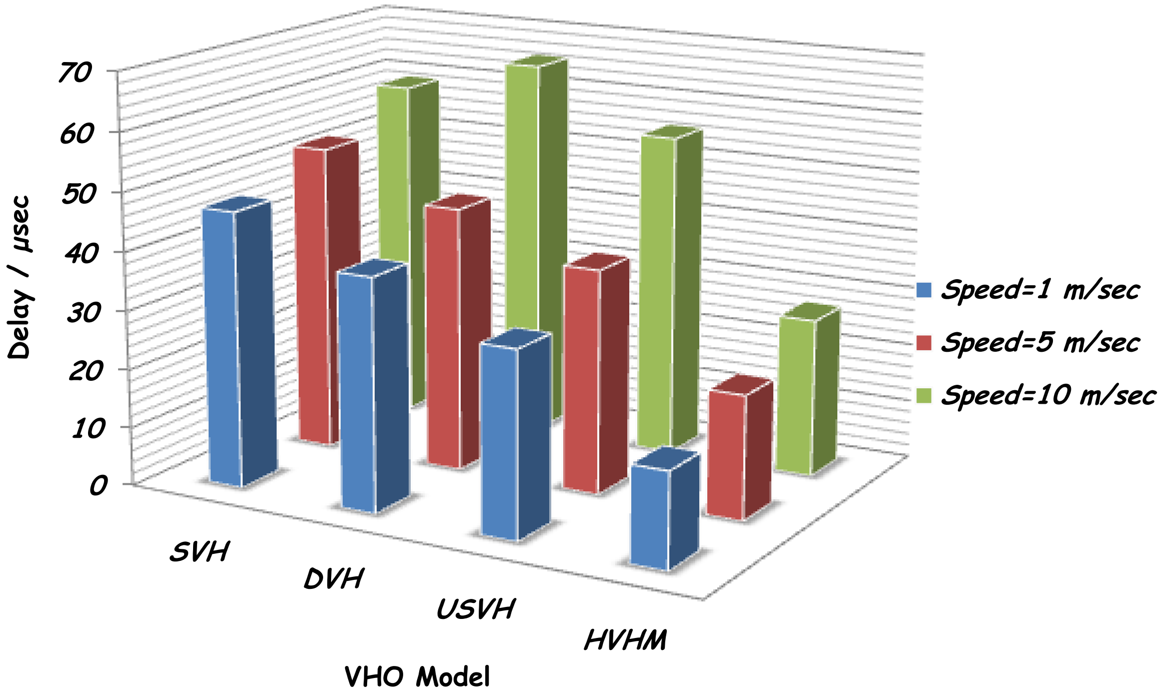


Figure 3-15: Overall delay when using different VHO mechanisms.

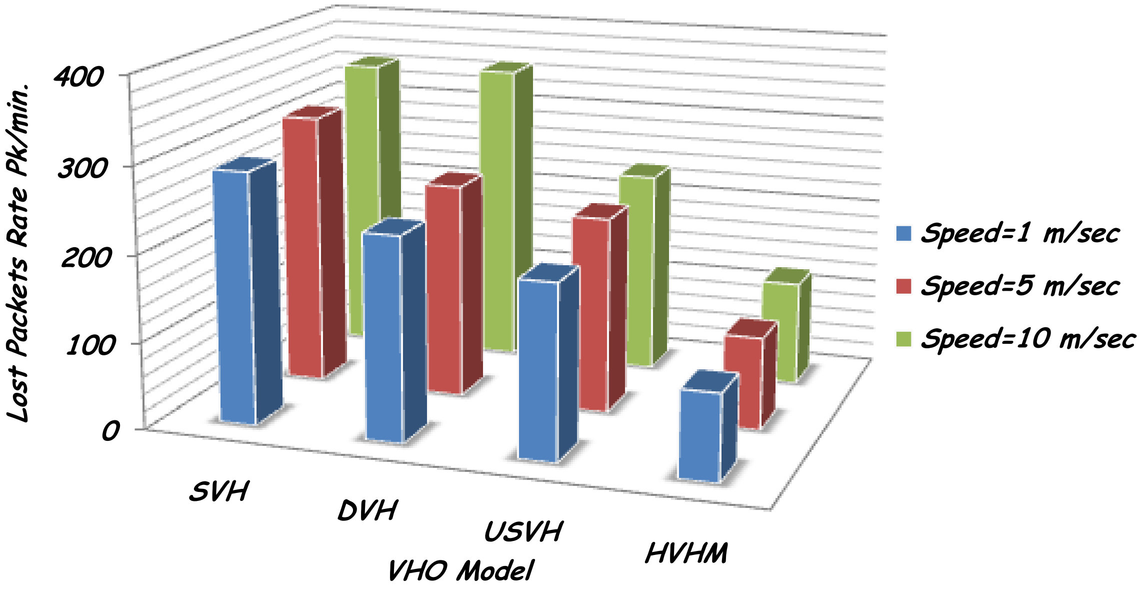


Figure 3-16: Rate of lost packets over different VHO mechanisms.

To sum up this section, the HVHM presented in the previous sections adapts three phases approach to improve the MN VHO's experience during the communication time, this approach consist of the priority phase, the normal phase and the decision phase. The discovery of all available networks, filtering out illegible APs based on RSS and MN's speed and assign priorities to these APs is done within the priority phase. The differences between the RSS and RssT and the MN speed measures the priority of each AP, the more the difference the higher the priority. The normal phase checks the user and the application needs to record the static factors (i.e. offered bandwidth, power consumption and service cost) of each AP. Finally, calculating the score function based on the weights from the previous phase is done within the decision phase to choose the right access point. The results show how this model managed to reduce the number of VHO's and the end-to-end delay and the overall number of lost packets during the simulation time.

## 3.7 Power Consumption in Multihomed Wireless Portable Nodes

So far, the VHO problem has been discussed in multihomed mobile devices. However, we must mention another drawback of such devices that is all its wireless interfaces are kept 'ON' over the entire communication time. This will consume a huge amount of its battery life, keeping in mind that the majority of mobile wireless devices depend on its battery to keep itself going. Each interface consumes cretin amount of energy for transmitting or receiving packets from the AP, as shown in Table 3-2, which depends on the technology the interface is operating on [26]. In order to solve such a problem, we present our Green Hybrid Vertical Handover Model (GHVHM). In this model the MN's interfaces will be turned 'ON' only to check if there is a chance to switch to a better AP when the HO is needed. Figure 3-16 below shows these two decision points defined in our design.

Traditionally, the HO mechanism initiated when the RSS value goes beyond a threshold value (i.e. RssT). However, since we have multiple interfaces, we defined another point (i.e. RssONT), which will be used by a controller as a trigger point for the other interfaces (different values of this point have been used and they all lead to similar results).

The mechanism works as follows; once the MN starts looking for a connection all the interfaces are turned 'ON'.

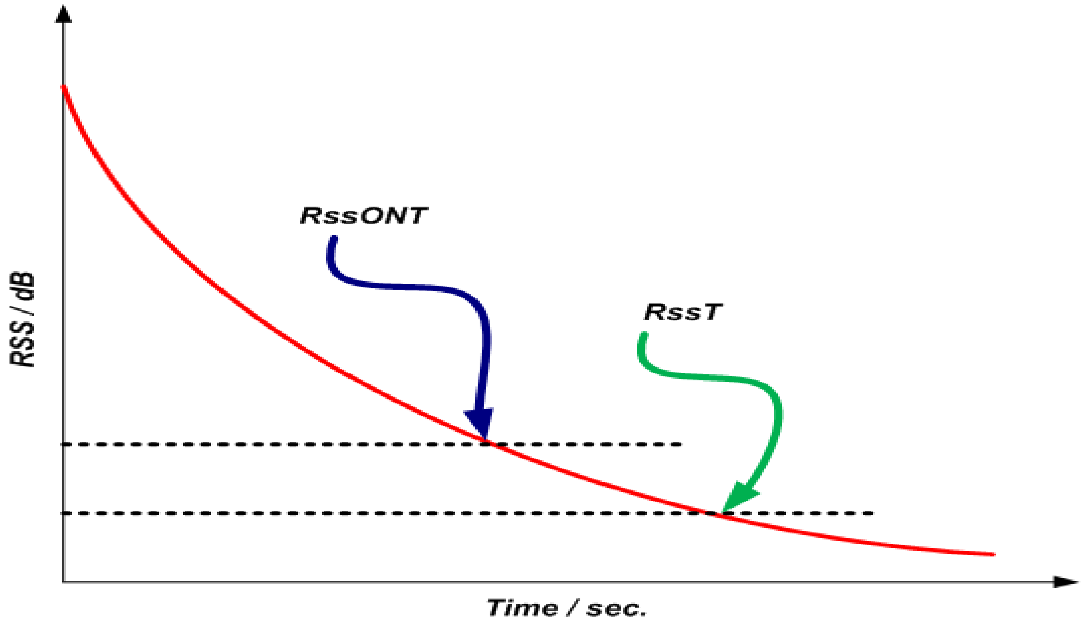


Figure 3-17: HO decision points.

The cost function defines the 'winner' AP, the communications start and the rest of the interfaces switched 'OFF'. Once the RSS value reached the RssONT point, the game controller will turn the rest of the interfaces and the cost function will work again, a new 'winner' will be defined and the HO mechanism will be executed once the RSS goes below the RssT point and the rest of the interfaces will turned 'OFF' again. One drawback of this mechanism is that, while only one interface is 'ON' and the rest are 'OFF', the MN might move across a better coverage in terms of QoS and the MN will not receive any advertisement from that AP as its compatible interface is switched 'OFF'. However, keeping in mind that the introduced mechanism will keep ongoing communication with acceptable QoS achieved from the current AP and save a considerable amount of energy during the communication time, this mechanism can be considered as a great success. Figure 3-17 below shows the mechanism works.

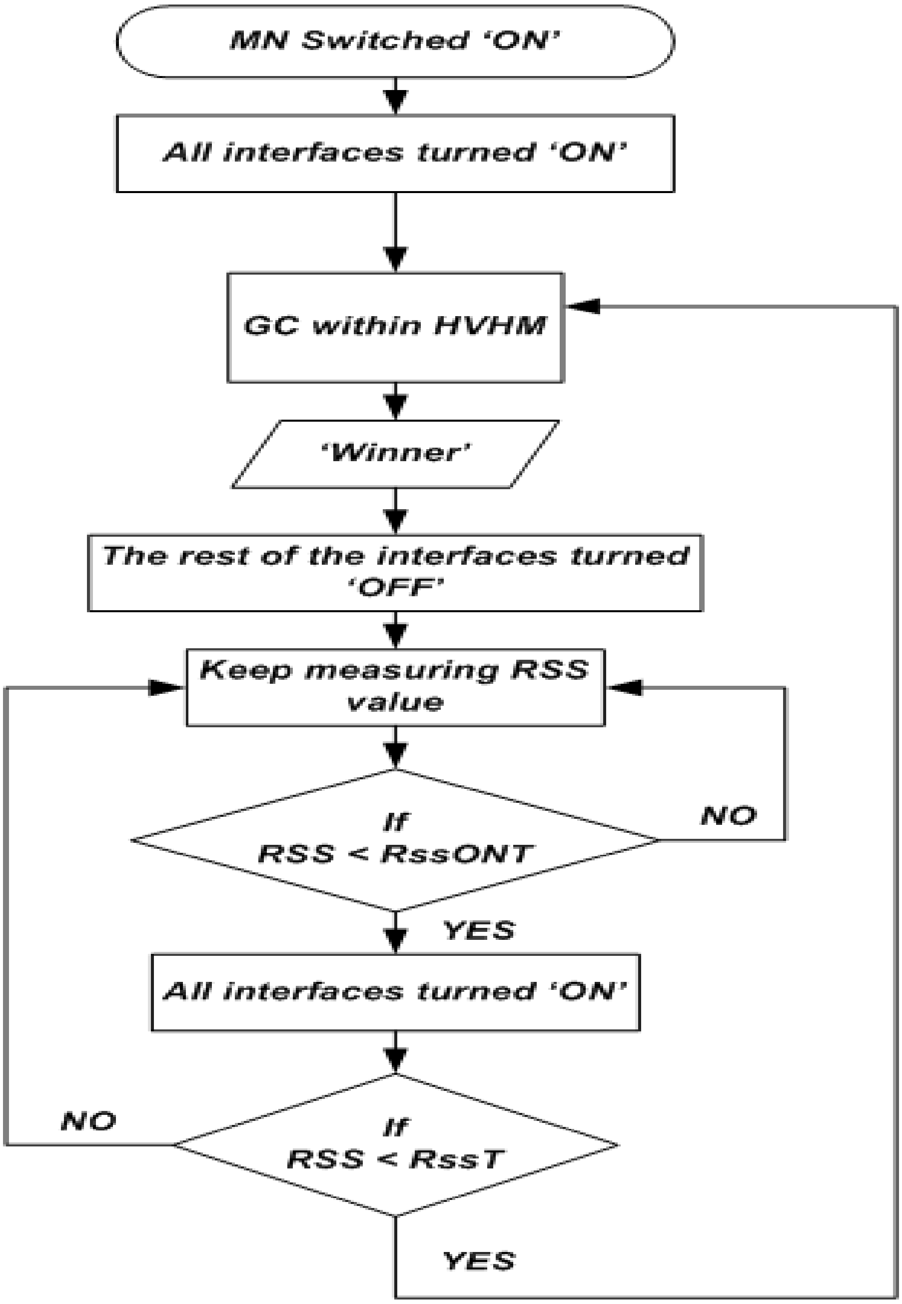


Figure 3-18: Structure of GHVHM mechanism.

In order to test this mechanism, we assumed that the MN has a 15000 Joule of energy in its battery and we repeated the previous scenario with the same HO mechanisms in order to measure the reaming energy in the MN after 24 minutes of communication time. We only take into account the power consumed by the MN interfaces, we did not take into consideration the amount of power consumed by the MN applications. The mechanisms will be compared over three different speeds (i.e. 1 m/sec, 5 m/sec and 10 m/sec) and the static factors weights are assumed to be as the following; $W_p = W_c = 0.35$ and $W_b$=0.3.

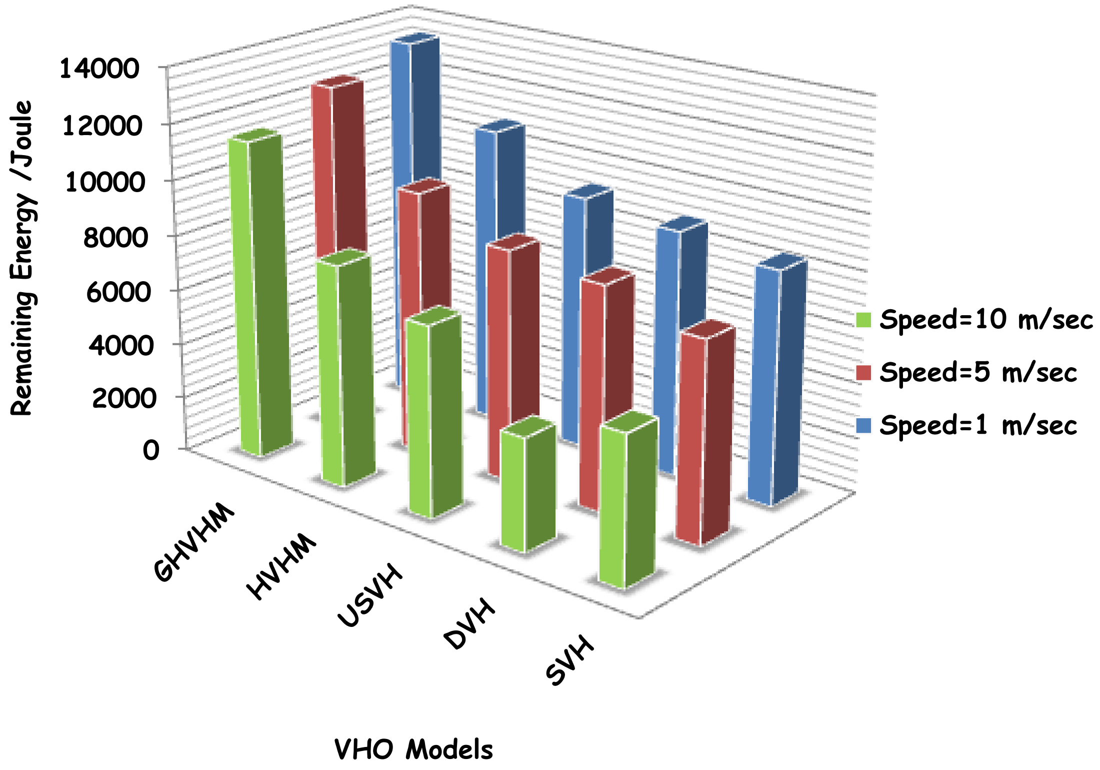


Figure 3-19: Power consumption using different VHO mechanism.

From Figure 3-19, we can easily recognize the massive amount of power saved by GHVHM as compared to the other mechanisms. This is simply because we managed to merge the advantages of both HVHM in the GHVHM reducing the number of unnecessary handoffs and choosing the AP that gives the best QoS at the right time. Moreover, forcing the interfaces that are not engaged in any communication to be switched 'OFF' until a handoff is needed. The MN will face a similar problem, as in the previous section, when MN's speed increases, the number of handovers increases as well, which means that the interfaces will be turned 'ON' more often and more energy to be consumed. However, since our GHVHM mechanism manages to reduce the number of handoffs to more than 50% as compared to the rest, the amount of power saved when the MN velocity is 10 m/sec is more than double the amount saved using other mechanisms. The DVH mechanism shows the worst results in terms of saving energy when the MN velocity reaches 10 m/sec, this is due to the same reasons explained earlier where the MN will face repeated HO's because the number of advertisements received from the around APs will increase while the node is crossing several coverage areas.

## 3.8 Summary

Throughout this chapter, Green Game-Based Hybrid Vertical Handover Model for heterogeneous wireless networks is proposed and explained in details. This model works as a game-based extension to the Hybrid Vertical Handover Model, which combines both dynamic and static factors to decide when a handover is needed. The model aims to reduce the number of unnecessary handovers and reduce the energy consumed from the mobile node's battery. A game theory-based decision model is introduced, which controls the handover decision process and insures that the mobile node will choose the right access point at the right time. A simulation-based comparison is made between different vertical handover models to show the advantages of the proposed model over other models.

The proposed model shows a novel advantage over previously introduced models by reducing the node power consumption. The model combines both static and dynamic factor in the handoff management process rather than using other works when authors used static factors only [7-10] or dynamic factors only [11, 13, 27-28], or using a server-based applications in order to deal with the scenario as a seamless handoff [14].

## 3.9 References

[1] D. Johnson and C. Perkins, "Mobility Support in IPv6", IETF draft, <draft-ietf-mobileip-ipv6-15.txt>, July 2001. Available online at: http://tools.ietf.org/wg/mobileip/draft-ietf-mobileip-ipv6/draft-ietf-mobileip-ipv6-16-from-15.wdiff.html [Accessd 22nd November 2007].

[2] D. Johanson, C. Perkins and J. Arkko, "Mobility Support in IPv6", June 2004. Available online at: http://www.ietf.org/rfc/rfc3775.txt [Accessed 22nd November 2007].

[3] A.S. Reaz, P.K. Chowdhury, M. Atiquzzaman and W. lvancic, "Signalling Cost Analysis of SINEMO: Seamless EndtoEnd Network Mobility", pp. 37-42, 2004.

[4] N. Montavont and T. Noël, "Handover Management for Mobile Nodes in IPv6 Networks", IEEE Communications Magazine, pp. 38-43, August 2002.

[5] V. Devarpalli, R. Wakikawa, A. Petrescu and P. Thubert, "Network Mobility (NEMO) Basic Support Protocol", RFC 3963. January 2005. Available online at: http://www.ietf.org/rfc/rfc3963.txt [accessed Augest 2007].

[6] M. Inoue, K. Mahmud, H. Murakami, and M. Hasegawa, "MIRAI: a solution to seamless access in heterogeneous wireless networks", in Proceeding IEEE ICC 2003, pp. 1033-1037, May 2003.

[7] J. Ylitalo, T. Jokikyyny, T. Kauppinen, A. Tuominen, and J. Laine, "Dynamic Network Interface Selection in Multihomed Mobile Hosts", IEEE Computer Society, proceedings of the 36th Hawaii International Conference on System Sciences (HICSS'03), Jan. 2003.

[8] M. Stemm, and R.H. Katz, "Vertical Handoffs in Wireless Overlay Networks", ACM MONET, 1998.

[9] J. Makela, M. Ylianttila, and K. Pahlavan, "Handoff Decision in Multi-Service Networks", IEEE PIMRC, pp. 655-659, September 2000.

[10] A. Hzahran, B. Liang, and A. Saleh, "Application Signal Threshold Adaptation for Vertica handoff in heterogeneous wireless networks", Mobile Network Application, Springer science, Vol 3462/2005, pp 1193-1205, 2005.

[11] J. McNair, and F. Zhu, ”Vertical Handoffs in Fourth-Generation Multinetwork Environments”, IEEE Wireless Communications, pp. 8-15, June 2004.

[12] H. Wang, R. Katz, and J. Giese, “Policy-enabled Handoffs Across Heterogeneous Wireless Networks”, Proceedings of Second IEEE Workshop on Mobile Computing Systems and Applications (WMCSA ’99), pp. 51-60, Feb. 1999.

[13] L.Y. Chen, T. Sun, B. Chen, V. Rajendran and M. Gerla, “A Smart Decision Model for Vertical Handoff”, The fourth ANWIRE International Workshop on Wireless Internet and Re-configurability, Athens, Greece 2004.

[14] L.J. Chen, T. Sun and M. Gerla, ”USHA: Simple and Practical Seamless Vertical Handoff Solution”, IEEE CCNC, 2006.

[15] A. Hasswa, N. Nasser, and H. Hossanen, **“**Generic Vertical Handoff Decision Function for Heterogeneous Wireless”, Second IFIP International Conference on Wireless and Optical Communications Networks, WOCN2005, 2005.

[16] W. Shen, and Q. Zeng, “A Novel Decision Strategy of Vertical Handoff in Overlay Wireless Networks”, Fifth IEEE International Symposium on Network Computing and Applications, 2006.

[17] Q. Song, and A. Jamalipour, “A Time-Adaptive Vertical Handoff Decision Scheme in Wireless Overlay Networks”, IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications, 2006.

[18] M. Liu, Z. Li, X. Guo, and H. Lach, **“**Design and Evaluation of Vertical Handoff Decision Algorithm in Heterogeneous Wireless Networks”, 14th IEEE International Conference on Networks, ICON '06. vol. 2, Sept. 2006.

[19] S. Navarro, and V.W.S. Wong, “A Vertical Handoff Decision Algorithm for Heterogeneous Wireless Networks”, IEEE Wireless Communications and Networking Conference, WCNC, 2007.

[20] R. Tawil, O. Salazar, G. Pujolle, and J. Demerjian,“ A Decision Scheme for Vertical Handoff in Overlay Wireless Networks”, The fourth International Conference on Innovations in Information Technology, Innovations '07, Nov.2007.

[21] S.Z. Ahmad, M.S. Akbar, and M.A Qadir, “A Cross-Layer Vertical Handover Decision Model for Heterogeneous Wireless Networks”, The fourth International Conference on Innovations in Information Technology, 2007. Innovations'07, pp. 441-445, Nov. 2007.

[22] H. Zhu, and K.S. Kwak, "An Adaptive Hard Handoff Algorithm for Mobile Cellular Communication Systems", ETRI Journal, vol. 28, no. 5, pp. 676-679, Oct. 2006

[23] N. Benvenuto, and F. Santucci, "A least squares path-loss estimation approach to handover algorithms", IEEE Transactions on Vehicular Technology, pp. 437-447, March 1999.

[24] N. Benvenuto, and F. Santucci, "A Generalized Least Squares Handover Algorithm for Wireless Systems", IEEE VTC2002-Fall, pp. 1570-1574, Sept. 2002.

[25] A.B. MacKenzie and L.A. DaSilva, "Game Theory for Wireless Engineering", Morgan&Claypool Publishers, 1st edition, 2006.

[26] G. Shor, "How Bluetooth, UWB, and 802.11 Stack Up on Power Consumption", April 15 2008, Power Management Design Line. Available online at: http://www.powermanagementdesignline.com/howto/207200948;jsessionid=P0S0O3OXNFAIPQE1GHOSKHWATMY32JVN?pgno=1 [Accessed 1st March 2010].

[27] A. Dvir, R. Giladi, I Kitroser and M. Segal, "Efficient Decision Handoff Mechanism for Heterogeneous Networks", International Journal of Wireless & Mobile Networks (IJWMN), vol.2, no. 1, February 2010.

[28] P. Goyal and S. Saxena, "A Dynamic Decision Model for Vertical Handoffs Across Heterogeneous Wireless Networks", World Academy of Science, Engineering and Technology 41, pp. 676-681, 2008.

[29] J. Kang, H. Ju, and J. Hong, "Towards Autonomic Handover Decision Management in 4G Networks", Lecture Notes in Computer Science, Springer Berlin / Heidelberg, vol. 4267/2006, pp.145-157, 2006.

[30] K. Mittal, E. Belding, and S. Suri, "A Game-Theoretic Analysis of Wireless Access Point Selection by Mobile Users", Computer Communications, vol. 31, Iss. 10, pp. 2049-2062, June 2008.

# CHAPTER 4

# *Design of a Green Game-Based Multi-Interface Fast-Handover Mobile IPv6 Protocol*

## 4.1 Introduction

In recent years, we have seen an increasing demand from end-users to access network resources from anywhere and at anytime from all kinds of devices. Mobile computing has become an important area of computer networking and is expected to play a fundamental role in the ubiquitous access of Internet resources in the future. A greater degree of connectivity is almost becoming mandatory in today's business world. In addition, mobility of end-users is placing further requirements on network systems and protocols to provide uninterrupted services.

Mobile IP is an open standard, defined by the Internet Engineering Task Force (IETF) RFC 2002 that allows users to keep the same IP address, stay connected, and maintain ongoing communications while roaming between IP networks. Mobile IP is scalable for the Internet because it is based on IP—any media that can support IP can support Mobile IP [1]. Roaming is a general term in Wireless Communications that means the ability of MN to extend connectivity in a location that is different from its home location where the service was registered. Mobile IP provides efficient, scalable mechanisms for roaming within the internet [2-3]. Moreover, the use of Mobile IP, allow MN's to randomly change their point of attachment and maintain ongoing communication with their destinations without changing their IP addresses.

Mobile network protocols such as Mobile IPv4 have emerged as one of the promising solutions capable of providing uninterrupted connectivity. It allows the users to travel beyond their home network while still maintain their own home IP address. Similarly, Mobile IPv6 is the protocol that deals with the mobility for the IPv6 nodes. This protocol allows an IPv6 node to be mobile, and randomly change its location on the IPv6 Internet while still maintaining its existing connections [3]. The following sections include brief definitions of some of the most important terms used within this chapter.

## 4.2 Mobile IPv4 and Mobile IPv6

### 4.2.1 Care-of-Address

In brief, Mobile IP works as follows; each MN can have tow addresses home address and a Care of Address (CoA), where the Care of Address is required by the MNs when it moves away from its home networking and getting a service from a new network known as the Foreign Network. Each MN can acquire this address in two ways:

a) FACoA (Foreign Agent CoA): which is the case where each MNs in the Foreign Network will have the same IP address provided by the Foreign Agent.
b) Collocated CoA: In this case, each MN will have its own IP address provided by the Foreign Agent.

### 4.2.2 Mobility Support in MIPv6

Mobility support in IPv6 is particularly important, as mobile computers are likely to account for a majority or at least a substantial fraction of the population of the Internet during the lifetime of IPv6 [4]. In fact, Mobile IPv6 allows MNs to move away from its home network without the need of changing their Home Address. Packets and data may be routed to the MN using its address regardless of the current location of the MN. Moreover, the MN may also continue to communicate with other nodes (Mobile or Stationary) after moving to the new link.

The Mobile IPv6 is just as suitable for mobility across heterogeneous media as suitable for mobility across homogeneous media [5]. For example, in the case of a MN running IPv6 protocol will keep the same communicate capability while it moves from Ethernet segment to another Ethernet segment or the case where the MN moves from Ethernet segment to a wireless local area network (WLAN) cell. In both cases, the MN IP address will remain the same.

### 4.2.3 Packet Forwarding

As mentioned above, each MN will have two addresses. The home address, which is visible to all the users and the other one, is the care-of-address, which is known only by the home agent. Where the care-of-address is a temporary address assigned to the MN, and any user or their applications do not know it. Both, Mobile IPv4 and Mobile IPv6 share the same ideas, but their implementations are somewhat different [6]. In the case of Mobile IPv4, the foreign agent is responsible for assigning a care-of-address to the MN dynamically, and forwarding the packets to it. All the packets destined to the MN will be encapsulated and tunnelled by the home agent and sent to the foreign agent. The foreign agent then de-capsulate the packets and send them to the MN. On the other hand, the Mobile IPv6 data delivery works in a similar way as Mobile IPv4 delivery, but if the Correspondent node is Mobile IPv6 compatible, then the data packets are sent directly to the MN's location on the IPv6 network. Moreover, if the correspondent node is not Mobile IPv6 compatible, data packets are sent to the MN's home address. The home agent then intercepts the data packets and tunnels them using IPv6-over-IPv6 tunnelling to the MN's care-of address. The data packets include a new routing extension header that contains the MN's home address.

### 4.2.4 Movement Detection in MIPv4

In the case of mobile IPv4, detection the movement of MNs is fundamental issue. If the MN does not act on moving, its connection to the Internet may be lost at any time. Furthermore, may the MN find itself in range of more than one access point, which means that, it must decide which one to connect with? The MN may choose to register with more than one foreign agent simultaneously, but that is not a very effective approach [7].

As a result, MNs need to make sure that they have moved from one foreign agent to another. The Mobile IP standard [8] specifies three such algorithms, lazy cell switching, eager cell switching, and prefix matching. In all three of these cases, a MN must hear a router advertisement from the new foreign agent before considering changing foreign agents [7].

#### 4.2.4.1 Lazy Cell Switching

Using lazy cell switching the MN waits until the lifetime of its registration with the current foreign agent expires and then tries to reregister or discover a new foreign agent to register with [6]. In general, each router advertisement includes a lifetime, the duration of a routing advertisement. With lazy cell switching, a MN will never switch its foreign agents unless it does not hear another router advertisement from the agent to which it is connected within that agent's last router advertisement lifetime. This does not prevent the MN from listening to other agents' advertisements. Indeed, a MN may immediately register with another agent once its previous agent's advertisement expires. Generally speaking, the lifetime is at least three times the interval between router advertisements. This means that a MN may remain disconnected for as long as 40 or more seconds before re-registering with another agent. Clearly, this is not ideal for rapidly moving nodes. However, for slow moving nodes, it does provide stability [9].

#### 4.2.4.2 Prefix Matching

Using prefix matching the MN analyzes the network prefix in the agent advertisements that it receives. In case the network prefixes changes, the MN determines that it has changed its network and tries to discover a new agent or obtain a new collocated address [6]. This algorithm uses routing advertisements, which may optionally contain a prefix length option, which, in combination with the advertisement's source address, may be used to calculate the originating subnet of the foreign agent. A MN may use this subnet to determine whether it is crossing into another foreign agent's domain and, therefore, needs to re-register with the new agent, or whether it remains within the same domain and does not need to re-register. Of course, this presumes that both the old and the new foreign agent include the prefix matching option in their advertisements [9]. It also implies that each foreign agent presides over its own subnet, which may not be the case.

#### 4.2.4.3 Low Latency Handover

Using eager cell switching the assumption is that the MN is moving towards the new network; therefore the best strategy is to register with a foreign agent of that cell as quickly as possible [6]. The strategy is to register with new foreign agents as soon as they are discovered. This makes it possible to maintain a constant connection to the Internet. In general, nodes tend to move along the same direction they are travelling. This simple, yet key, fact means that once a node hears from a new foreign agent, it will likely enter and cross that new foreign agent's domain and, likewise, quit its previous foreign agent's domain. Under eager cell switching, a MN registers with a new foreign agent as soon as it hears that agent's first advertisement. It will remain with that agent until it hears an advertisement from a new agent. A new foreign agent in this context means either an agent whom the node has never heard before or an agent, which has not sent a new advertisement before the expiration of its previous advertisement. In this way, the eager cell-switching algorithm avoids oscillating registration between two foreign agents when both are reachable by the MN. It does not, however, prevent oscillation in the case where foreign agents become visible and invisible for periods longer than their router advertisement lifetimes.

### 4.2.5 Movement Detection in MIPv6

To detect a movement, Mobile IPv6, like Mobile IPv4, relies on Router Advertisements, but extends and modifies them to better support mobility [10]. Firstly, it reduces the minimum Router Advertisement advertisement interval from 3 seconds to 0.05 seconds and the maximum from 1800 seconds to 1.5 seconds. Secondly, MNs may send

Router Solicitations messages more often than the specified three every 4 seconds. Thirdly, it adds a Router Advertisement Interval option, which contains the maximum interval at which advertisements are sent. MNs can assume they have missed at least one advertisement if the interval passes without receiving an advertisement [11]. Router Advertisements are just one piece of the IPv6 Neighbour Discovery mechanism. Mobile IPv6 nodes can use Neighbour Unreachability Detection (NUD) to detect link failures by receiving hints from upper layer protocols as to whether connections are making "forward progress" [12]. In this way, the MN knows whether it is still attached to its default router. MNs can also use link-layer information to guess whether the MN has changed its IP links, however, changing link-layer cells does not mean that the IP link has changed [10]. Indeed, many sites use one IP subnet per group of cells. For this reason, MNs should send Neighbour Solicitations messages to determine whether they have actually changed IP links.

MNs may use any policy to decide whether they have actually changed links. Mobile IPv6 MNs will likely have more movement information available to them than Mobile IPv4 nodes, so they will have more algorithms available than the eager and lazy cell switching algorithms in Mobile IPv4.

### 4.2.6 Route Optimization

Using Mobile IP protocol, all datagram's destined to a MN are routed through that MN's home agent, which then tunnels each datagram to the MN's current location through the new foreign agent [13]. These indirect routing delays the delivery of the datagram's to MNs, and places an unnecessary load on the networks and routers along their paths through the Internet. To reduce such delays, datagram's can be routed directly from a correspondent node to a MN without going to the home agent first [11], collectively referred as Route Optimization. Route Optimization extensions provide a means for nodes to reserve the binding update of a MN and to then tunnel their own datagram's designated to the named MN directly to the care-of address indicated in that binding, ignoring the MN's home agent. Extensions are also provided to allow datagram's in flight when a MN moves, and datagram has sent based on an out-of-date cached binding, to be forwarded directly to the MN's new care-of address [13]. However, this binding messages is then used to modify the handling of outgoing (as well as the processing of incoming) packets, leading to security risks [14].

When a MN's home agent receives a datagram from the home network, it tunnels it to the MN via the foreign agent. Meanwhile, the home agent may find that the original source of the datagram does not have the binding cache entry for the destination MN. In this case, the Home agent should send a binding update message to the source node, informing it of the MNs current car-of-address (the current mobility binding). No acknowledgment for such binding update messages is needed, because the home agent may receive additional future datagram when the MN changes its location. For security reasons, both the MN and its home agent must have established a mobility security association in order to the binding update messages to be authenticated.

Finally, the MN is responsible for frequently retransmitting a binding update message to its previous foreign agent until the matching binding acknowledge message is received by the MN, or until it make sure that foreign agent has expire its binding. Moreover, the MN is likely the one how select a small timeout value for these frequent binding messages to be sent to the previous foreign agent, as shown in Figure 4-1 below.

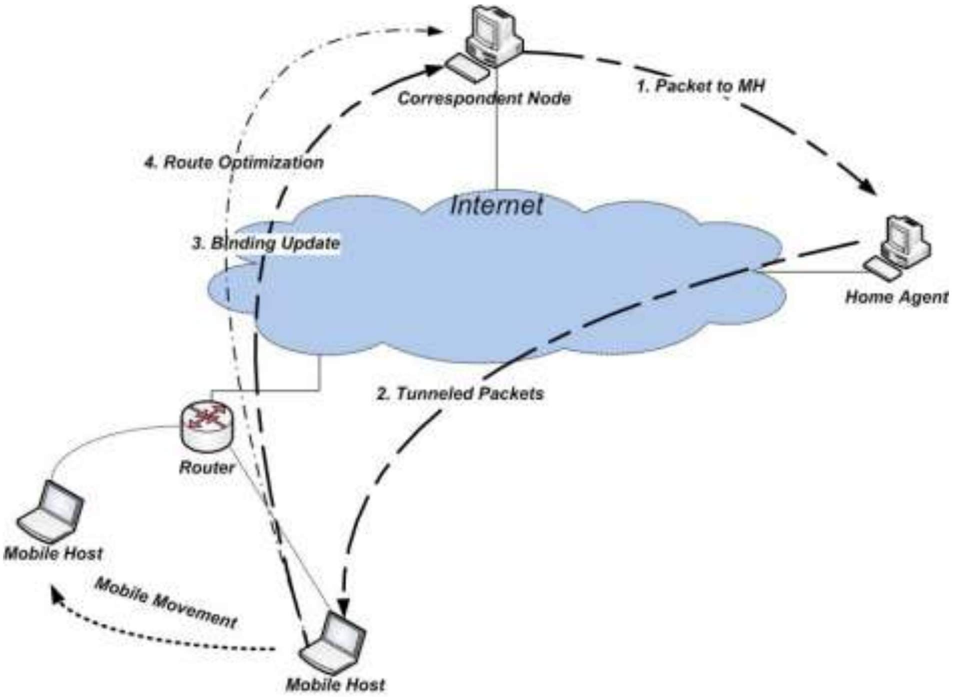


Figure 4-1: Route optimization in MIP.

## 4.3 Recent Development to MIPv6 Protocol

### 4.3.1 Introduction

Nowadays wireless technologies are widely used in IPv6 [15] communications. In addition to sharp increase of mobile terminals, various kinds of wireless technologies are available for MNs. Therefore, many MNs begin to have multiple wireless interfaces and every user wants to use them simultaneously to reinforce connectivity to the Internet. Selection of the most efficient and suitable access network to meet a specific application's QoS requirements has thus recently become a significant topic, the actual focus of which is maximizing the QoS experienced by the user. The main concept is that users will rely on intelligent network selection decision strategies to aid them in optimal network selection. Fast-handover Mobil IPv6 (FMIPv6) [16] already offers some rudimentary handover features. For instance, a MN may send a Binding Update to its Present Access Router (PAR). This causes the PAR to redirect packets towards the new Care-of-Address (CoA) of the MN. In the present context, while the MN moves around a certain area, it keeps checking the around Access Routers (AR's), once it receives that there is an AR around it, it will start the handover procedure between the PAR and the New Access Router (NAR). Yet, there is no way for the user and/or the application to force the MN not to make the handover in order to stay with the AR that offers a better service. On the other hand, Game Theory [17] is a set of tools developed to model interactions between agents with conflicting interests, and is thus well suited to address some problems in communications systems, which might be related to interface and/or network selection mechanisms. Game theory skills can be easily adapted for use in radio resource management mechanisms in a heterogeneous environment. Accordingly, the following sections present a mechanism for combining interface and/or network selection mechanisms and game theory. In such a way that the user and/or the application will have the ability to dynamically control which network to access while moving around different AP's.

### 4.3.2 Recent Extensions to MIPv6

Recently, various kinds of wireless technologies are available for the MNs. Mobile IPv6 [1] describes the protocol operations for a MN to maintain connectivity to the Internet during its handover from one AR to another. As mentioned earlier that the solution of keeping ongoing connectivity on the move is by using several interfaces and use them simultaneously. However, the basic Mobile IPv6 protocol [15] cannot support the simultaneous usage of multiple interfaces, because MIPv6 does not allow a MN to register multiple CoA's corresponding to multiple attachments of several interfaces. The reason why everybody is looking to add multiple wireless technologies to a MN is clearly, that they can be used for various purposes. For example, an interface can be used as backup to recover from possible loss of Internet connectivity of another interface. Moreover, two or more interfaces can be used simultaneously to increase the aggregate bandwidth, or load sharing of different applications. Lately, the multiple CoA registration protocol [18] extends Mobile IPv6 protocol with an option called "Binding Unique Identifier (BID) sub option" to associate multiple CoA's with one home address. Although the Mobile IPv6 protocol describes a procedure to maintain connectivity to the Internet during handover, the involved handover latency may degrade the quality of the Internet applications, which are delay-sensitive or throughput-sensitive. However, in the case of Mobile IPv6 using multiple CoA registration, packet tunnelling to a NAR during handover of one interface can incur performance degradation due to severe packet reordering when multiple interfaces are simultaneously used for load sharing. This is because the partial traffic flow destined to the interface involved in handover is suspended during the handover process and later tunnelled to NAR, but the MN may receive continuously the other partial traffic flow through another interfaces not involving handover. That could incur severe reordering if the handover procedure is delayed or unstable by ping-pong effects, the repeated handoffs between two access points caused by rapid fluctuations in the received signal strengths from both access points. In case the traffic is a TCP flow, this reordering severely degrades the throughput performance by turning on the TCP congestion control. This could also affect real-time applications.

As a result, the fast handover Mobile IPv6 (FMIPv6) protocol [16] has been proposed to reduce the handover latency. Generally, FMIPv6 tries to reduce the movement detection latency and the new CoA configuration latency by processing the handover signalling in advance. The basic idea behind the FMIPv6 is that the PAR forwards the arriving packets designated to the MN to the NAR by setting up a tunnel to the NAR in order to prevent packet losses incurred by handover latency during handover procedure. For the same reason, it is necessary for the multiple interface Mobile IPv6 [15] protocol to adopt a fast handover procedure to enhance its handover performance by reducing handover latency and packet losses. The FMIPv6 Protocol works as follows; essentially the handover procedure starts when a MN sends an RtSolPr (Router Solicitation for Proxy, which is a message from the MN to the PAR requesting information for a potential handover [16]) message to its AR through a handover-interface to resolve one or more Access Point Identifiers to subnet-specific information. In response, the AR sends a PrRtAdv (Proxy Router Advertisement, which is a message from the PAR to the MN that provides information about neighbouring link facilitating expedited movement detection [15]) message containing one or more access point ID and information. The MN may send an RtSolPr as a response to some link-specific event (a "trigger") or after performing router discovery. However, prior to sending RtSolPr, the MN should have discovered available APs by link-specific methods such as AP scanning procedure in IEEE 802.11 wireless LAN. The RtSolPr and PrRtAdv messages do not establish any state at the AR [16]. The exact details about the packet format are out of the scope of this thesis. However, more details about them can be found in [15]. With the information provided in the PrRtAdv message, the MN formulates a prospective NCoA (New CoA) and sends an FBU (Fast Binding Update) message. For a single interface FMIPv6, the main purpose of the FBU is to inform PAR of binding PCoA (Previous CoA) to NCoA (New CoA), so that arriving packets can be tunnelled to the new location of the MN. The PAR will send FBack (Fast Binding Acknowledgment) message to the MN and NAR to initiate the handover mechanism. The MN disconnects from the PAR and sends FNA (Fast Neighbour Advertisement) message to the NAR in order to start the communication and that will reduce the handover latency. Figure 4-2 shows the handover procedure for the FMIPv6 protocol.

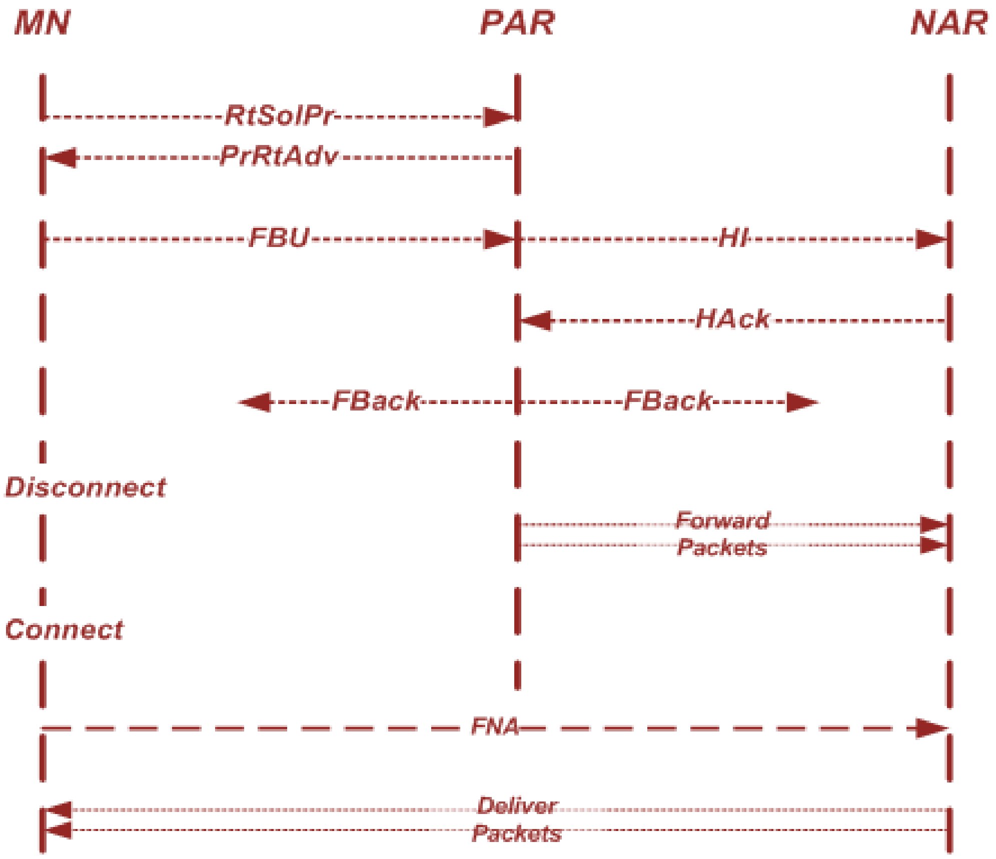


Figure 4-2: Handover procedure in FMIPv6 protocol.

In the literature [19] a Multi-interface Fast Handover Mobile IPv6 (MFMIPv6) protocol have been proposed. As an extension to the FMIPv6 that can mitigate the reordering problem during handover when MN's have multiple wireless interfaces and multiple CoA registrations. This procedure can indicate a specific tunnelling destination except the NAR, for example, one of the other interfaces (or CoA's) in the same MN. One of the main advantages of the MFMIPv6 protocol is that the throughput of a TCP flow would increase by avoiding the unnecessary congestion control. Moreover, the named mechanism can improve the handover signalling performance because data traffic is redirected to another interface during handover signalling. After the successful handover of the corresponding interface, the redirected traffic flow is restored to be directed to the NAR and finally to the original interface. In general, the MFMIPv6 Protocol works very similar to the FMIPv6. However, instead of forwarding the packets to the NAR during the handover process, the packets are forwarded to the other interface of the same MN. However, for a multi-interface FMIPv6, tunnelling packets to NCoA may degrade traffic performance by severe reordering as mentioned before. In the propose extension, the FBU message not only carries the NCoA but also a “tunnel destination” mobility option which could be another CoA that is registered for other interface of the same MN. This message is called as “Multi-interface Fast Binding Update (MFBU) message” to distinguish it from the FBU message of the basic FMIPv6 protocol, as shown in Figures 4-3 and 4-4.

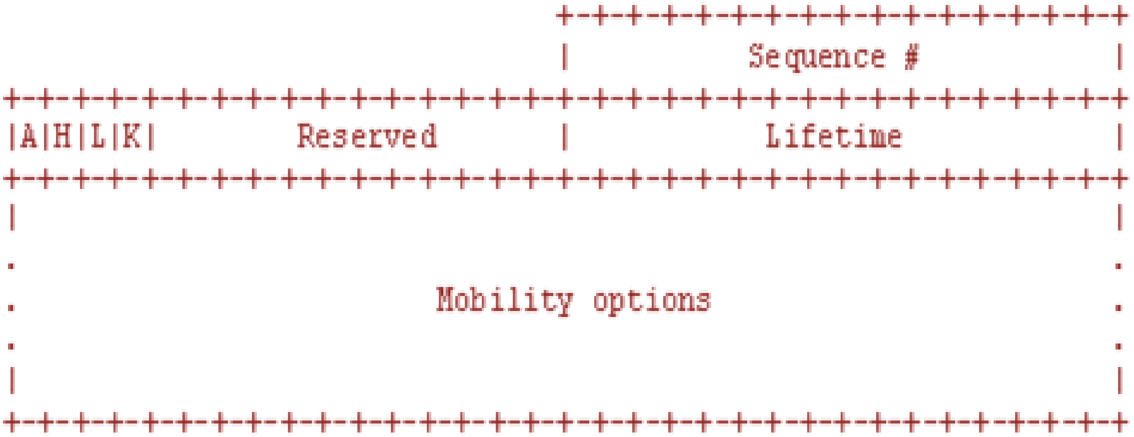


Figure 4-3: FBU message.

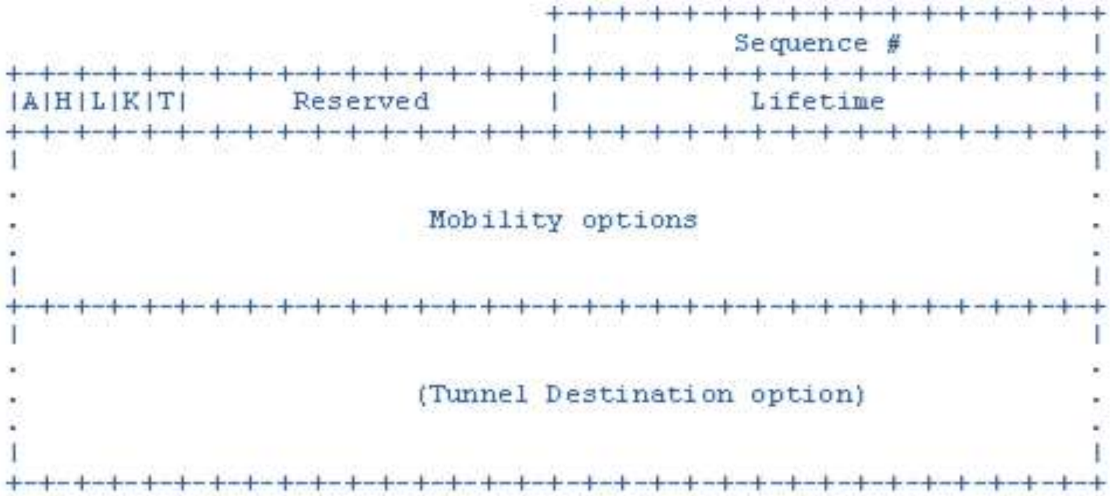
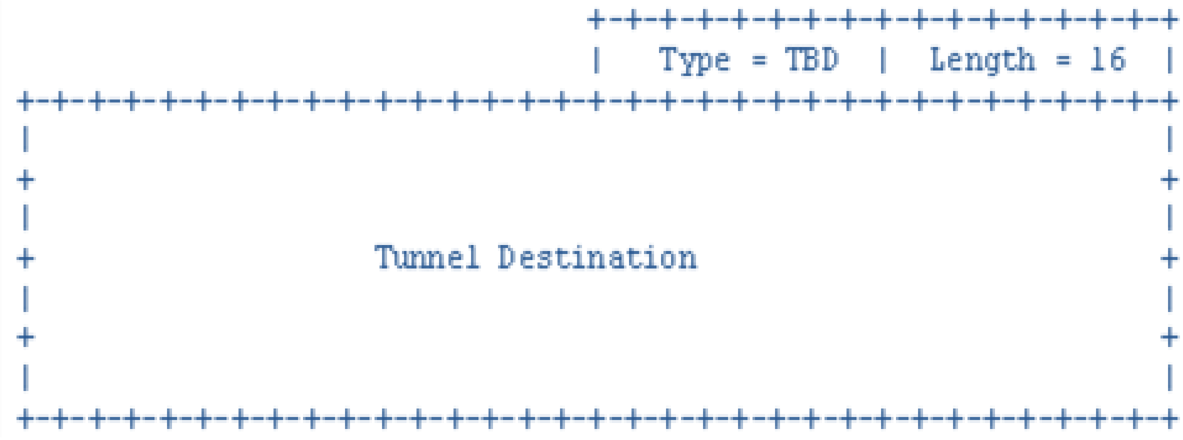


Figure 4-4: MFBU message.

More details about each field of these two messages in [16-18]. However, the Tunnel Destination option SHOULD be included as a mobility option in the MFBU message in order to inform the PAR of the tunnel destination address to redirect traffic toward the handover interface of the MN to other interface CoA. This option is valid only in MFBU message. The format of the Tunnel Destination option is shown below in Figure 4-5.

Where the type filed is to be determined by IANA (Internet Assigned Number Authority). The length filed represents the length of an IPv6 address and the tunnel destination is the CoA of an interface of the MN to which traffic to the handover interface is tunnelled in MFMIPv6 protocol.



```
                                +-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
                                |   Type = TBD  |  Length = 16  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                                                               +
|                                                               |
+                      Tunnel Destination                       +
|                                                               |
+                                                               +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 4-5: Tunnel destination option in the MFBU message.

When the MN composes an MFBU message, it first checks the number of CoAs registered for multiple interfaces. Then, the MN selects candidate CoAs for tunnel destination, which are not being involved in handover. Among them, the MN checks each interface whether or not it has appropriate characteristics for the traffic to be tunnelled. The MN also examines the available bandwidth of candidate interfaces whether they can accommodate the traffic. Finally, the CoA of the selected interface is inserted into the “tunnel destination” mobility option of the FBU message and the flag “T” is set to indicate the existence of the “tunnel destination” option. After the PAR receives the MFBU message, the PAR begins tunnelling packets arriving for PCoA to the “tunnel destination”, in other words, to the CoA of the other interface of the MN. Such a tunnel remains active until the MN completes the registration of a new CoA with its Home Agent or correspondents. After that, the HI (Handover Initiate), HACK (Handover Acknowledge), FBAck (Fast Binding Acknowledge) and FNA (Fast Network Attachment) messages are used in the protocol as the same way in the basic FMIPv6 protocol [16]. The overall handover procedure of MFMIPv6 is illustrated below in Figure 4-6.

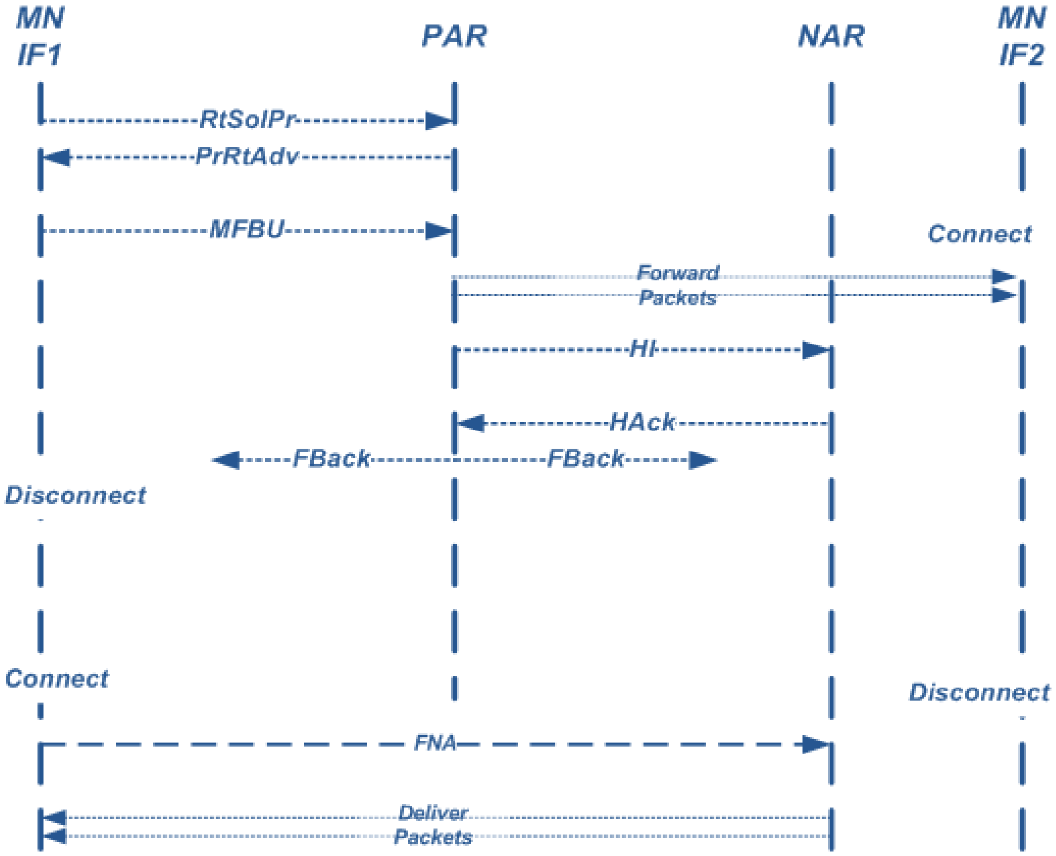


Figure 4-6: Handover procedure in MFMIPv6 protocol.

After the successful handover of the corresponding interface, the redirected traffic flow is restored to direct to the NAR and finally to the original interface. In this protocol, a mobility option that indicates a tunnel destination point for the coming traffic flow to a PAR. The ARs should recognize the tunnel destination option and redirect the traffic flow to another AR that is connected to another active interface of the same MN. There are no special requirements for a home agent to behave differently with respect to the basic FMIPv6 procedure.

In a handover scenario, the second interface of the MN (IF2) is about to begin handing over from one AR to another. The first interface (IF1) is attached to PAR and remains stable. If the MN runs the original FMIPv6, the NAR begins buffering the traffic to the MN when it receives the FBU message and tunnelling to the NAR starts after exchanging the HI and HAck messages. During this fast handover procedure, half of the traffic is continuously transferred to the MN through the first interface (IF1). This process MAY cause severe packet reordering if the handover delay is large or traffic load is heavy. For example, it is assumed that the characteristics of the two paths such as delay and bandwidth between the HA and two interfaces of the MN are similar, and the HA divides the traffic alternatively to If1 and If2 as follows [19]:

IF1 (CoA1): 1 3 5 7 9 11 13 15......
IF2 (CoA2): 2 4 6 8 10 12 14......
|
|< handover instant
(FBU or MFBU message arrival to PAR)
|
FNA message arrival to NAR > |

Then, the MN can receive in-order packets when the MN is not involved in any handover. However, when IF2 starts handing over from one AR to another and the MN runs the original fast handover procedure, the order of packet arrivals may become as follows if the MN's handover events occur as

1 2 3 4 5 7 9 11 6 8 10 12 13 14 15......

Then, because it is assumed that the traffic is a TCP flow, the above reordering issues three duplicate ACK’s when the MN receives packet number 11. The corresponding node (CN) receives these three duplicate ACKs, takes this event as a packet loss and starts a congestion control procedure. Therefore, the CN reduces its sending rate, which causes performance degradation. In contrast, when the MN runs the MFMIPv6, the traffic toward IF2 is redirected to CoA1 of IF1 when the PAR receives the MFBU message that includes "tunnel destination" option equal to CoA1. Then, the order of packet arrivals may become as follows if the MN's handover events occur,

1 2 3 4 5 7 9 6 11 8 13 10 15 12 14......

In this scenario, although the packet reordering could occur, three duplicate ACKs do not occur frequently because the CoA1 is not involved in the handover process at this moment and stable. Even if the handover latency of the handover interface becomes very large, only one or two duplicate ACKs may occur. This event does not trigger the TCP congestion control in the CN because the TCP regards three or more duplicate ACKs as a packet loss. Thus, the congestion window does not decrease during handover and performance is not degraded.

However, neither FMIPv6 nor MFMIPv6 protocols offer the MN any ability to choose the right AR at the right time. Moreover, as the two interfaces in the case of the MFMIPv6 are 'ON' all the time that will add the power consumption problem as another drawback to this protocol. Furthermore, both protocols uses only static factors to decide whether the handover is needed or not and both suffer from the ping-pong effect.

## 4.4 Game-Based Dynamic Network Selection Mechanism for MIPv6 Wireless MN's

Admission control schemes are the decision making part of networks with the objective of providing services to users with guaranteed QoS in order to reduce the network congestion and call dropping probability and achieve as much resource utilization as possible [20]. When several radio technologies may at the same time attend the user services demand, a decision is necessary to select the most suitable radio access technology on a per user basis. The decision about the target network can be based on either user or network/operator criteria. This section presents a game theory based network selection mechanism for a MN equipped with two wireless interfaces. The mechanism consists of two steps; the first step focuses on finding factors indicative of each network's weak points. Qualitative relations between the QoS parameters must be defined in this step in order to calculate the weight of each parameter and how it affects the overall QoS obtained. When this step is finished, priorities should be assigned to each parameter according to their weight. The higher a weight is, the higher the priority that should be given to the corresponding parameter. The second step investigates all available networks in order to find the optimal choice. A questionnaire filled by the users of the networks might give a great understanding of the weight of each QoS parameter mentioned earlier. To estimate how each parameter fails to satisfy the system specifications, the ratio $\frac{\Delta x}{x} = \frac{|x - x_{\mu}|}{x}$ is used to determine how much worse the network's performance as compared to the desired one. Where $(x)$ is a set of values, which considered as optimal, and $(\mathrm{x}_{\mu})$ is the measurement mean value of each QoS parameter, $(\mathrm{x}_{\mu})$ is always assumed to be worse than $(x)$ (i.e. $\mathrm{x}_{\mu} < x \; or \; \mathrm{x}_{\mu} > x$ for the values considered to be larger or smaller than the better respectively). With this ratio, the mechanism manages to assign each parameter a weight proportional to the extent at which it fails to satisfy the specifications. Moving forward to find the optimal solution where matrices are used to synthesize all problem-deciding factors. With the matrix form, the elements are compared in each level of the hierarchy in order to provide a degree of preferences of one parameter against the other, as shown in Figure 4-7.

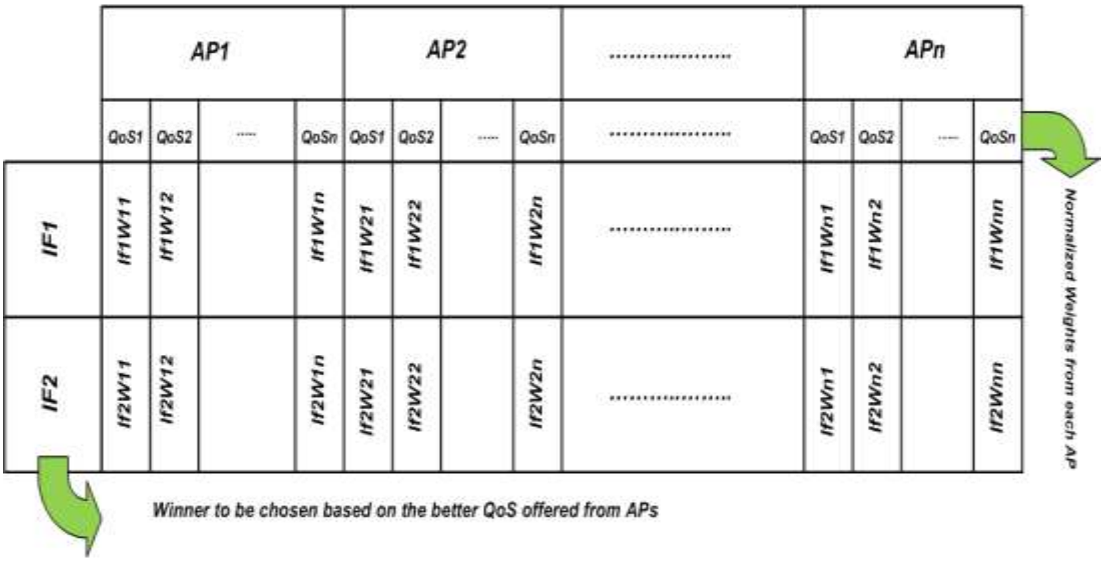


Figure 4-7: Matrix format of the game mechanism.

More specifically, depending on the factors from each interface under comparison, the following cases exist:

1) $w_{i,j} = 1$, when a factor is compared to itself.
2) $w_{i,j} > 1$, then factor $i$ is assumed to be more important than factor $j$.
3) $w_{i,j} < 1$, then it's the opposite, when factor $j$ is more important than $i$.

Relative weights generated after a repetitive process with which the decision elements participate in the configuration of the final objective of the mechanism.

The mechanism consists of two main parts, Network Discovery and Network Analysis. In the Network Discovery model, all available networks are identified and priorities are assigned to them. This process is divided into two parts: Firstly, the networks are added to the candidate list if the Received Signal Strength (RSS) is higher than its threshold value and its mobility threshold is greater than the velocity of MN. We assume that $N = \{n_1, n_2, n_3, \dots., n_k\}$ is the set of available network interfaces in our MN. $RssT = \{rt_1, rt_2, rt_3, \dots., rt_k\}$ is the set of threshold values of RSS of respective networks. The set of values of difference between the RSS and its threshold value is represented by $RssDiff = \{rd_1, rd_2, \dots, rd_k\}$. The set of eligible candidate networks into which the handoff can take place is represented by CN. $P = \left\{0, \frac{1}{k}, \frac{2}{k}, \dots., \frac{j}{k}, \dots.1\right\}$ is the set of priorities of the $j^{th}$ network, and $j = 1,2, \dots k$. The network Access Point (AP) and MN is observed for the RSS and mobility respectively at the specified time intervals and the decisions are taken as the algorithm below to select the candidate networks, assuming that MN is currently in network $n_i$:

```
If $RSS_j > rt_i$ then
For all $n_j$ where $j \neq i$
If $(RSS_j > rt_i \text{ and } m_j < mt_i)$ then
$\{CN\} = \{CN\} \cup \{n_i\}$
$RssDiff_j = RSS_j - rd_i$
```

Then, the network with the highest *RssDiff* will be assigned with a higher priority. This is because a higher *RssDiff* means the MN is nearer to the AP of the named network and hence the MN can stay in that cell for longer before looking to handoff to another network. This will reduce the number of unnecessary handoffs and improve the overall performance of the system. The priorities are assigned according to the following algorithm, assuming that $n$ networks are available in the list;

```
While $j \leq k$ Do
if $j$ is not in the candidate list then
$P_j = 0$
                    else if $j$ is the only network in the candidate list then
$P_j = 1$
else if $j$ is at the $i^{th}$ posotion, the list will be ordered in an ascending order then
$P_j = i/k$
```

Secondly, the Network Analysis model is based on a static score function *SC*, which is a function of the offered bandwidth by the network ($BW_n$), interface energy consumption ($P_n$) and service charge ($C_n$).

$$SC_n = f(BW_n, P_n, C_n) \qquad (4\text{-}1)$$

where, SCn is the static score function of network $n$. Normalization is needed to ensure that the sum of the values in different units is meaningful. If there are $k$ factors to be considered in the score function, the score function of the interface $i$ will be a sum of $k$ weighted factors.

$$SC_i = \sum_{j=1}^{k} w_i nf_i \qquad 0 < SC_i < 1, \quad \sum_{j=1}^{k} w_i \qquad (4\text{-}2)$$

In equation (4-2), $w_i$ represent the weight of factor $j$ of interface $i$, and $nf_i$ is the normalized score value of factor $j$ for interface $i$. For our model;

$$SC_i = w_{bw} f_{bw,i} + w_c f_{c,i} + w_p f_{p,i} \qquad (4\text{-}3)$$

where $w_{bw}$, $w_c$, and $w_p$ are the weight factors of the offered bandwidth, service cost, and the power consumed by the network interface respectively. $f_{bw,i}$, $f_{c,i}$, and $f_{p,i}$ are the normalized values of interface $i$'s offered bandwidth, power consumption and service cost respectively. Whereas;

$$nf_{bw,i} = \frac{e^{\delta_i}}{e^{bw_i}} \qquad \delta_i \geq 0 \qquad (4\text{-}4)$$

$$nf_{c,i} = \frac{1}{\frac{c_i}{e^{\beta_i}}} \qquad \beta_i = \frac{1}{pk_i}\ , pk_i \text{ is the packets to be sent} \qquad (4\text{-}5)$$

$$nf_{p,i} = \frac{1}{\frac{p_i}{e^{\gamma_i}}} \qquad \gamma_i = \frac{1}{t_i}\ , t_i = \text{time in hours} \qquad (4\text{-}6)$$

The coefficients $\delta_i$, $\beta_i$, and $\gamma_i$ are defined same way as in chapter three. The exponential functions used to increase the sensitivity of the functions to the respective parameters they are related to. Finally, they are inversed in order to bind the functions to a value between zero and one. It can be observed from these equations that high bandwidth value contributes proportionately to the SC function, whereas cost and power consumption contribute inversely to SC. This is because, an interface with a better bandwidth is a better choice to the MN, while an interface costing more or consuming more power is a poor choice to the MN.

Given that the two interfaces are wireless, thus all requested services are of equal priority, therefore are characterized by similar requirements, we aim to distribute a set of requests to a number of access networks so that all of them gain the maximum payoff. The information needed in order to deduce the user preferences and thus the optimal distribution of service requests involves two parameters: network efficiency and network status. Network efficiency is taken into consideration based on the static and dynamic factors mentioned earlier to decide whether the handover is needed or not. A normalized value of each element of the mentioned factors is to be considered in order to get an overall weight factor to represent each individual AP. On the other hand, the second parameter, network status, that affects user preferences, is involved taking into account information such as the static and dynamic factors needed to decide the handoff process [7]. Therefore, network preferences are roughly reflected by the following equation:

$$Network\ Preferences(NP) = Network\ Efficiency\ (NE)\ \times\ Network\ Capacity\ (NC) \qquad (4\text{-}7)$$

NE will be calculated the same way the cost function been calculated, as in equation (4-1), so NE can be represented as;

$$NE = SC\ \times RSS_N \qquad (4\text{-}8)$$

Where $RSS_N$ is the normalized value of the RSS,

$$RSS_N = \frac{e^{\varepsilon}}{e^{RSS}} \qquad \varepsilon \geq 0 \qquad (4\text{-}9)$$

However, NC should indicate the network's current capability to fulfil the request's requirements and therefore should include both the network's available bandwidth, as well as the service's required bandwidth. This will lead us to the following fact:

$$NC = \frac{Availabe\ BW}{Required\ BW} \qquad (4\text{-}10)$$

Then, combining the two equations will give us;

$$NP = SC \times RSS_N \times \frac{BW_{av}}{BW_{req}} \qquad (4\text{-}11)$$

The proposed game can be represented as $G = \{N, A, S_i, U_i\}$, where $N = \{1, 2, \ldots., n\}$ is the number of players in the game, in this case AP's. The number of actions is represented by $A = \{1, 2, \dots., n\}$. $S_i$ denotes the set of strategies for each player, *i.e.* all possible choices of a specific request from set $A$. Finally, $U_{ij}$ denotes the payoff assigned to the MN by selecting player $i$ after choosing resource $j$. This payoff can be modeled as described in equation (4-11). The game is played in rounds, in each round of the game the MN decide which request will maximize its own payoff and then select it. Another aspect that needs to be clarified is the one where more than one network provides the same services. In this case, we randomly let the network with the highest payoff handle the service and move on to the next round of the game, without removing a second request. In the case of multiple Nash equilibriums, for simplicity reasons, we will assume that the MN will choose the first one, since it possesses chronological priority. The proposed game is also a non-zero sum game.

The proposed extension to the MFMIPv6 is shown below in Figure 4-8, and works as follows: as the MN receives the PrRtAdv messages from the PAR as it moves around, the game controller will be responsible of extracting the QoS parameters of them. The network interface receives all the packets at the node channel from other nodes or access points. Each transmitted packets is stamped by the interface with the meta-data related to the transmitting interface [21]. The meta-data in the packet header includes information such as transmitting power, wavelength, available QoS, security authentication etc., of the transmitted packets. The Game Controller is to be inserted at the network interface in the MN. The game controller extracts the packet header in the same way used in the propagation model, where the meta-data in the packet header is used by the propagation model to determine if the packet has the minimum power to be received and/or captured and/or detected. When the MN sends and receives the RtSolPr and PrRtAdv messages, the game controller will know the source of each PrRtAdv message and extract the QoS information from it and by using the mechanism mentioned earlier. The MN will decide which AR is the best to go with. The MN will send the address of the NAR to the PAR by the MFBU message.

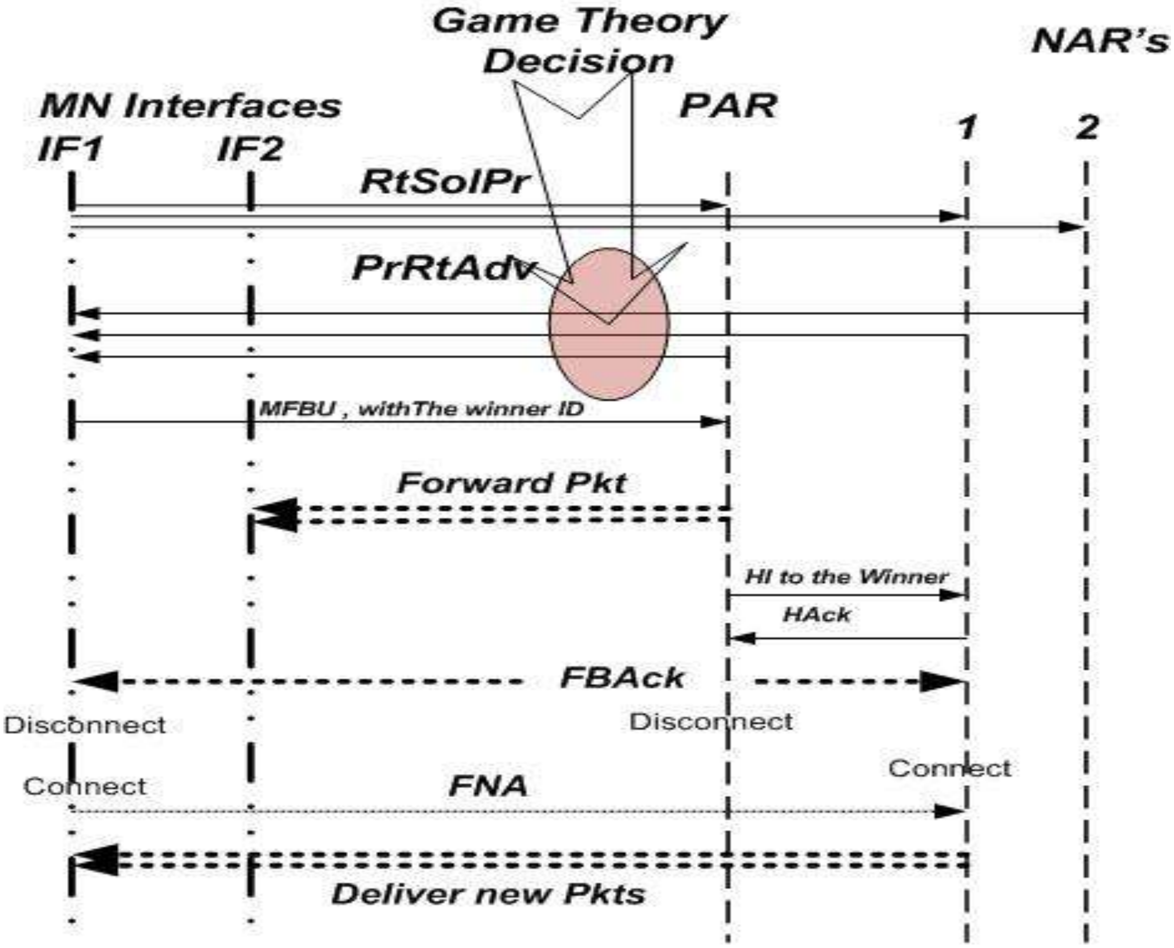


Figure 4-8: Using game mechanism to choose the best AP.

Similar to the MFMIPv6 [19], the game decision is based on the information obtained from the PrRtAdv message (as discussed in section 4.3.2). Then, using the MFBU message, the winner (i.e. the access point that offers the best services) ID will be sent to the PAR in order to forward the packet to it, as shown in Figure 4-8. During the game, the MN might face different cases. If there were two or more AP's offering the same services to the MN (i.e., multiple-Nash equilibrium case), the MN will not face any problem in choosing any one of them at that point. On the other hand, if one of the AP's managed to improve the offered QoS to the MN, the MN will switch to it (*i.e.,* the Pareto efficient case explained in (chapter 2, section 2.4), where it is impossible to improve the utility of one player without harming the others. However, the last point that we need to look at will be the energy consumption in the MN as the two interfaces are 'ON' all the time to insure getting the full advantage of the MFMIPv6 protocol. In order to solve such an issue, we used the following scheme (similar to one introduced in section 3.7):

Received Signal Strength 'ON' Threshold ($Rss_{ONT}$) point; with this method, one of the interfaces will be turned OFF until the RSS from the AP reaches a certain point "$RSS_{ONT}$", which means that the MN is moving away from the AP and reaching the boundaries of its coverage, as shown in Figure 4-9. Once the MN reaches the named point, the game mechanism will work as explained earlier saving more energy to the MN by keeping the other interface 'OFF' most of the time. However, the drawback of the $RSS_{ONT}$ point model will be the chance that the MN might lose to handoff to a better network within the coverage of the bigger network. To solve this problem, the first interface will trigger the second interface once it receives any advertisement messages from the around APs. The game mechanism will work to check whether a handover is needed or not, if so, the game process will proceed, if not, the second interface will be turned 'OFF' and wait for either the $RSS_{ONT}$ point or forced by the other interface.

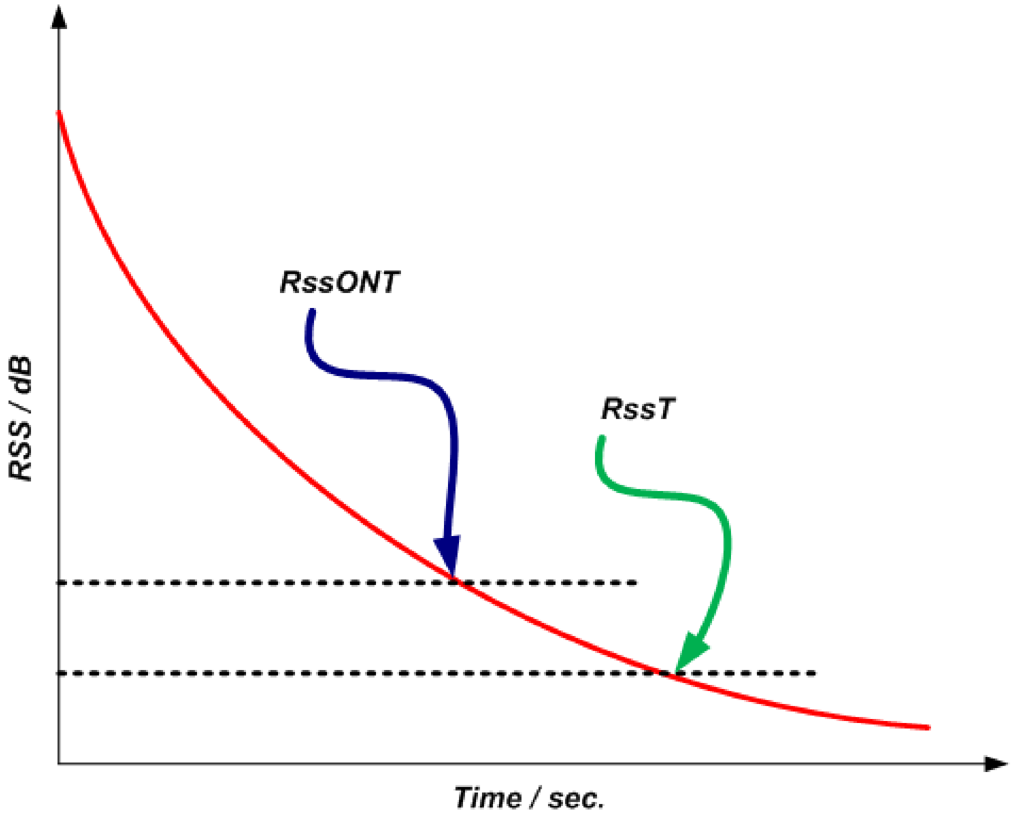


Figure 4-9: Handover decision points.

Finally, the previous additions to the MFMIPv6 protocol leads to our proposed Game-based Multi-interface Fast-handover Mobile IPv6 (GMFMIPv6). By adding game theory to the MFMIPv6 the MN will choose the “best” AP at the right time, making the handover decision more accurate and save the MN more energy.

To this end, in order to evaluate the performance of the proposed mechanism, we implement a similar design of the MFMIPv6 simulator introduced in [19] using NS-2 [21] and its extension MobieWan [22]. One more wireless interface was added and one channel, the game controller was added between the network interfaces (NetIF0 and NetIF1 shown in Figure 4-10), which will decide which AR to go with.

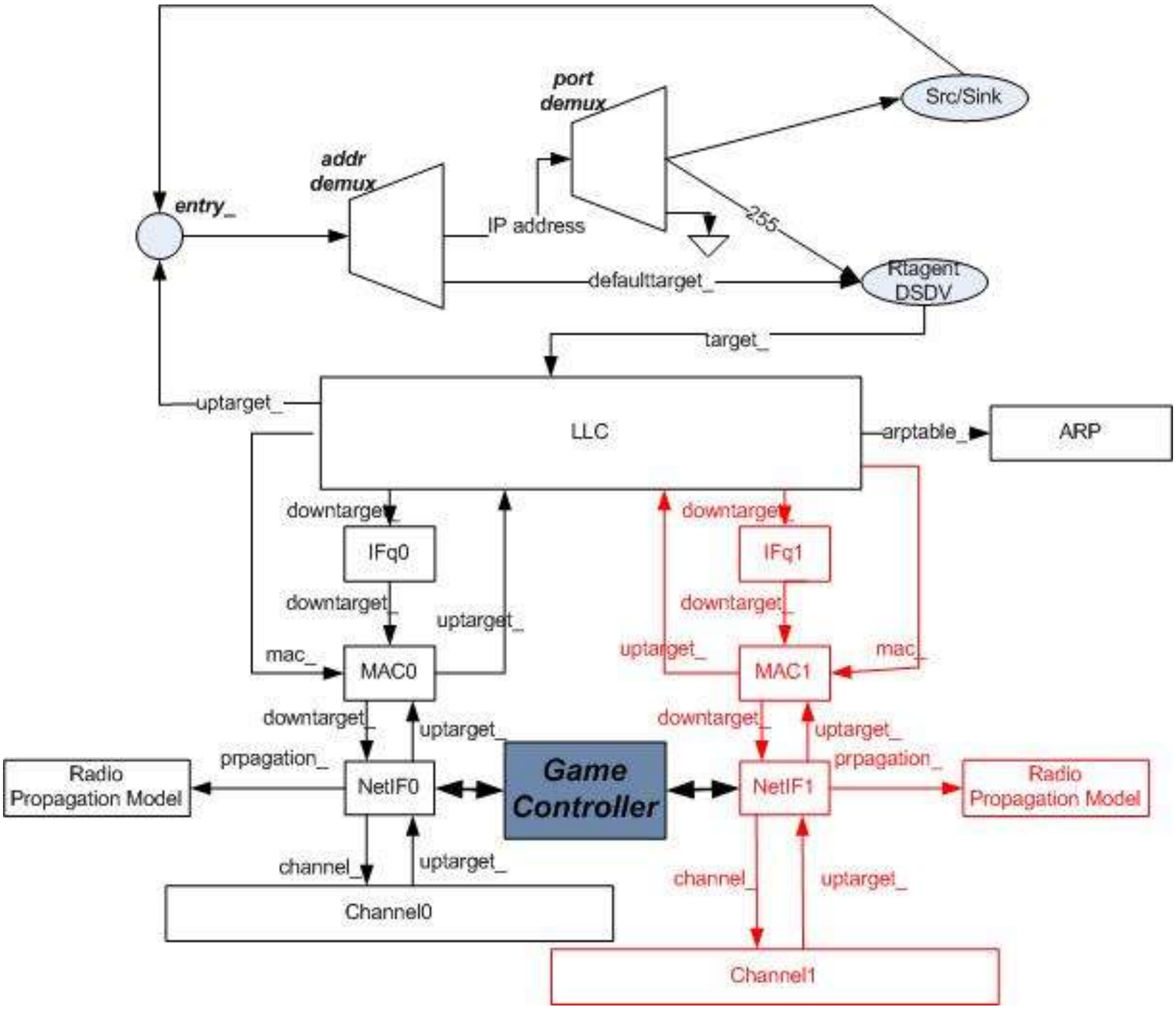


Figure 4-10: Multiple-Interfaces mobile node.

## 4.5 Simulation Scenario and Results

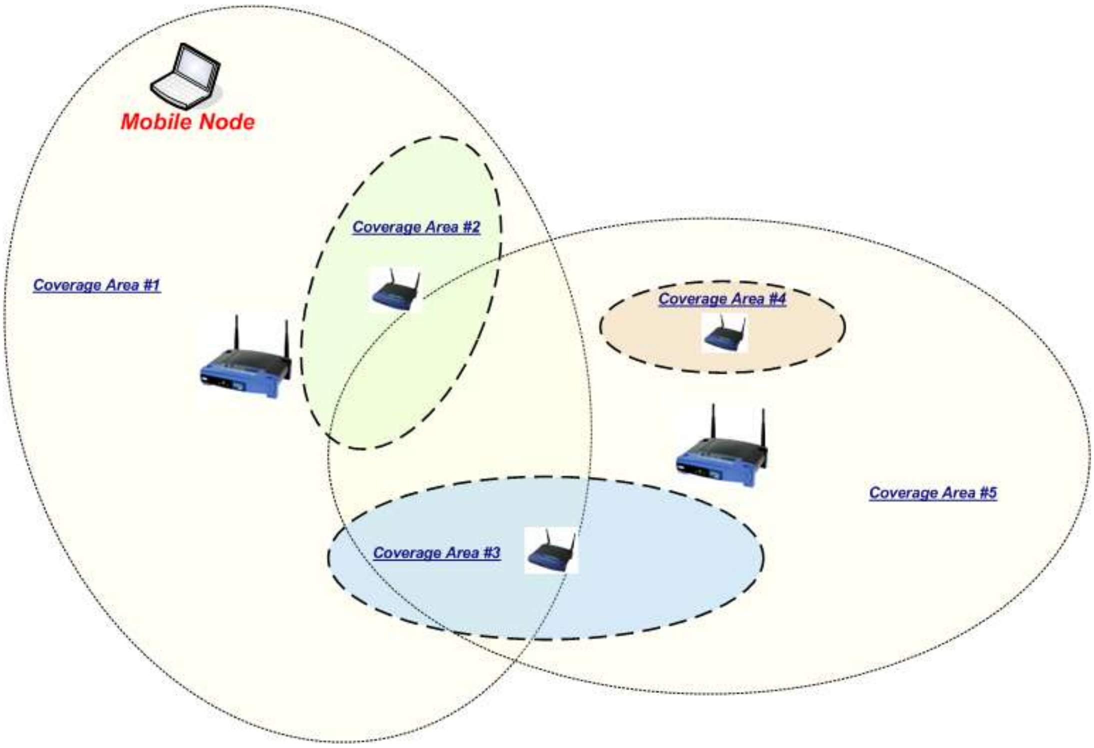


Figure 4-11: Simulation Scenario.

The network topology for our simulation is shown in Figure 4-11, five 802.11b access points are assumed to cover the simulation area of $(440 \times 440\ m)$ with different characteristics. At the beginning of the simulation, the MN is assumed to be settled within the coverage area of access point number one. Throughout the simulation time, which is set to be 24 minutes, the MN is assumed to have a data of 50000 packets to transmit. The MN is assumed to cross all coverage areas several times and it will never stop in one position with an average speed of 1 m/sec. Table 4-1 below shows our scenario assumptions starting with the service cost, available bandwidth, delay and power consumption of each AP in the network. The MN battery is assumed to have 10 KJ of energy.

Table 4-1: Simulation statistics.

| | ***QoS parameters*** | | | | |
|---|---|---|---|---|---|
| | *Service Cost (£/h)* | *Bandwidth (Mbps)* | *Delay (μsec)* | *Power consumption per every transmitted bit* | *Power consumption per every received bit* |
| ***AP#1*** | *Free* | 4.5 | 12 | 320 $mW$ | 300 $mW$ |
| ***AP#2*** | *Free* | 4 | 16 | 250 $mW$ | 230 $mW$ |
| ***AP#3*** | *Free* | 4 | 16 | 250 $mW$ | 230 $mW$ |
| ***AP#4*** | 1.5 | 8 | 4 | 200 $mW$ | 170 $mW$ |
| ***AP#5*** | *Free* | 5 | 11 | 320 $mW$ | 300 $mW$ |

Simulation results compare the number of successfully received packets, the number of dropped packets, the overall end-to-end delay and the MN power consumption using four different protocols namely MIPv6, FMIPv6, MFMIPv6 and GMFMIPv6.

Figures 4-12 and 4-13 compare the number of acknowledgements of every successfully delivered packet and the number of dropped packets over the simulation time using four different protocols. Both MFMIPv6 and GMFMIPv6 show the same number of acknowledgments received and the same number of dropped packets over the simulation time. The two protocols show a much better performance as compared to both MIPv6 and FMIPv6, as both GMFMIPv6 and MFMIPv6 use two interfaces to pack up the communication link as compared to other protocols.

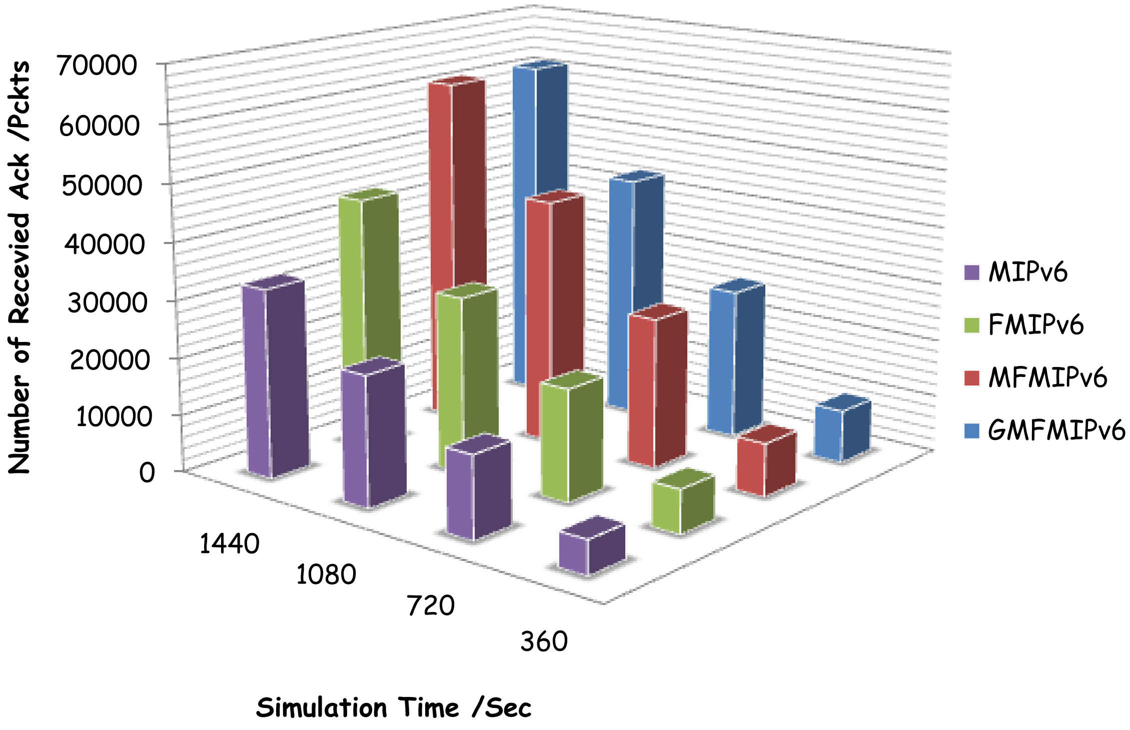


Figure 4-12: Number of received ACK's.

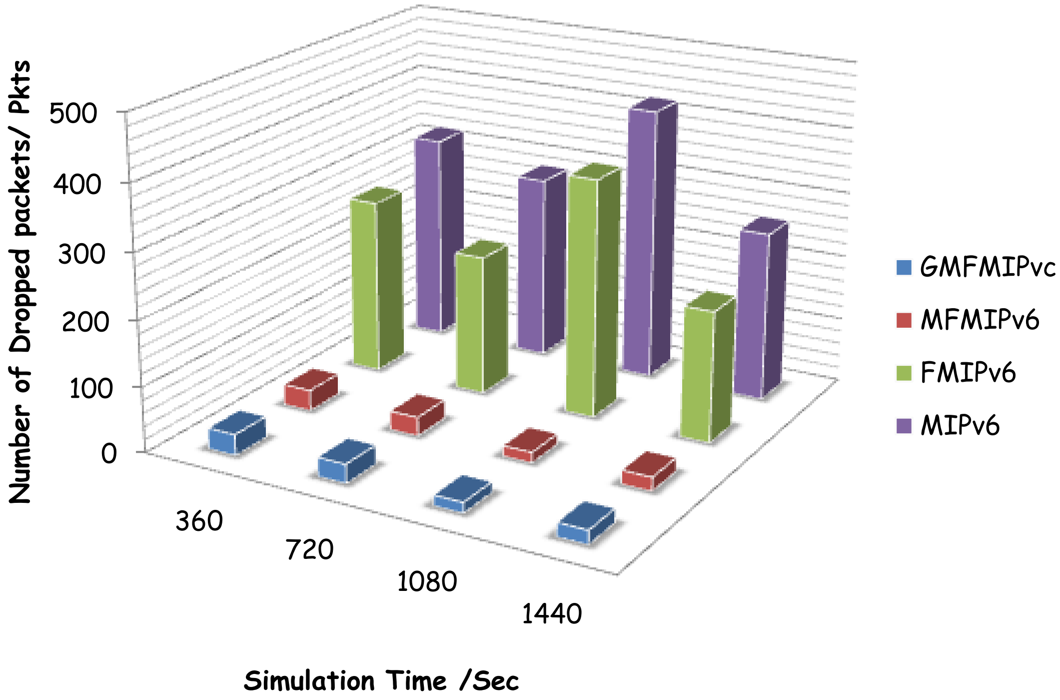


Figure 4-13: Number of dropped packets.

Figure 4-14 shows the total number of handovers the MN forced to go through during the simulation time when using the four protocols one at a time. It can be easily observed that GMFMIPv6 protocol shows a sharp decrease in the number of handoffs as compared to the other three protocols and this is because of the game-controller introduced in the previous section. Since the MN is using GMFMIPv6 protocol, it has the ability to decide whether switching to another AP will achieve a better QoS or not. By reducing the number of handovers, the communication link will not be disturbed, thus a better end-to-end quality. Moreover, reducing the number of handovers will reduce the need to switch the other interface 'ON', accordingly, saving more energy.

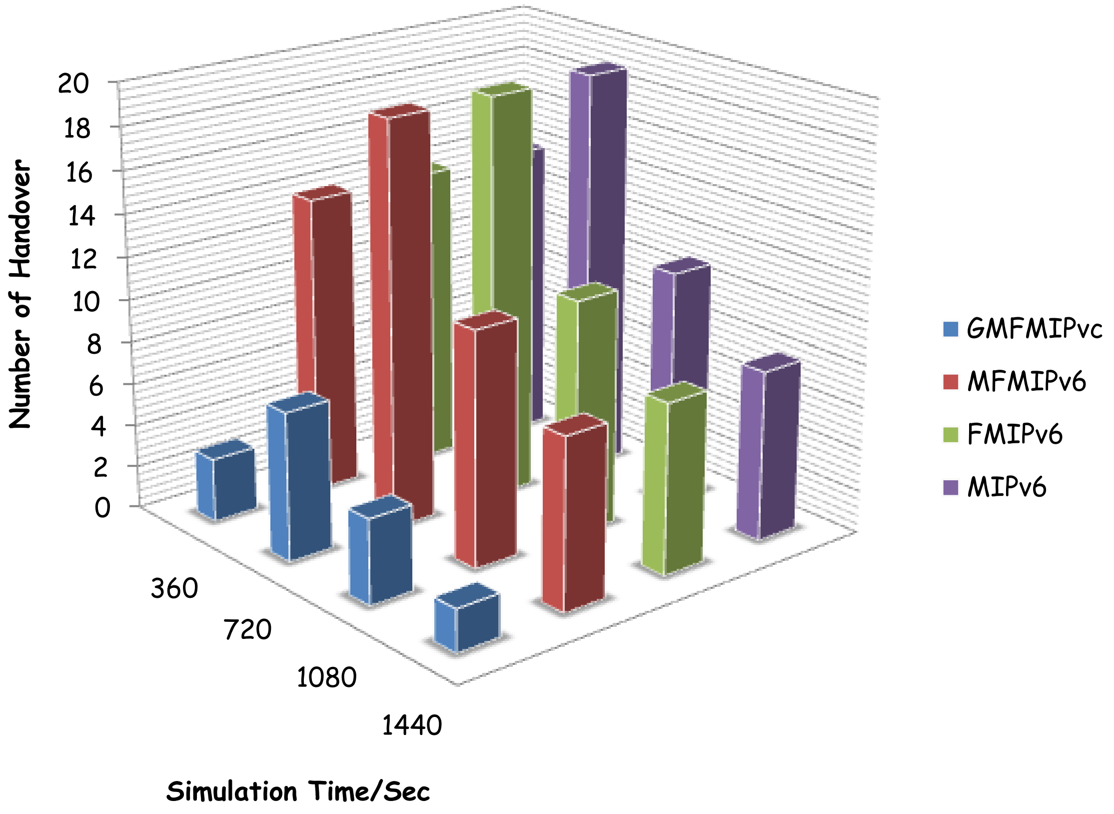


Figure 4-14: Overall number of handovers.

Figure 4-15 shows the end-to-end delay of the four protocols, GMFMIPv6 shows the lowest end-to-end delay as compared to the other protocols. This is because of its ability to decide whether a handoff is needed or not and the fact that the MN is using two interfaces to pack up its communication. FMIPv6 shows a better response when compared with MIPv6 protocol, as the MN tries to reduce the movement detection latency and the new CoA configuration latency by processing the handover signalling in advance. As explained earlier, when the MN uses FMIPv6, the PAR forwards the arriving packets designated to the MN to the NAR by setting up a tunnel to the NAR in order to prevent packet losses incurred by handover latency during handover procedure.

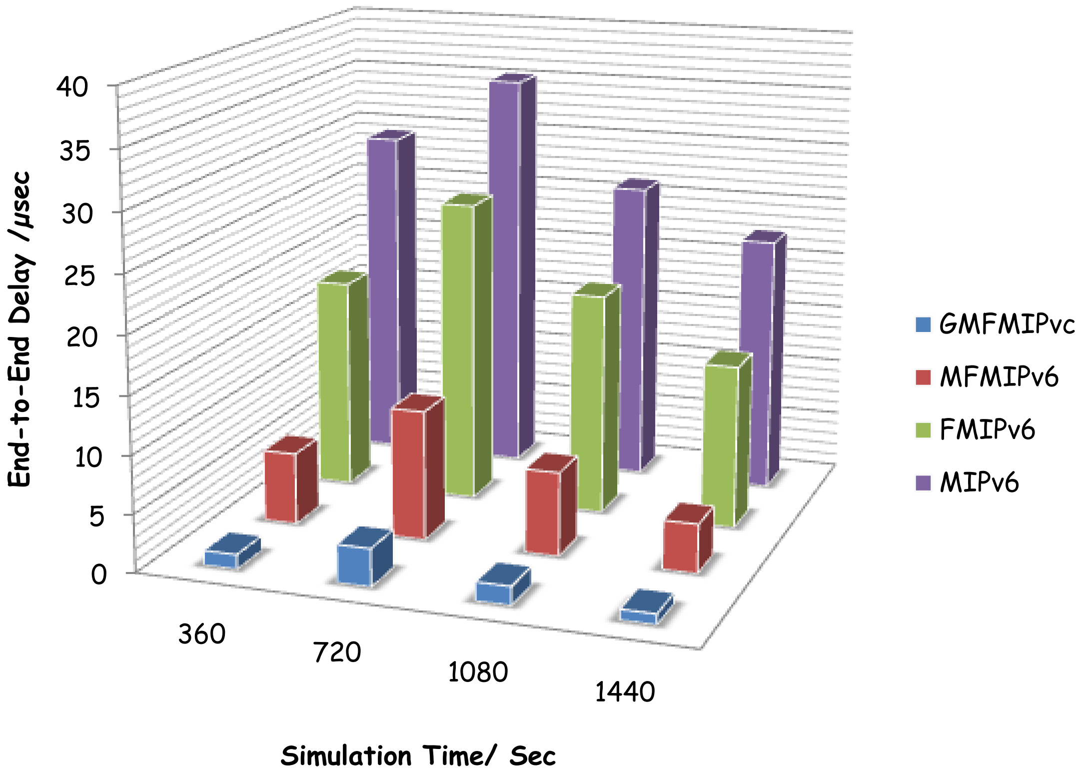


Figure 4-15: End-to-End delay over the simulation time.

Finally, the amount of energy consumed by the MN is a very critical factor as the MN depends exclusively on its battery to keep its communications and applications active for a longer time. In order to test the protocol ability to consume less energy, a modification has been done to the EnergyModel Class in NS2 [21] to calculate the amount of energy consumed per every transmitted and received bit through the MN interfaces.

```
class EnergyModel : public TclObject {
public:
  EnergyModel(double energy) { energy_ = energy; }
  inline double energy() { return energy_; }
  inline void setenergy(double e) {energy_ = e;}
  virtual void DecrTxEnergy(double txtime, double P_tx) {
    energy_ -= ((P_tx/8) * txtime);
  }
  virtual void DecrRcvEnergy(double rcvtime, double P_rcv) {
    energy_ -= ((P_rcv/8) * rcvtime);
  }
protected:
  double energy_;
};
```

Where, energy_ is the single class variable and represents the level of energy in the MN at any given time. The constructor EnergyModel(energy) requires the initial_energy to be passed along as a parameter. The other class methods are used to decrease the energy level of the node for every bit transmitted (DecrTxEnergy(txtime, P_tx)) and every bit received (DecrRcvEnergy(rcvtime, P_rcv)) by the MN. Moreover, P_tx and P_rcv are the transmitting and receiving power respectively, required by the MN's interface. At the beginning of simulation, energy_ is set to initialEnergy_ (set to be 10000 joule), which is then decremented for every transmission and reception of packets at the MN. When the energy level at the node goes down to zero, no more packets can be received or transmitted by the node, i.e. the node is dead.

Figure 4-16, shows the amount of energy left in the MN battery during the simulation time. Both MIPv6 and FMIPv6 show more energy left in the battery when compared to the MFMIPv6 protocol, this is because the MFMIPv6 protocol uses two interfaces and keeping them 'ON' during the entire simulation time to achieve a better communication. However, the GMFMIPv6 protocol shows almost similar results as compared to the MIPv6 and FMIPv6 and a much better results as compared to the MFMIPv6. This is again because of its ability to use one interface at a time and use the other interface only when a handoff is needed.

Although, the amount of energy consumed by the GMFMIPv6 protocol is slightly more as compared to the MIPv6 and FMIPv6 protocols, it can be easily deduce the magnificent advantage throughout the fact that the MN is using two interfaces at the same time. Thus, reducing the number of dropped packets all the way through the communication time. The other advantage of this protocol is by reducing the number of unnecessary handoffs (i.e. eliminating the problems of the ping-pong effects), thus reducing the end-to-end delay and improving the QoS throughout the entire communication time.

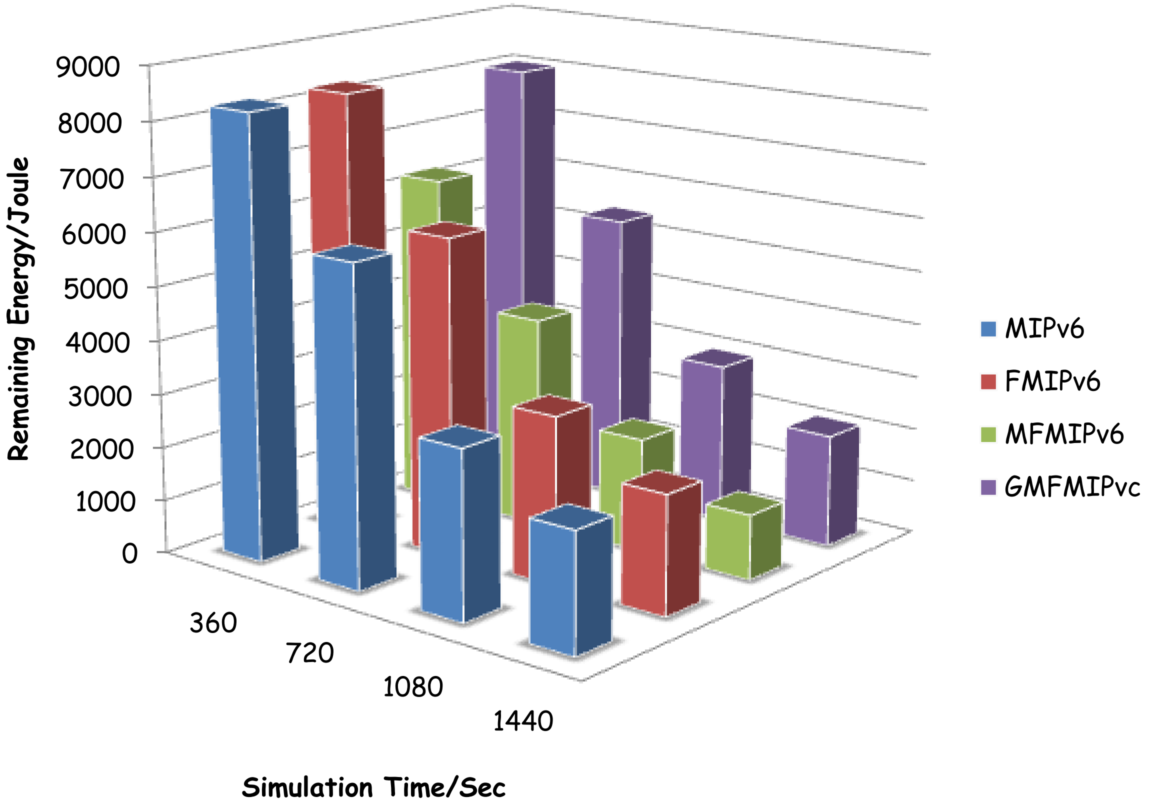


Figure 4-16: Energy consumption in the mobile node.

## 4.6 Summary

This chapter presents a novel methodology for combining Game Theory and wireless network selection mechanisms in multiple-interfaces MIPv6 wireless portable devices. What's more, it presents an extension to the MFMIPv6, by which the MN can decide whether to make the handover or not when it have multiple CoA's and/or multiple wireless interfaces. The proposed mechanism can indicate the best access point to choose during the handover procedure by sending the "winner" destination address (i.e. the NAR address) to the PAR using the FBU message. Moreover, the mechanism switches the mobile nodes interfaces 'ON' and 'OFF' when needed to control the mobile node's energy consumption and improves the handover latency.

A simulation-based comparison is made between the introduced protocol along with MFMIPv6, FMIPv6 and traditional MIPv6 protocols. The introduced protocol shows an improvement in the overall system performance when compared to other protocols in terms of reducing unnecessary handovers, reducing the end-to-end delay, reducing the number of dropped packets and increasing the number of received acknowledgment all the way through the communication time. The introduced protocol shows consumes less power when compared to other protocols, which gives the node a better chance to increase its active time when compared with the named protocols.

## 4.7 References:

[1] "Introduction to Mobile IP", Cisco IOS IP, 10/08/2001, avaliable online at: http://www.cisco.com/en/US/docs/ios/solutions_docs/mobile_ip/mobil_ip.html [Accessed 14th March 2010].

[2] T. Ernst, “The Information Technology Era of the Vehicular Industry”, ACM SIGCOMM Computer Communication Review, 2nd edition, April 2006.

[3] V. A. Clincy and P. Mudiraj, “The Future Leading Mobility Protocol- Mobile IPv4 or Mobile IPv6?”, Journal of Computing Sciences in Colleges, vol. 22, Iss. 6, pp. 197-203, June 2007.

[4] T. Ernst and H.Y. Lach, “Netwrok Mobility Support Terminology”, RFC 4885. July 2007. http://www.isi.edu/in-notes/rfc4885.txt [Accessed Augest 2007].

[5] P.K. Chowdhury, M. Atiquzzaman, and W. Ivancic, “SINEMO: An IP-diversity based Approach for Netwrok Mobility in Space”, 2nd IEEE International Conference on Space Mission Challenges for Information Technology. IEEE, 2006.

[6] T. Ernst, “Network Mobility Support Goals and Requirements”, October 2004. http://www.nautilus6.org/doc/drafts/draft-ietf-nemo-requirements-05.html [Aaccessed Augest 2007].

[7] A.H. Svendsen, and R.H. Nielsen, "Mobile Network, Movement Detection", Mobile Networks. June 2001. Available online at: http://www.hjortskov.dk/apparater.dk/maindoc/node64.html [Accessed 16th March 2010].

[8] C. Perkins et al, "IP mobility support for IPv4", RFC 3220, IETF. January 2002. Avaliable onlie at: http://www.rfc-editor.org/rfc/rfc3220.txt [Accessed 16th March 2010].

[9] N.A. Fikouras, K. El-Malki, S.R. Cvetkovic and C. Smythe, "Performance of TCP and UDP during Mobile IP Handoffs in Signal-Agent Subnetworks", Link; http://citeseerx.ist.psu.edu/viewdoc/summary?doi=?doi=10.1.1.4.1899, IEEE, 1999.

[10] G. Daley and J.Choi, "Movement Detection Optimization in Mobile IPv6 draft-daley-mobileip-movedetect-01.txt", IETF. May 2003. Available online at: http://tools .ietf.org/html/draft-daley-mobileip-movedetect-01 [Accessed 20th March 2010].

[11] A. Hasson, N. Ventura and S. Shepstone, "Mobile IP Movement Detection Optimizations in 802.11 Wireless LANs", pp. 393-397, September 2004.

[12] The Cable Guy, "Performance Enhancements in the Next Generation TCP/IP Stack", November 2005, Available onlie at: http://www.microsoft.com/technet/community /columns/cableguy/cg1105.mspx [Accessed 21st March 2010].

[13] C. Perkins and D. B. Johnson, "Route Optimization in Mobile IP draft-ietf-mobileip-optim-09", Mobile IP Working Group, February 2000. Available onlie at: http://people.nokia.net/charliep/txt/optim/optim.txt [Accessed March 2010].

[14] P. Nikander, J. Arkko, T. Aura, G. Montenegro and E. Nordmark, “Mobile IP Version 6 Route Optimization Security Desiagn Background”, Network Working Group. December 2005. Available online at: http://www.armware.dk/RFC/rfc/rfc4225.html [Accessed March 2010].

[15] D. Johnson, C. Prekins, and J. Arkko, “Mobility Support in IPv6”, RFC 3775, June 2004, Available online at: http://www.ietf.org/rfc/rfc3775.txt [Accessed March 2010].

[16] R. Koodli, “Fast Handovers for Mobile IPv6”, RFC 4068, July 2005, Availalbe online at: http://www.ietf.org/rfc/rfc4068.txt [Accessed 21st March 2010].

[17] E. Rasmusen, “Games and Information, An Introduction to Game Theory”, Blackwell Publishers, Fourth Edition, October 2006.

[18] R. Wakikawa, T. Ernst, and K. Nagami, “Multiple Care-of Addresses Registration”, RFC 5648, October 2009. Available online at: http://tools.ietf.org/html/rfc5648 [Accessed 5th May 2010].

[19] M.K. Park, J.Y. Lee, B.C. Kim and D.Y. Kim, “Design of Fast Handover Mechanism for Multiple Interfaces Mobile IPv6”, IEEE ISWPC 2008, pp 697-701, 2008.

[20] A.B. MacKenzie and L.A. deSilva, “Game Theory for Wireless Engineering”, Morgan&Claypool Publishers, 1st edition, 2006.

[21] “The Network Simulator ns-2.1b6”, Available online at: http://www.isi.edu/nsnam/ns/ [Accessed May 2009].

[22] MOTOROLA Labs and INRIA PLANETE Team MobiWan: NS-2.1b6 extensions to study Mobility in Wide-Area IPv6 Networks, May 2002. Available online at: http://www.inrialpes.fr/planete/mobiwan/ [Accessed May 2009].

# CHAPTER 5

# *Novel Game-Based Resource Allocation and Routing Mechanisms in Ad-Hoc Wireless Networks*

## 5.1 Introduction

A wireless Ad-Hoc network is characterised by a distributed, dynamic, self-organizing architecture. In such a network, each node is capable of independently adapting its operation based on the current environment according to predetermined algorithms and protocols. In multi-hop wireless Ad-Hoc networks, networking services are provided by the nodes themselves. Generally, the nodes must make a mutual contribution to packet forwarding in order to ensure an operable network. If the network is under the control of a single authority, as is the case for military networks and rescue operations, the nodes cooperate for the critical purpose of the network. However, if each node is its own authority, cooperation between the nodes cannot be taken for granted; on the contrary, it is reasonable to assume that each node has the goal to maximise its own benefits by enjoying network services and at the same time minimising its contribution. In this chapter, we investigate the case where a group of wireless nodes in an Ad-Hoc network are interested in some information within server node. In order to get such information, the nodes will compete between each other, using auction theory, to grant the access to these data. The node that appreciates the offered data more, will value it more, and win the bid. In this chapter, we have discussed the first and second price auctions [1-3]. Generally, the mechanisms works as follows; the destination will pay some money to the source and the source will try it is best to compensate the intermediate nodes in order to insure the reliability of the end-to-end route. The intermediate nodes will decide whether to participate on this route or not depending on the price the source will pay and on how much energy is needed to forward the packets to the next hop. We will see that there are two kinds of sources, *cooperative* and *selfish* source. Where the first will accept any positive payoffs and will do it’s best to cooperate with the destination to insure the reliability of the route. On the other hand, the *selfish* source will try to maximise its own profit without taking care of choosing the most reliable path.

## 5.2 Auction Theory: A Brief History

Economists consider auctions as one of oldest surviving classes of economic institutions [4]. One of the earliest reports of an auction was from interpreting the biblical account of the sale of Joseph (the great son of Abraham) into slavery as being an auction sale [5]. Another report was by the Greek historian Herodotus, who described the sale of women to be wives in Babylonia around the fifth century B.C. [6-7] these auctions use to begin with the woman the auctioneer considered the most beautiful and progressed to the least. In fact, at that time, it was considered illegal to allow a daughter to be sold outside of the auction method. During the closing years of the Roman Empire; the auction of plundered booty was common, following military victory, Roman soldiers would often drive a spear into the ground around which the spoils of war were left, to be auctioned off. Later slaves, often captured as the "spoils of war", were auctioned in the forum under the sign of the spear, with the proceeds of sale going towards the war effort [6]. Moreover, the personal belongings of deceased Buddhist monks were sold at auction as early as the seventh century A.D. in China. In some parts of England during the seventeenth and eighteenth centuries auction by candle was used for the sale of goods and leaseholds. This auction began by lighting a candle after which bids were offered in ascending order until the candle spluttered out. The high bid at the time the candle extinguished itself won the auction [8]. During the end of the 18th century, French started auctioning art, soon after the French Revolution, daily in taverns (which was used to be considered as a place of business and social activities) and coffeehouses, during these auctions, catalogues used to be printed to show available items. Which lead us to mention the oldest auction house in the world, known as “Stockholm Auction House”, it was established in Sweden in 1674 [9-10].

As impressive as the historical facts of auctions is the remarkable range of situations in which they are currently used in our day-to-day life. There are auctions for livestock, auctions for rare and unusual items like diamonds, work of arts and other collectibles. Reports from recent researches can be seen in the United States in the 1980's, where every week, the U.S. treasury sells billions of dollars of bills and notes using a sealed-bid auction. The Department of the Interior sells mineral rights on federally-owned properties at auction. Furthermore, many examples can be seen throughout the public and private sectors, purchasing agents solicit delivery-price offers of products ranging from office supplies to specialized mining equipment; sellers auction antiques and artwork, flowers and livestock, publishing rights and timber rights, stamps and wine and many other market transactions [4]. From the academic point of view, [11-12] can be considered as one of the influential contributions of auction theory; it was followed by a large amount of literature, which examined the behaviour of competitive bidders in auctions. [13-15] define an auction to be a market institution with an explicit set of rules determining resource allocation and prices on the basis of bids from the market participants. Consequently, the auctioned good is to be sold with a price resulted from direct competition of the potential buyers, who know exactly their individual willingness to pay better than the seller. Finally, the development of the internet, however, has led to a significant increase in the use of auctions as sellers can seek for bids via the internet (such as the bidding system in eBay [16-17]) from a wide range of buyers in a much wider range of commodities than was previously practical [6].

It is important to mention that for several reason this work is restricted to the discussion of a single object auctions. On one hand, in order to analyze such auctions, it might get rather difficult if multiple objects are to be allocated. On the other hand, the results derived for single unit auctions definitely give a good understanding over the effects auction rules and behavioural assumptions have on the bidding behaviour.

Generally speaking, there are four standard auctions that are discussed in the literature [2-5]. These standards are; the ascending-bid auction (known as the English auction), the descending-bid auction (known as the Dutch auction), first-price auction and the second-price auction (known as Vickery auctions). All of these auctions apart from Vickery auction are used in business transactions, while Vickery auctions is rarely used but it has some theoretically appealing properties. These mechanisms assigns the highest bidder to be a winner, however, they can be classified basically by two main factors. Firstly the bidders can submit open or sealed bids; secondly the price may be determined by the highest or the second highest bid.

The ***ascending-bid auction*** is the most common auction form. In this type of auctions, the price is successively raised until only one bidder remains. This can be done either by the auctioneer, announcing prices, or by the bidders calling for higher bids themselves. Thus, the remaining bidder receives the object paying only the second highest bid. A very important feature of this auction is that each bidder knows the current highest bid at any point in time.

The ***descending-bid auction*** is the converse of the ascending-bid auction. The seller begins by announcing a price that exceeds the willingness to pay of every bidder (i.e. a very high price). Then he lowers the price until one bidder accepts the actual offer. This bidder pays the price at which he claimed the object.

In the ***first-price sealed-bid auction*** bidders submit sealed bids and the highest bidder gets the object for the price he bid. In the ***second-price sealed-bid auction***, however, the highest bidder is awarded the item and pays the second highest bid.

## 5.3 Proposed Auction Mechanism

In order to reflect user $i's$ valuation about the data information in the server, a simple valuation function is proposed:

$$I = C_i \times v_i \qquad (5\text{-}1)$$

where $I$ is the importance of the data information offered by the source node; which is assumed to be known to all destinations and its set by each destination randomly according to the need of each individual node. $C_i$ is the normalized channel capacity, which can be expressed as the tightest upper bond on the amount of information that can be reliably transmitted over a communication channel, and $v_i$ is user $i'$s valuation to the data offered by the source about his strategic situation defined in percentage. Shannon Channel capacity is defined as:

$$C_i = B \ log_2(1 + \frac{f_i \, p}{N_\circ}) \qquad (5\text{-}2)$$

where $f_i$ is the channel coefficient between user $i's$ transmitter and user $j's$ receiver (i.e. the transmission data rate between the two points over the named channel). $B$ is the channel bandwidth in $(Hz)$; $p$ is the amount power that the source need to transmit the data to the next hop, and $N_\circ$ is the mean channel noise power (The mean noise power in the receiver N is given by ; $N = kT_\circ B \quad (W)$. Where $k$ is the Blotzmann's Constant $= 1.38 \times 10^{-23}\, JK^{-1}$and $T_\circ$ is the system temperature, which is generally assumed to be $290K$). Then each user valuation can derived from equation (5-2) and expressed as:

$$v_i = \frac{I}{B \times log_2(1 + \frac{f_i\, p}{N_\circ})} \qquad (5\text{-}3)$$

The valuation of the data information can be interpreted that user $i$ uses the importance of the data (already known to all users) as a ruler to set his bid in the auction. This valuation measures the destination (if he wins the auction) capabilities to bid more for the offered data keeping in mind the capacity of his channel. We can see that when the channel condition is good (according to equation (5-2)), the user will be more willing to increase his bid for the offered data. As a result, a higher bid would be expected from him and vice versa.

It must be mentioned that the auction mechanism is designed in such a way that $v_i$ does not represent the real price that a destination node has to pay during the auction. Simply it is an interpretation of the strategic situation that a node is facing. In fact $v_i$ reflects the relationship between the node valuation and the channel condition. Additionally, since the channel coefficient $f$ is a constant random variable with a known distribution to each user, the distribution of the valuation $v_i$ is also known (according to their relationship shown in equation (5-2)), which means that; $v_i$ lies in the interval $[v_{min}, v_{max}]$.

$Bid$ is defined as the bid space in the auction,$\{bid_0, bid_1, bid_2, \ldots, bid_n\}$, which represent the set of possible bids submitted to the source. We can simply assign $bid_0$ to zero without loss of generality, as it represent the null bid. Accordingly, $bid_1$ is the lowest acceptable bid, and $bid_n$ is the highest bid. The bid increment between two adjacent bids is taken to be the same in the typical case. In the event of ties (*i.e.* two bidders offer the same final price), the object would be allocated randomly to one of the tied bidders.

To find the winner of the first-price sealed-bid auction, a theoretical model is defined based on the work of H.J. Parrsch and J. Robert [1]. The probability of detecting a bid $bid_i$ is denoted as $\pi_i$, the probability of not participating in the named auction will be denoted as $\pi_0$. Then the vector $\pi$, which equals to $(\pi_0, \pi_1, \pi_2, \ldots, \pi_n)$, and it is denoted as probability distribution over $Bid$, where $\sum_{i=0}^{n} \pi_i = 1$ . Now we introduce the cumulative distribution function, which is used to find out whether a user $i$ will bid with $bid_i$ or less, $\Pi_i = \sum_{j=0}^{i} \pi_i$ , all of them are collected in the vector $\Pi$, which equals to $(\pi_0, \Pi_1, \ldots, \Pi_{k-1}, 1)$.

Then, any rational potential bidder with a known valuation of $v_i$ faces a decision problem of maximizing his expected profit from winning the auction; i.e.

$$\max_{<b_i \epsilon Bid>}(v_i - bid_i)Pr\ (winning|bid_i) \qquad (5\text{-}4)$$

The equilibrium probability of winning for a particular bid $bid_i$ is denoted as $\vartheta_i$, and these probabilities are collected in $\vartheta$, $(\vartheta_0, \vartheta_1, \vartheta_2, \ldots, \vartheta_n)$. Using $\pi$, the elements of the vector $\vartheta$ can be calculated. It can be easily found that $\vartheta_0$is known to be zero, as if any bidder submitted a null bid to the source, he is not going to win. We can calculate the remaining elements of $\vartheta$ as it can be directly verifying that the following constitute a symmetric, Bayes-Nash equilibrium of the auction game:

$$\vartheta_i = \frac{(\Pi_i)^n - (\Pi_{i-1})^n}{n(\Pi_i - \Pi_{i-1})}\ \forall i = 0, 1, 2, \ldots, n \qquad (5\text{-}5)$$

Throughout this chapter, we will use the notation of Bayes-Nash equilibrium as defined in [3], there approach is to transform a game of incomplete information into one of imperfect information, and any buyer who has incomplete information about other buyers' values is treated as if he were uncertain about their types.

From equation (5-5), it can be seen that the numerator is the probability that the highest bid is exactly equal to $bid_i$, while the denominator is the expected number of user how are going to submit the same bid (i.e. $bid_i$). For any user in the game, the best response will be to submit a bid which satisfies the following inequality;

$$(v_i - bid_i)\vartheta_i \geq (v_j - bid_j)\vartheta_j\ \forall\ j \neq i$$

The above inequality shows that user $i's$ profit is weakly beat any other user $j's$ profit. The above inequality is the discrete analogue to the equilibrium first-order condition for expected-profit maximization in the continuous-variation model [1], which takes the form of the following ordinary differential equation in the strategy function $\delta(v_i)$;

$$\acute{\delta}(v_i) + \delta(v_i)\frac{(n-1)f(v_i)}{F(v_i)} = v_i\frac{(n-1)f(v_i)}{F(v_i)} \qquad (5\text{-}6)$$

where $f(v_i)$ and $F(v_i)$ are the probability density and cumulative distribution functions of each bidder valuation respectively. We assume that they are common knowledge to bidders along with $n$, the number of bidders in the system. The reserve price is denoted by $r$, (In many instance, sellers reserve the right not to sell the object if the price determined in the auction is lower than some threshold amount [2-3], say $r > 0$), and the above differential equation has the following solution;

$$\delta(v_i) = v_i - \frac{\int_r^{v_i} F(u)^{n-1} du}{F(v_i)^{n-1}} \qquad (5\text{-}7)$$

In order to get to equation (5-7), we simply multiply both sides of equation (5-6) by $\frac{F(v_i)}{(n-1)f(v_i)}$. This will lead us to; $\frac{F(v_i)}{(n-1)f(v_i)}\ \acute{\delta}(v_i) + \delta(v_i) = v_i$, which can be easily arranged to; $\delta(v_i) = v_i - \acute{\delta}(v_i)\ \frac{F(v_i)}{(n-1)f(v_i)}$, and based on the fact that $\frac{d}{dv}F(v)^{(n-1)} = (n-1)f(v)$, it can be easily shown that the solution is straight forward and lead us to equation (5-7).

In the case of the first-price sealed-bid auction, the bidder $i$ will submit a bid of $b_i = \delta(v_i)$ in equilibrium and he will pay a proportional price to his bid if he wins. On the other hand, for the second-price sealed-bid auction, a user $i$ will submit his valuation truthfully. This is because the price a user has to pay if he wins the auction is not the winning bid but the second highest one. Therefore, there is nothing to drive a user to bid higher or lower than his true valuation to the data offered by the server. In this case, $b_i = v_i$, shown in equation (5-3), and the payment process is the same as in the first-price auction.

## 5.4 Modelling of Traditional Routing Techniques

One of the recent application of game theory to Ad-Hoc routing [18-26] focuses on the analysis of the effectiveness of three Ad-Hoc routing techniques, namely link state routing, distance vector routing and multicast routing (reverse path forwarding), in the event of frequent route changes. The objective of the analysis is to compare and contrast the techniques in an Ad-Hoc setting. These techniques are evaluated in terms of:

1. *Soundness* – whether routers have a correct view of the network to make the correct routing decisions under frequent network changes;
2. *Convergence* – length of time taken by the routers to have a correct view of the network topology as nodes move; and
3. *Network overhead* – amount of data exchanged among routers to achieve convergence.

Routing is modelled as a zero sum game between the two players; the set of routers and the network itself. In a zero-sum game [27-28] the utility function of one player (minimizing player's utility) is the negative of the other's (maximizing player's utility). The game has equilibrium when the $(min, max)$ value of any player's payoff is equal to its $(max, min)$ value. In a zero sum game, the $(max, min)$ value is defined as the maximum value that the maximizing player can get under the assumption that the minimizing player's objective is to minimize the payoff to the maximizing player. *In other words*, the $(max, min)$ value represents the maximum among the lowest possible payoffs that the maximizing player can get; this is also called the *safe* or *secure payoff*.

In the routing game, the payoff to each player (i.e. wireless nodes) consists of two cost components, one being the amount of network overhead and the other varying with the performance metric under consideration. For example, for evaluating soundness the cost to the routers is "0" if all routers have a correct view of the topology when the game ends and "1" if any one router does not. The objective of the routers is to minimize the cost function. The action for the routers involved is to send routing control messages as dictated by the routing technique and update their routing information, and for the network to change the state of existing links from up to down and vice versa. The game is solved to determine the $(min, max)$ value of the cost function. It serves to compare the different routing techniques in terms of the amount of routing control traffic required to achieve convergence and the soundness of the routing protocol to network changes. One of the main conclusions reached in the comparative analysis was that reverse path forwarding requires less control traffic to achieve convergence, against traditional link state routing.

Another issue related to routing involves studying the effect of selfish nodes on the forwarding operation, as to be discussed in the following sections.

## 5.5 Selfish Behaviour in Forwarding Packets

The establishment of multi-hop routes in Ad-Hoc networks relies on nodes' forwarding packets for one another. However, a selfish node, in order to conserve its limited energy resources, could decide not to participate in the forwarding process by switching off its interfaces. If all nodes decide to alter their behaviour in this way, acting selfishly, this may lead to the collapse of the network. The works of [29-34] develop game theoretic models for analysing selfishness in forwarding packets. Under general energy-constraint assumptions, the equilibrium solution for the single-stage game results in none of the nodes' cooperating to forward packets. A typical game theoretic model that leads to such equilibrium is parameterized in this section.

Generally, in wireless games, $N$ is the number of wireless nodes in the network, $S_k$ is the actions set for node $k$ in the network; $S_k = \{0,1\}$.

$$S_k = \begin{cases} 0, & when\ the\ node\ action\ is\ not\ participate \\ 1, & when\ the\ node\ action\ is\ participate \end{cases} \tag{5-8}$$

Where, $S$ is the joint action set; $S = X_{k \in N}\, S_k$. $s = \{s_1, s_2, \ldots\ldots, s_n\}$; $s \in S$. $\alpha_k(s)$ is the benefit accrued when other nodes participate; $\left(\alpha_k(s) = \sum_{i=1, i \neq k}^{n} s_k\right)$. $\beta_k$ is the energy consumption of the node when it participate; $(\beta_k = -s_k)$. $u_k(s)$ is the utility function for each node:

$$u_k(s) = \alpha_k(s) + \beta_k(s) \tag{5-9}$$

However, in practical scenarios, Ad-Hoc networks involve multiple interactions among nodes/players with a need for nodes to participate. In order to account for such interactions, the basic game is extended to a repeated game model. Different repeated game mechanisms such as tit-for-tat [36] and generous tit-for-tat are investigated in [22, 30 and 33] to determine conditions for a desirable Nash Equilibrium – one in which all nodes would forward packets for one another leading to a high network-wide social welfare. The tit-for-tat based mechanisms provide an intrinsic incentive scheme where a node is served by its peers based on its past behavioural history. As a result, a node tends to behave in a socially beneficial manner in order to receive any benefit in the later stages.

The work in [36-37] extends this concept of exploiting the intrinsic 'fear' among nodes of being punished in the later stages of the game by deriving the conditions under which a grim-trigger strategy is a Nash equilibrium in a game where nodes are asked to voluntarily provide services for others (examples of these include peer-to-peer networks and distributed clusters, as well as Ad-Hoc networks). A node following the grim trigger strategy in a repeated game is characterized by a behaviour wherein it continues to cooperate with other nodes until a single defection by any of its peers, following which it ceases to cooperate for all subsequent stages. The sustainability of the equilibrium for this strategy depends on the number of nodes in the network and the exogenous beliefs that the nodes have regarding the possible repetitions of the game. The authors conclude that the greater the number of nodes in the network the higher the chances of achieving a desirable equilibrium, even if the likelihood that the game will be repeated is low. These games are different from those analysed in [30-34] as the decisions of the nodes are not based on an external incentive scheme such as reputation.

Other functions related to the network layer or to the management plane, such as service discovery and policy-based network management, are also amenable to a game-theoretic analysis. There is scarce literature on those issues, with the notable exception of [14], which studies management in a sensor network.

The algorithm represented in this chapter is mainly focusing on keeping the defined path stable, where all the participating nodes are faithful to forward the packets to the next hop all the time is really important in this case. Game theory defines such a point as Nash Equilibrium. Adding some suitable modifications to the well known $Dijkstra\ algorithm$ [42], a polynomial-time solution to find the Nash Equilibrium is shown in the following sections, as shown in Figure 5-1. Simulations have been presented to evaluate the reliability of the obtained route as a function of the destination and source offered payments, the source to intermediate nodes payments, power consumption and degree of source-destination cooperation for different network parameter settings.

Finally, we have to mention that these investigations are motivated by the works of Kannan, Sarangi and Lyengar on reliable query routing [38-41]. To the knowledge of the authors, they are the first to formulate a game where the node utilities show a tension between path reliability and link costs, and they have considered different interesting variants of this problem. A key difference in this work is that we explicitly allow the null strategy in which nodes may choose not to forward packets to any next-hop neighbour. This allows us to provide a polynomial time algorithm for obtaining an efficient Nash equilibrium path. Another key difference in our work is that we consider the notion of destination and source payments and the amount of consumed power in each intermediate node when participating in any defined path and incorporate them into the utility functions. Every intermediate node will have the right to decide whether to participate in a route or not, based on the amount of energy the node has by the time the request is received from the source. The nodes will not argue with any request if it has more than 50% of its battery life, it will take into account the source compensation when it has less than 50% and will not participate in any route if it has less than 30% of energy. Finally, we used auction theory to decide the winner of the data information offered by the source.

## 5.6 Price and Power-Based Routing Algorithm

In this section, we define the destination driven pricing and power saving routing problem formally. A wireless network is modelled as non-cooperative game $Game\ (N, L)$ where $N$ denotes all the nodes in the network and $L$ represents the link set. Each node $n_i$ in $N$ is associated with a reliability parameter $R_i$; $(0 \leq R_i \leq 1)$. $R_i$ indicates the node availability and stability – the probability that it can forward a packet sent to it. Each link $l = (n_i, n_j) \in L$ has a link cost parameter $C_{i,j}$ , which represent the communication set up cost between two end nodes. Each link $l = (n_i, n_j) \in L$ has a link power consumption parameter $P_{i,j}$, which represent the power consumed by node $i$ when it communicate with node $j$ (i.e. node $i$ forwards a packet to node $j$).

There are three kinds of nodes in the network: destination node $(dst)$ (i.e. the winner of the auction), source node $(scr)$ (i.e. the server node, which offers the data information) and other intermediate nodes $n_i$ (where $n_i \in N/\{dst, scr\}$) that are candidates for participating in a route between the source and the destination. We assume that both destination node and source node always have node reliability (While the destination does play a role in offering the payment $G$ ($G$ must be more than or equal to the source reserved price $G \geq r$), this is a constant that only affects the utility of the source). The destination node offers to the source node a payment of $G_d$, which is equal to $v_i$ defined in equation (5-3) (i.e. $G_d = v_i$). The source in turn offers a payment $G_s$ (for each successfully delivered packet) that will be given to any intermediate node if it participates in the routing path. Similarly, we are assuming that each node in the network, which will participate in any defined path, will lose some of its power $P_f$ when forwarding any packets to its neighbours. To formulate the core game, we now give the definition of the triplet $(I, (S_i)_{i \in I}, (u_i)_{i \in I})$ where $I$ is the set of players; $S_i$ is the set of available actions with $S_i$ be the non-empty set of actions for player $i$; and $u_i$ is the set of payoff functions. In this game, we define $I = N \backslash \{dst\}$ which means that all nodes except the destination are players (While the destination does play a role in offering the payment $G_d$, this is a constant that only affects the utility for the source). In an $n$ nodes network (including source and destination nodes), for each node $n_i \in N \backslash \{dst\}$, its strategy is an $n$-tuple $Si = (s_{i,1}, s_{i,2}, \ldots s_{i,n})$ where:

$$S_{i,j} = \begin{cases} 1, & if\ node\ n_j\ is\ n_i^{\prime}s\ next\ hope\ in\ path \\ 0, & otherwise \end{cases} \qquad (5\text{-}10)$$

It should be mentioned that $n_i \in N \backslash \{dst\}$ and $n_j \in N$. Each strategy tuple has at most one 1. That is, $\forall n_i, \sum_{j=1}^{n} s_{i,j} \leq 1$.

If node $n_i$'s strategy tuple contains all zeros, node $n_i$ does not participate on packet forwarding in the game. A system strategy profile $(S_i)_{i \in I}$ is a profile which contains all players' strategies in the network. Given this strategy profile, there is either no path from the source to the destination, or else, there is exactly one path $Path$ (since each node can point to only next-hop). Without loss of generality, let's denote $Path = (src, n_1, n_2, \ldots, n_h, dst)$. Here $h$ denotes the number of hops between the source node and the destination node (not inclusive). The utility function for each player is defined as follows:

For the source node:

$$u_{src} = \begin{cases} 0 & , if\ no\ path\ exists \\ (G_d - h.G_s - P_{tr}) \prod_{n_i \in Path} R_i - C_{src,n1} & , otherwise \end{cases} \qquad (5\text{-}11)$$

The utility of the source node equals to the difference between the expected income of the source and the link set up cost from the source node to the first next hop routing node. The expected income of the source is the destination payment (i.e. $G_d$) minus the source pay to all the intermediate nodes (i.e. $h.G_s$) minus the power lost to transmit packets to the next hop ($P_{tr}$) times the probability that the packet is successfully delivered (i.e. $R_i$).

For each other node $n_i$:

$$u_{node} = \begin{cases} 0 & , if\ no\ path\ exists\ or\ n_i \notin Path \\ G_s \prod_{n_{i+1}}^{n_h} R_i - C_{n_i,n_{i+1}} - P_f, & otherwise \end{cases} \qquad (5\text{-}12)$$

$n_i$ is the $i^{th}$ node in the path if the named node is going to participates in the defined path. The utility of each intermediate routing node equals to the expected payment (i.e. $G_s$) it obtains from the source node times the ongoing route reliability (i.e. $\prod_{n_{i+1}}^{n_h} R_i$) minus the transmission cost per packet to its next hop neighbour (i.e. $C_{n_i,n_{i+1}}$) minus the power lost to forward the packets to the next hop (i.e. $P_f$).

It should be mentioned that the cost is made proportional to the square of the distance between two nodes if they are in each other's transmission range and how much power is consumed. If the two nodes are out of each other's transmission range, the link cost between these two nodes is set to be infinity. The mathematical representation is as follows:

$$C_{i,j} = \begin{cases} P_f.\varepsilon.d(i,j)^2, & if\ d(i,j) \le \partial \\ \infty & , otherwise \end{cases} \tag{5-13}$$

where $d(i,j)$ is the distance between node $n_i$ and node $n_j$; and $\partial$ is the transmission range of the wireless nodes. In the simulation settings, ε is set to 0.1 (we also did extensive simulations for different ε values, similar curve trends are observed).

The link reliability can be represented in the form;

$$R_{i,j}(t) = \frac{\sum_{i,j} P_{kts}{}_{i,j}^{f}(t)}{\sum_{i,j} P_{kts}{}_{i,j}^{g}(t) + \sum_{i,j} P_{kts}{}_{i,j}^{r}(t)} \tag{5-14}$$

The link reliability between two nodes (i.e. $i\ and\ j$) is defined as the ratio of the number of packets forwarded to the total number of received and generated packets the two nodes at time $t$.

If the node does not participate in the routing, it gains (and loses) nothing. We now develop an algorithm to obtain an efficient Nash equilibrium for this game. We have to mention that both values of $G$ and $P$ must be normalized in order to get the normalized value of the utility for each node. The following two equations shows how the more the source pays to the intermediate nodes the more the nodes participate in forwarding packets to its neighbours. Furthermore, the more power and cost the node have to consume in order to forward the source packets the less the node will be willing to contribute in the path. $nf_{G_s,i} = \frac{1}{e^{\frac{\propto_i}{G_{s,i}}}}$ , $nf_{C_{ni,ni+1}} = \frac{1}{e^{\frac{C_{ni,ni+1}}{\gamma_i}}}$ and $nf_{P_f,i} = \frac{1}{e^{\frac{P_{f_i}}{\beta_i}}}$ , where, $\alpha_i \ge 0, \gamma_i \ge 0, \beta_i \ge 0.$

The exponential functions have been used to increase the sensitivity of the functions to the respective parameters they are related to. Finally, they are inversed in order to bind the functions to a value between zero and one.

## 5.7 Improvement Schemes for the Auction and Routing Algorithms

The auction mechanism mentioned earlier, is repeated every time the offered data have been successfully delivered to the destination node, the winner of the auction. We are assuming that the source has different types of data that he offers to other nodes, the reservation price will change according to the data the source is offering for sale. We also considered the case of *winner retreat* (*i.e.* Pareto Efficiency case, section (2.4)), by which the winner is not interested anymore in the offered data (*for example*; link failure, the node run out of power, etc.). In such a case, a *counter* with a random value is introduced in the server to check whether the winner node is still interested in the offered data or not. Once the source finishes sending the data to the winner, it should wait for an acknowledgement that the data been received and starts a new auction for another pair of data, and that's when the *counter* value is set. If there is no acknowledgement been received when $counter = 0$, the source send a message to the winner node to confirm the receiving of the data. If no reply been received after this message, the source will assume that the node is no longer in the network and starts a new auction.

From the routing point of view, our goal is to develop an algorithm for computing an efficient Nash equilibrium path that provides maximum reliability while ensuring that all nodes obtain non-negative payoffs (We should note that in our model even any shortest-hop path that ensures non-negative payoffs to all nodes are in Nash equilibrium). The algorithm we present could be potentially modified to provide such a shortest-hop Nash equilibrium path; however, our interest is in finding an efficient equilibrium path that also provides maximum reliability. This allows us to characterize the performance of the most efficient equilibrium path that can be obtained under different prices). The link between non-negative payoffs and the equilibrium path is given by the following simple lemma.

$\boldsymbol{Lemma\ 1}$: *If a path exists and it is a Nash Equilibrium, every node on the path must have non-negative payoff*.

The proof for this lemma is straightforward. According to the payoff function, a node would rather choose not to participate in routing (with payoff 0) if joining the routing makes its payoff negative. However, it must be noted that it is not necessary for all the paths with non-negative payoff to be Nash equilibrium. Such path is defined as PPP (Positive Payoff Path). On the other hand, a path with all routing nodes having non-positive payoff is defined as NPP (Negative Payoff Path).

To find a PPP, we first simplify the problem to a more concise representation. According to the definition, we need that for each intermediate routing node $n_i$, its utility $u_{ni} \geq 0$. This implies:

$$\prod_{k=1}^{n} R_k \geq \frac{C_{i,i+1}}{G_s} \qquad (5\text{-}15)$$

where $R$ is the link reliability. In order to convert the product to summation, we take the logarithm of both sides and get:

$$\sum_{k=i}^{n} log_{10} R_k \geq log_{10} \frac{C_{i,i+1}}{G_s} \qquad (5\text{-}16)$$

Notice that $0 \leq R_k \leq 1$; we take the inverse of each $R_k$ to make each term in the summation positive. The original formula now transforms to;

$$\sum_{k=i}^{n} log_{10} \frac{1}{R_k} \leq log_{10} \frac{G_s}{C_{i,i+1}} \qquad (5\text{-}17)$$

For each $n_i$. Replacing $log \frac{1}{R_k}$ by $r_k$ (when $r_k \geq 0$) and replacing $log \frac{G_s}{C_{i,i+1}}$ by $C_{i,i+1}$, we formulate the problem of finding a PPP in the original graph to an equal problem of finding an NPP in a transformed network graph, where each node has a positive value $r_k$ and each edge is assigned a value $C_{i,j}$ , according to the following transformed utility functions $\tilde{u}$. For the intermediate node,

$$\widetilde{U_{n_\iota}} = C_{i,i+1} - \sum_{k=i}^{n} r_k \qquad (5\text{-}18)$$

For the source node, we get

$$\sum_{k=i}^{n} log_{10} \frac{1}{R_k} \leq log_{10} \frac{G_s h_p}{C_{scr,n1}} \qquad (5\text{-}19)$$

Replacing $log \frac{1}{R_k}$ by $r_k$ and replacing $log \frac{G_s h_p}{C_{scr,n1}}$ by $C_{scr,nbr}$, we will have

$$\widetilde{u_{n_{scr}}} = C_{scr,nbr} - \sum_{k=i}^{n} r_k \qquad (5\text{-}20)$$

With these log-transformed formulae, in the following, we will first find an NPP of smallest $\sum r_k$ from each neighbour of source node. Then, if the source node is selfish, it picks up a feasible path provided by neighbours that gives it smallest $C_{scr,nbr} - \sum r_k$ or else if cooperative with the destination, it picks the path with the smallest $\sum r_k$. In either case, the source only participates in routing if its own original expected utility will be positive.

A polynomial time algorithm modified from $Dijkstra's\ algorithm$ can be applied to find the NPP with the smallest $\sum r_k$ from each neighbour of the source to the destination. The pseudo code for the algorithm is given below. Note that the original source does not participate in this algorithm, so we denote the neighbour in question as $src$ in the algorithm. In brief, the algorithm starts labelling nodes from the destination, applying $Dijkstra's\ algorithm$, with adding negative utility checking step. In the algorithm, each node has a label, which is a tuple $(from, L(n_i), \widetilde{u_{n\iota}})$. The first item in the tuple indicates from which node the label comes (i.e., the next hop of current node starting from source). The second term in the tuple records the summation of $r_k$, which is analogous to the length in $Dijkstra's\ algorithm$. The third term tracks the current $\tilde{u}$ value. This algorithm is applied in turn for each neighbour of the source before the source picks one of these neighbours to form the path, as described above. Since the $r$ value is related to nodes instead of the links, we need a definition of neighbourhood set for vertices in a given game $G(N, L)$.

$\boldsymbol{Theorem}$: The path found by the algorithm is a Nash equilibrium path in the PPP finding problem.

Proof (by contradiction): Assume that the algorithm returns a path $Path = (n_1, n_2, \ldots, n_i, n_{i+1}, \ldots, n_j, \ldots n_N)$, which is not a Nash equilibrium. Without loss of generality, suppose only one node $n_i$ wants to switch his next hop from $n_{i+1}$ to $n_j$, where $j > i + 1$.

Path $\tilde{P}ath = (n_0, n_1, \ldots., n_i, n_j, \ldots, n_n)$ is also a PPP, since the payoff of the nodes before $n_j$ increases by the increase of path reliability (remember $0 \leq R_k \leq 1$) and the payoff after $n_i$ (including $n_j$ ) keep unchanged. Thus path $\tilde{P}ath$ is one of the feasible paths. Since the path abandoned some intermediate nodes, the path reliability of $\widetilde{\mathrm{P}}\mathrm{ath}$ is larger than $Path$. This would imply that the algorithm should return path $\widetilde{\mathrm{P}}\mathrm{ath}$ instead of $\mathrm{Path}$, which contradicts the assumption. By construction, the node has no incentive to switch its next hop to a node that is not on the returned path since those nodes do not pick any next-hop neighbour.

As we mentioned before, the algorithm runs to obtain a positive payoff path to destination from each neighbour of the source node. If the source node is selfish, among all the feasible paths reported from its set of neighbours, it will pick the one that gives its maximum profit according to the source's utility function. If the source node is cooperative, it will pick the path, which gives the highest path reliability.

```
Finding an NPP with Minimum $\sum r_k$ in Transformed Network Game
1) Initialization:
Set $FS = \{dst\}$
All other nodes labeled as $(-, \infty, -)$, $L(dst) = 0$
2) while $src \notin FS$ && $N \backslash (FS) \neq 0$
        • for each $n_i \in N \backslash (FS)$
                – while ($\exists n_k \in FS$ such that $(n_i, n_k) \in E$)
                _ $L(n_i) = min(L(n_i),$
                $min\ n_j \in FS$ && $(n_i, n_j) \in E(L(n_j) + r_i))$ let $n_j$ be the corresponding next hop node
                    ✓ if $\widetilde{u_{n_i}} - c_{i,j} \leq 0$: delete edge $(n_i, n_j)$.
                    ✓ else: update the label triplet to $(n_j, L(n_i), L(n_i) - c_{i,j})$;
                add $n_i$ to FS;
                break
                – end while
        • end for
end while
```

Figure 5-1: Modified Dijkstra Algorithm to fir the defined auction-game scheme.

## 5.8 Simulation Results

This section shows the introduced auction mechanism and the improvement scheme added to it in the previous section, along with the dynamic routing algorithm in Ad-Hoc networks. We used a fixed $450m \times 450m$ as our simulation area and a maximum of 35 intermediate nodes within the network. The node's transmission range is set to an average of 21 meters with very low mobility speed (<1m/sec). The node reliability is uniformly chosen at random in interval [0.1, 1]. Furthermore, we assumed that the packets length is 1000 bytes, and the bandwidth of the channel to be 1MHz, all nodes to use $250\,mW$ transmitting power. The importance of the data is defined in each user, for simplicity, each user will choose the importance of the data at random from the interval [1, 95]. The importance of the data information offered by the source is measured in percentage, the user need will change whenever a new auction is announced by the source.

The model is compared with similar model with a game-based model only, which is similar to the ones introduced in [38-41], where the source will assign the data to the first buyer without waiting for any other offers and pays all intermediate nodes the same amount of compensation. Also the model is compared with a similar combination of Auction and Game theories, but with using first and second-price sealed-bid auctions.

Figure 5-2; below shows a very simple example of an auction scenario. Where the source node announces the auction and waits for the users' bids.

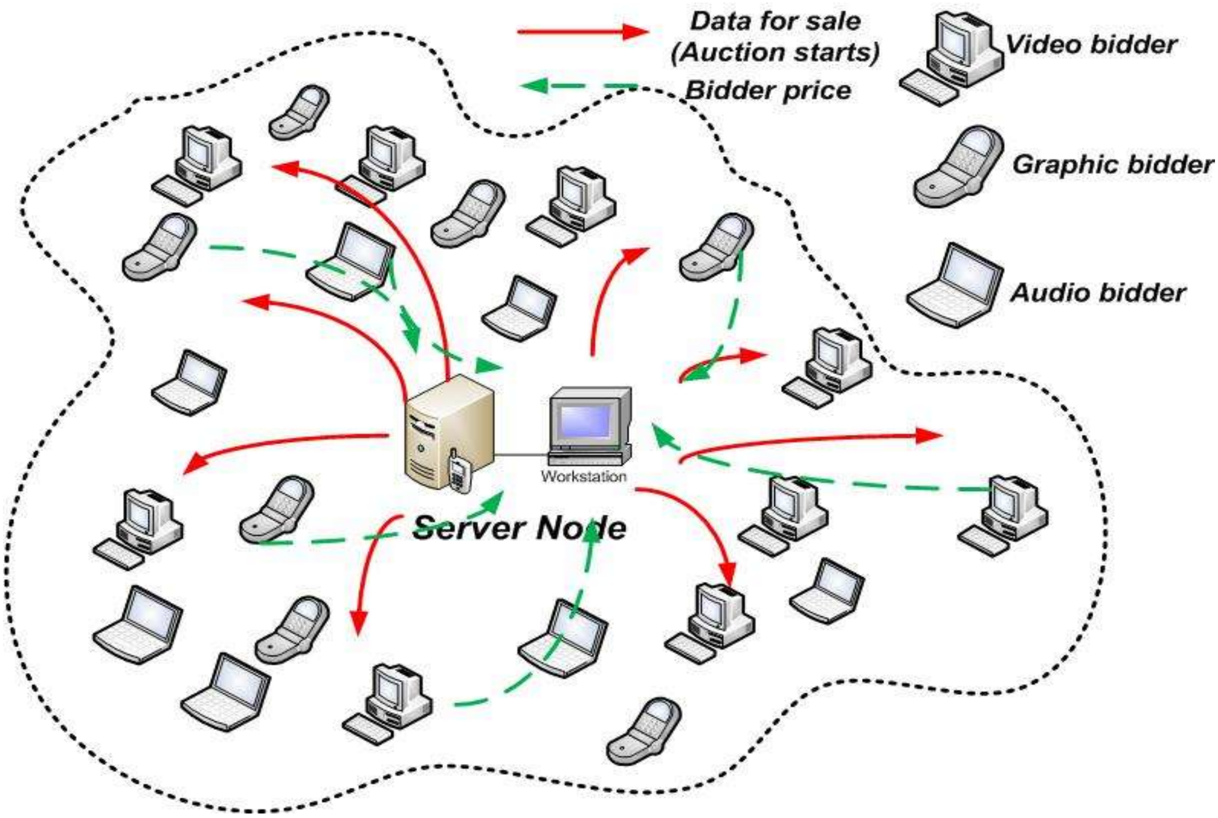


Figure 5-2: Example of an auction scenario.

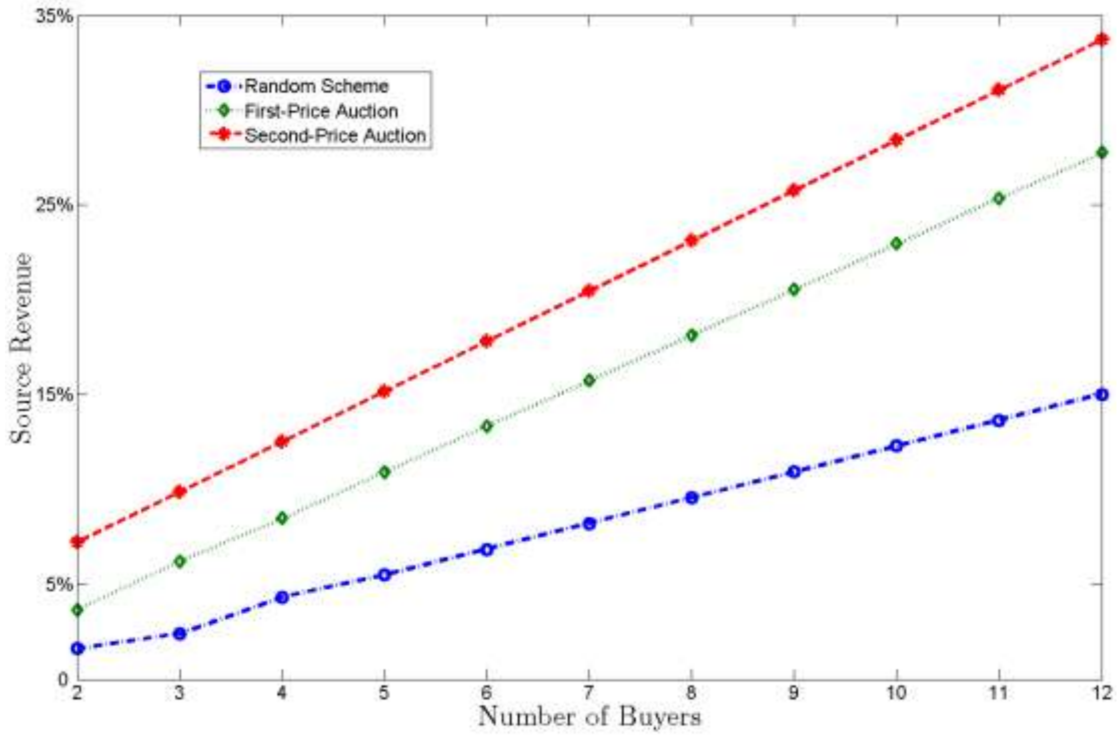


Figure 5-3: Source revenue with few competitors.

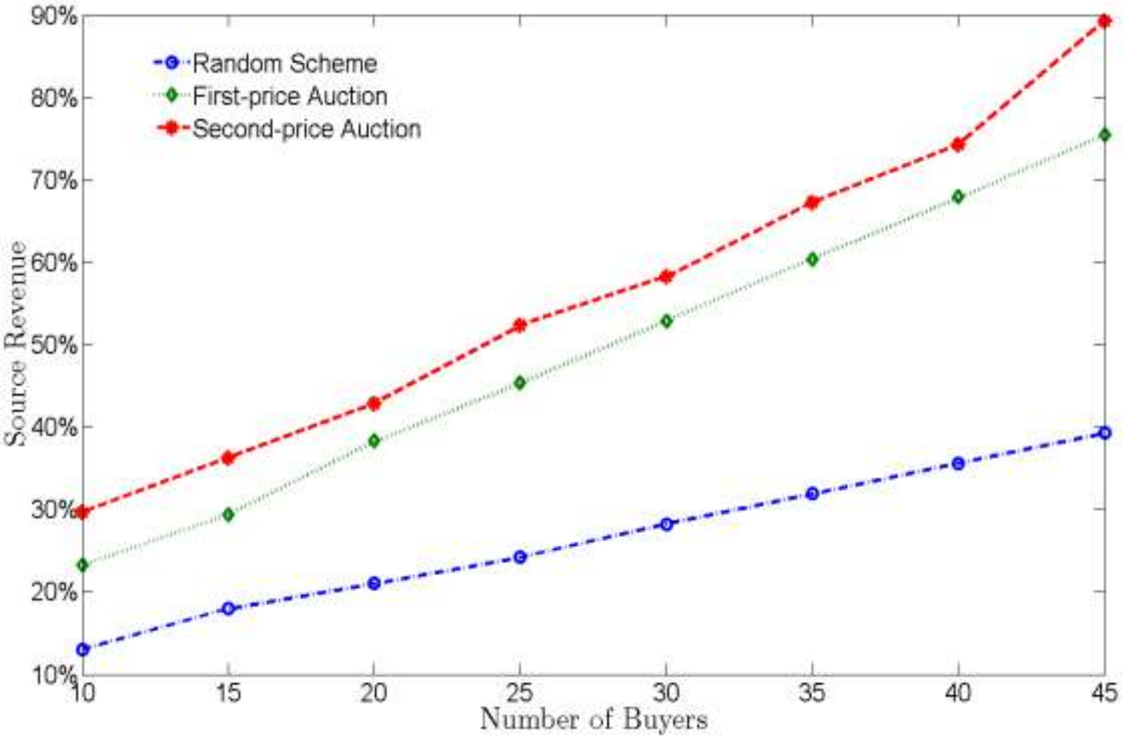


Figure 5-4: Source revenue with large number of competitors.

Figure 5-3 shows the source revenue when the number of users competing between each other is low, where the auction only starts when there are two users or more competing with each other. If there is only one user interested in the offered data, then it's up to the source to accept his offer when it's more than the reserved price. The revenue is measured on how much the source will gain more than the reserved price.

From the two Figures 5-3 and 5-4, it is clearly shown that when the number of competitors increase the source revenue will increase dramatically. The second-price sealed-auction gives better revenue to the seller as it force the buyers to offer their true valuation of the offered good. This might not be so obvious in the first-price sealed-auction, as the bidder is trying to maximize their own profit from winning by lowering the bid below its true valuation. However, in equilibrium, as every bidder adopts the same strategy, the bidder with the highest valuation still stands out. Compared with the game-based random allocation scheme, introduced in [38-41]. Where the source sells the data to the first node that offers a price, any price, and pays in advance for all the intermediate nodes and waits for their response whether to participate or not (all intermediate nodes will receive the source payment, which is why the source revenue will go down when the number of intermediate nodes rise). We can observe that the auction-based schemes are significantly better in terms of improving the seller's revenue and improving the system efficiency.

Figure 5-4 illustrates the path reliability versus source pay for intermediate nodes when fixing $G_d$ to $300\%$ of the reserved price (a sufficient large amount). From this figure, we can see that the density of the deployments increases, the maximum reachable path reliability increases. This result is expected; when the source pays more to intermediate nodes, the expected path reliability increase too. It should be noticed that in both cases that when $G_s$ exceeds some threshold point; the path reliability will remain almost constant. We must mention that the source payment to the intermediate nodes is measured in percentage, of how much the source is ready to offer the network of his revenue.

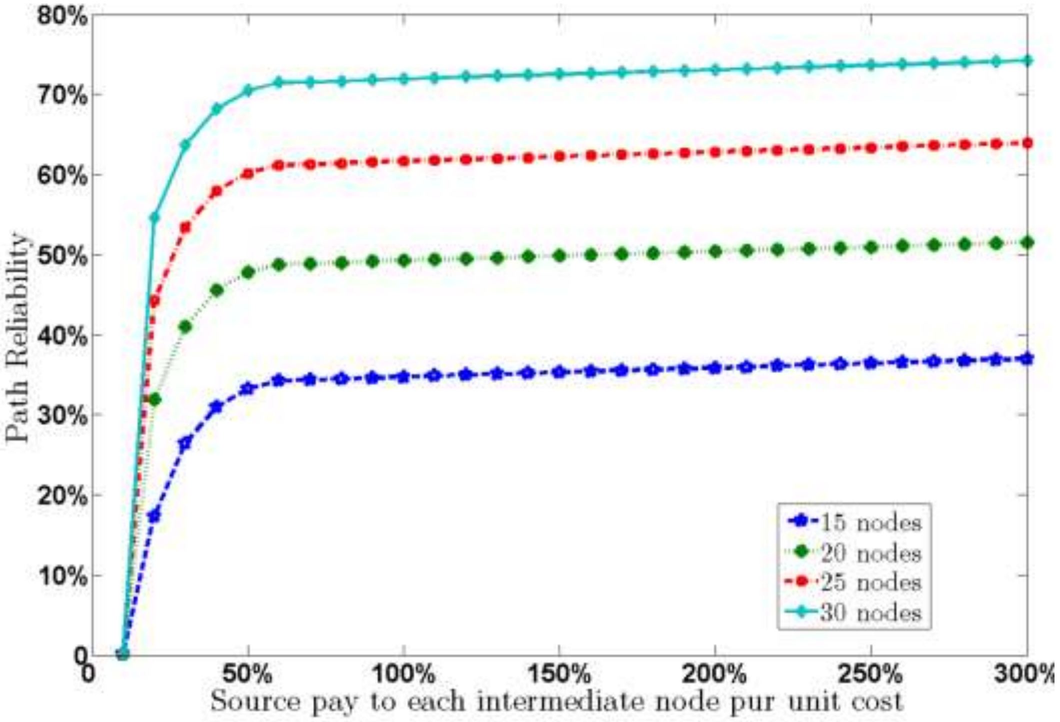


Figure 5-5: Path reliability versus source pay to each routing node when changing number of nodes in a fixed area.

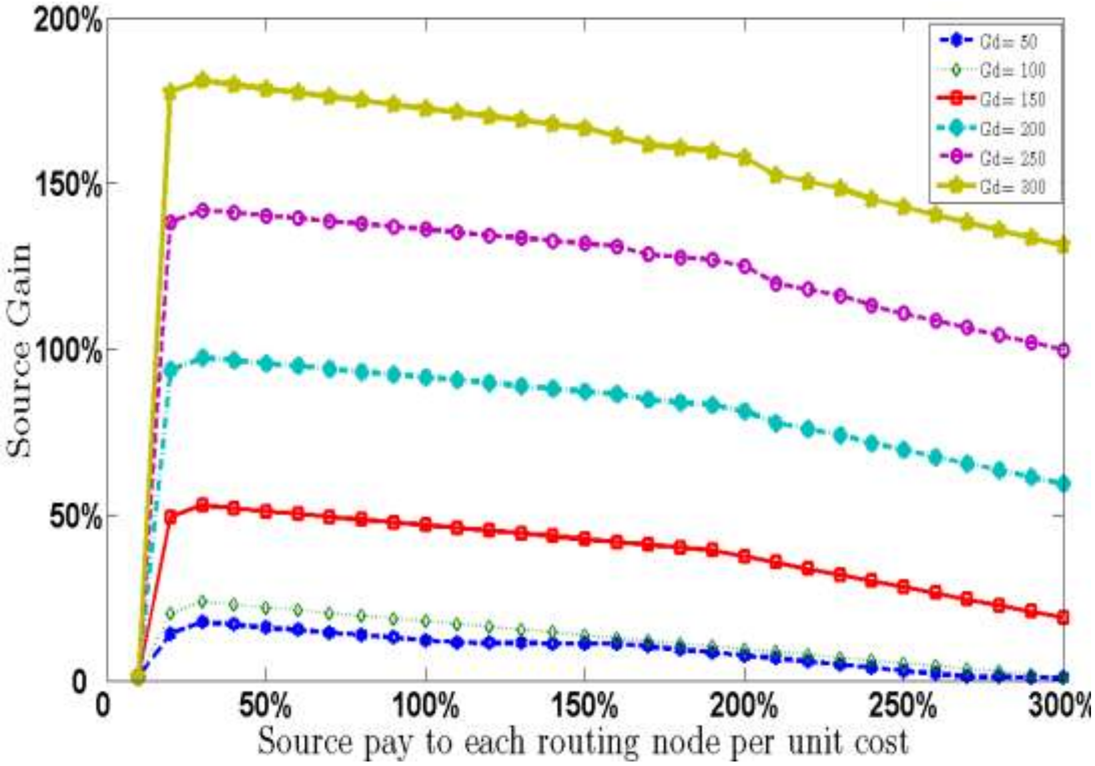


Figure 5-6: Source gain versus source pay to each routing node for different destination pay, when fixing number of nodes and area size.

Figure 5-5 plots the source gain versus the source pay to the intermediate nodes with fixed number of nodes (25 nodes) and the area size. Recall that from the source utility function in section 5.7, source utilities in most cases are dominated by the term of $(G - h.G_s)\prod_{n_i \in Path} R_i$. Increasing $G_s$ can lead to decreasing of $h$ and increment of $\prod_{n_i \in Path} R_i$. Figure 5-4 shows that there exists a best strategy point for the source to maximize its payoff, which is at the same routing price no matter how much destination pay is given in a fixed network topology. The other observation of Figure 5-5 is that; the portion of source gain increases as the destination pays increases. This indicates that even if the destination increase the pay to the source to request a certain reliability path, most of the money goes to the source instead of the routing nodes. It implies that even if the destination increases the pay, it will not get a path with more reliability.

If we examine Figures 5-4 and 5-5 together, we will find that at the maximum gain of the source node, the path reliability is close to the maximum path reliability which the network can reach.

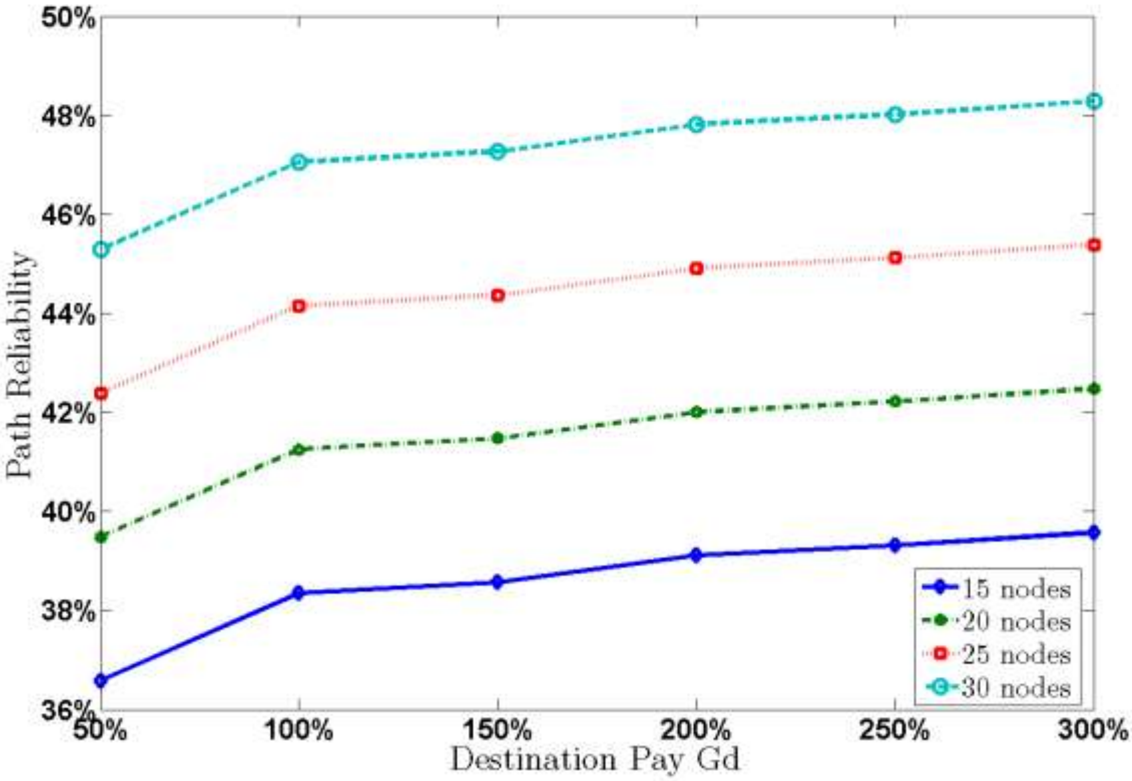


Figure 5-7: Behaviour of selfish source node effect on the path reliability.

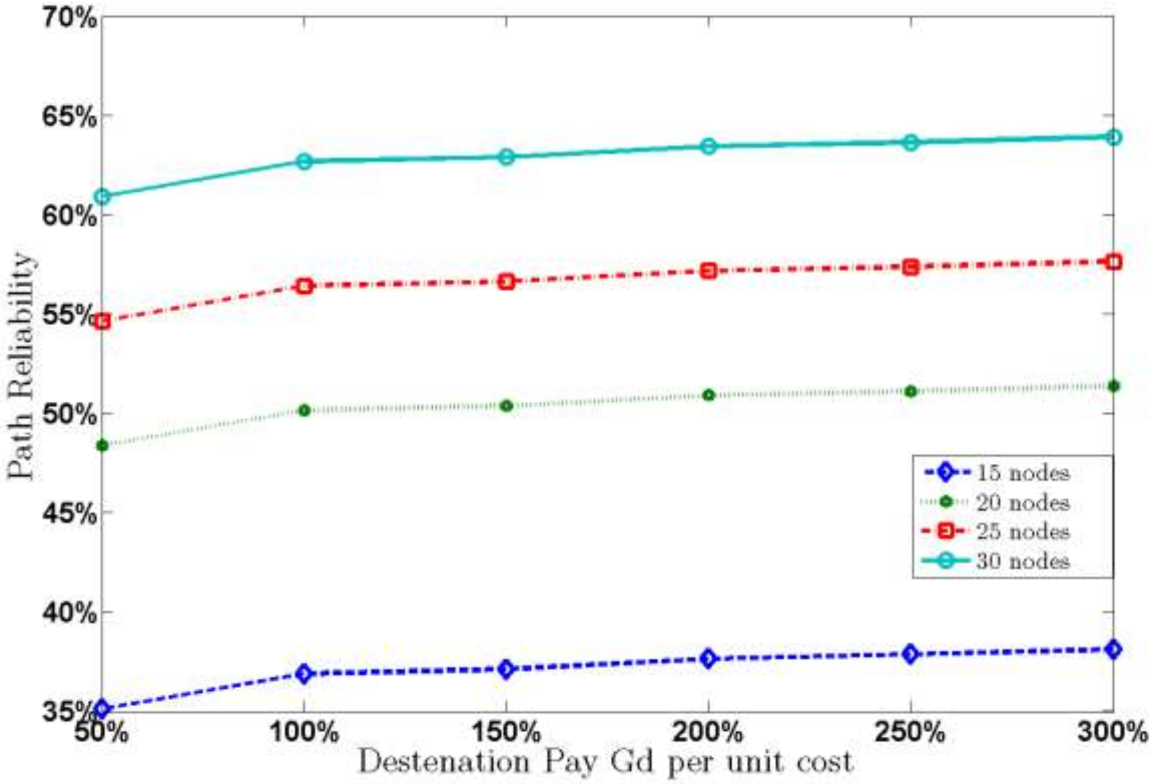


Figure 5-8: Behaviour of cooperative source node effect on the path reliability.

Figures 5-7 and 5-5 show a comparison of source node behaving cooperatively and selfishly. This gives us an important insight: selfish behaviour of source node in such system will not hurt system performance much. These figures demonstrate that there exist some improvement to the path reliability when the source acts cooperatively, but the improvement is not significant. We also see that the maximum path reliability will not have significant improvement for any fixed network parameter when destination pay exceeds some threshold (around 100% more of the reserved price) that is necessary to obtain a path. On the other hand, the routing path reliability will increase significantly (from 0.35 to 0.64) when changing network parameters (in this particular simulation, we increase the number of nodes in the fixed area).

Figure 5-9 shows the probability that a positive payoff Nash equilibrium path exists as a function of the price offered by the source. For each case, we see that the curve increases to a point where it is close to one. This shows the existence of critical threshold prices (independent of the exact configuration) that ensure the existence of a Nash equilibrium path with high probability. It should also be seen that this price threshold decreases with the density, a trend that is concrete visualized in the distance-based model, which is affected by node distance more seriously. This trend is because with growing density, there are more choices to pick the path from, and there are a greater number of high quality links, which incur low transmission cost.

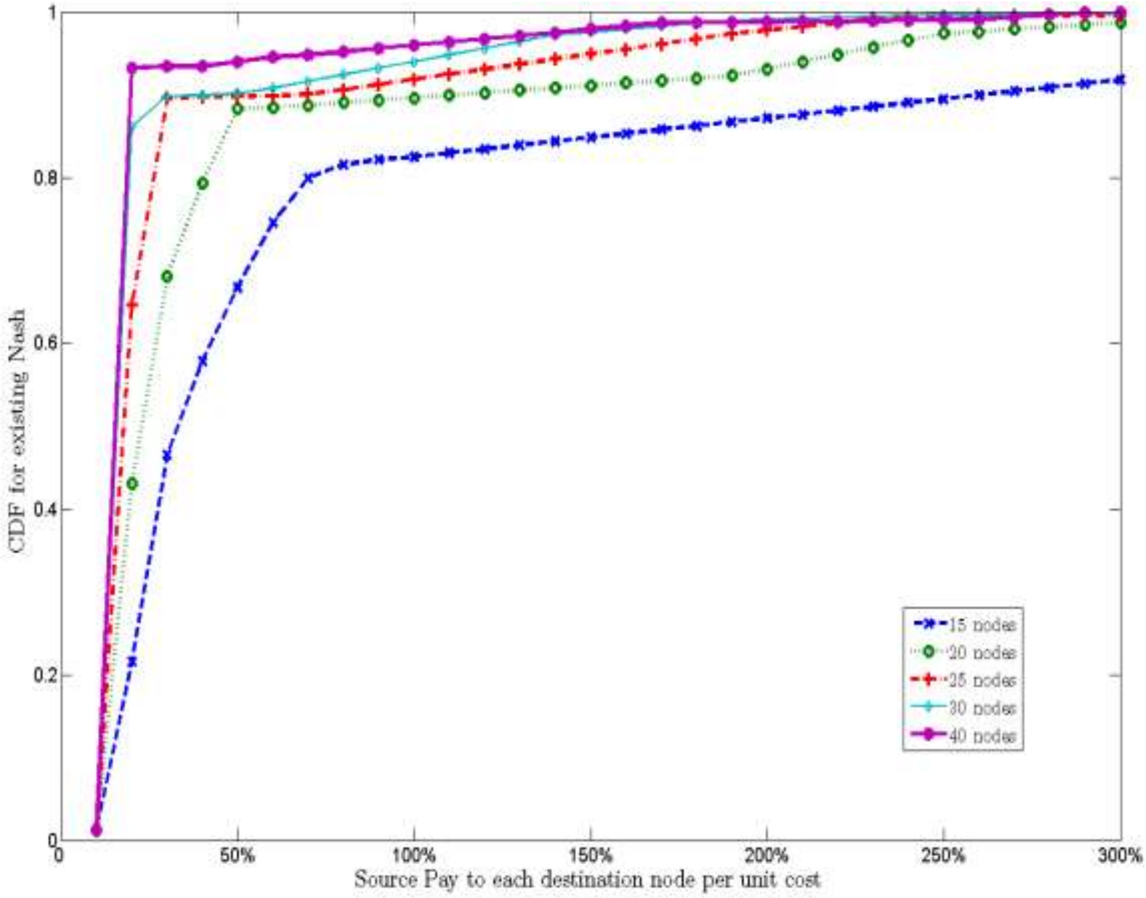


Figure 5-9: Cumulative distribution function for the existence of Nash Equilibrium path when increasing source pay to each routing node.

## 5.9 Summary

This chapter presents a game theory based routing algorithm, which involves three types of nodes in the network: the destination node, the source node and all the intermediate nodes. Defining the best route based on the power consumption that each intermediate node will suffer to forward a packet, the price the destination will pay to the source and the amount of compensation the source will pay to each intermediate node. The paper also presents a polynomial time algorithm that can give a *Nash Equilibrium* path and use it to evaluate the performance of the performance of the game with respect to parameters mentioned earlier. We can summarize the key findings of the introduced mechanism by;

1. The auction mechanism insures a fare allocation of the data to the user who values it the most.
2. The second-price sealed-bid auction gives better revenue to the source when compared to the random allocation scheme and the first-price sealed-bid mechanism.
3. The game mechanism combines both source compensation to the intermediate nodes and the power consumption to improve the path reliability between the source and the destination (i.e. the winning bidder).
4. The source payoff will increase once the network density increases (i.e. the number of intermediate nodes increases). This is because the routing paths become cheaper and more reliable and even if the source is acting selfishly, the path reliability will not be downgraded significantly.

Finally, the simulation results prove that the introduced auction mechanism dramatically increases the seller's revenue whether he decide to choose the first or second-price auction. Moreover, the results briefly evaluate the reliability of predefined route with respect to the data prices and source and destination cooperation for different network settings.

## 5.10 References

[1] H.J. Parrsch and J. Robert, "Testing Equilibrium Behaivour at First-Price, Sealed-Bid Auctions with Discrete Bid Increments", 2003s-32, scientific series, Montreal, June 2003.

[2] F.M. Menezes and Paulo K. Monteiro, "An Introduction to Auction Theory", Oxford University press, November 2004.

[3] V. Krishna, "Auction Theory", Elsevier, Second Edition, 2009.

[4] P.R. Milgrom, "A theory of Auction and competitive bidding", Econometrica, vol. 50, no. 5, pp. 1089-1122, September 1985.

[5] R. Cassady, "Auction and Auctioneering", Berkeley: University of California Press, 1967,

[6] M. Shubik, "The Theory of Money and Financial Institutions: Volume 1", Cambridge, Mass., USA: MIT Press, pp. 213–219, March 2004.

[7] V. Krishna, "Auction Theory", Elsevier, San Diego, 2002.

[8] R.W. Patten, "Tatworth Candle Auction", Folklore (London, United Kingdom: Taylor & Francis, Ltd. on behalf of Folklore Enterprises, Ltd.), pp. 132–135, 1970.

[9] J. Varoli, "Swedish Auction House to Sell 8 Million Euros of Russian Art", Bloomberg.com News, October-2007, available online at: http://www.bloomberg.com/apps/news?pid=20601088&sid=aGlwT7.MHwzw&refer=muse [Accessed 3rd March 2010].

[10] About the Company, Stockholm, Sweden: Stockholms Auktionsverk, available online at: http://www.auktionsverket.se/historike.htm [Accessed 5th March 2010].

[11] W. Vickrey, "Counter speculation, Auctions, and Competitive Sealed Tenders", Journal of Finance, vol.16**,** pp. 8-37, 1961.

[12] J. Laffont, and E. Maskin "Optimal Reservation Prices in the Vickrey Auction", Economics Letters, vol. 6, pp. 309-313, 1980.

[13] R. McAfee and J. McMillan, "Auctions and Bidding", Journal of Economic Literature, vol. 25, pp. 699-738, 1987.

[14] R. McAfee and J. McMillan, "Auctions with a Stochastic Number of Bidders", Journal of Economic Theory, vol. 43, pp. 1-19, 1987.

[15] R. McAfee and J. McMillan, “Bidding Rings”, American Economic Review, vol. 82, pp. 579-599, 1992.

[16] D. Houser, and J. Wooders, “Reputation in Auctions: Theory and Evidence from eBay”, Working paper, University of Arizona, 2001.

[17] P. Resnick, and R. Zeckhauser, “Trust Among Strangers in Internet Transactions: Empirical Analysis of ebay’s Reputation System”, in The Economics of the Internet and E-Commerce, ed. by M. R. Baye, vol. 11 of Advances in Applied Microeconomics. Amsterdam, Elsevier Science, 2002.

[18] T. Zaikiuddin, Hawkins and N. Moffat, “Towards a Game-Theoretic Understanding of Ad-Hoc Routing”, Proceeding of Workshop on Games in Design and Verification, July 2004, in Electronic Notes in Theoretical Computer Science, vol. 119, no.1, pp. 67-92, February 2005.

[19] M. Felegyhazi, M. Cagalj, S. Bidokhti, and J. Hubaux, "Non-Cooperative Multi-Radio Channel Allocation in Wireless Networks", 26th IEEE International Conference on Computer Communications. IEEE , vol., no., pp.1442-1450, May 2007.

[20] J. Yuan, and W. Yu, "Joint source coding, routing and power allocation in wireless sensor networks", IEEE Transactions on Communications, vol. 56, no. 6, pp. 886-896, June 2008.

[21] D. Yang, and M. Chen, "Efficient Resource Allocation for Wireless Multicast", IEEE Transactions on Mobile Computing, vol. 7, no. 4, pp.387-400, April 2008.

[22] M. Abaii, L. Yajian, and R. Tafazolli, "An Efficient Resource Allocation Strategy for Future Wireless Cellular Systems", IEEE Transactions on Wireless Communications, vol.7, no.8, pp.2940-2949, August 2008.

[23] H. Abuzanat, B. Trouillet, and A. Toguyeni, "Routing Fairness Model for QoS Optimization in Wireless Network", SENSORCOMM '08. Second International Conference on Sensor Technologies and Applications, pp. 776-781, Aug. 2008.

[24] H. Zhu, and K.J.R. Liu, “Noncooperative Power-Control Game and Throughput Game Over Wireless Networks”, IEEE Transactions on Communications, vol. 53, no. 10, pp. 1625- 1629, Oct. 2005.

[25] H. Jianwei, H. Zhu, C. Mung, and H.V. Poor, “Auction-Based Resource Allocation for Cooperative Communications”, IEEE Journal on Selected Areas in Communications, vol. 26, no. 7, pp.1226-1237, September 2008.

[26] P. Coucheney, C. Touati, and B. Gaujal, "Selection of Efficient Pure Strategies in Allocation Games", Game Theory for Networks, GameNets '09, pp. 658-666, 13-15, May 2009.

[27] P.K. Dutta, “Strategies and Games: Theory and Practice”, MIT press, 2001.

[28] A. Das, A. Neishaboori, and G. Kesidis, "Wireless mesh networking games", Game Theory for Networks, 2009. GameNets '09, pp. 565-574. May 2009.

[29] M. Urpi, Bonuccelli, and S. Giordano, “Modeling Cooperation in Mobile Ad-Hoc Networks: a Formal Description of Selfishness”, Proceeding of the 1st Workshop on Modeling and Optimization in Mobile, Ad-Hoc and Wireless Networks, March 2003.

[30] M. Felegyhazi, L. Buttyan, and J.P. Hubaux, “Nash Equilibria of Packet Forwarding Strategies in Wireless Ad-Hoc networks”, IEEE Transactions on Mobile Computing, vol. 5, Iss. 5, pp. 463-476, May 2006.

[31] P. Michiardi, and R. Molva, “Analysis of Coalition Formation and Cooperation Strategies in Mobile Ad-Hoc networks”, Journal of Ad-Hoc Networks, vol. 3, no. 2, pp. 193-219, March 2005.

[32] V. Srinivasan, P. Nuggehalli, C.F. Chiasserini, and R.R. Rao., “Cooperation in Wireless Ad-Hoc networks”, Proceeding of IEEE INFOCOM, vol. 2, pp. 808-817, April 2003.

[33] M. Felegyhazi, L. Buttyan, and J.P. Hubaux, “Equilibrium Analysis of Packet Forwarding Strategies in Wireless Ad-Hoc networks – the Dynamic Case”, Proceeding of the 2nd Workshop on Modelling and Optimization in Mobile, Ad-Hoc and Wireless Networks, March 2004.

[34] E. Altman, A.A. Kherani, P. Michiardi and R. Molva, “Non-cooperative Forwarding in Ad-Hoc networks”, INRIA, Sophia-Antipolis, France, Report no. 5116, February 2004.

[35] R. Axelrod, “The Evolution of Cooperation”, Basic Books, reprint edition, New York, 1984.

[36] A. DaSilva and V. Srivastava, “Node Participation in Peer-to-Peer and Ad-Hoc networks: A Game Theoretic Formulation”, Workshop on Games and Emergent Behaviour in Distributed Computing, September 2004.

[37] J.F. Lee, W. Liao, and M.C. Chen, "An Incentive-based Fairness Mechanism for Multi-hop Wireless Backhaul Networks with Selfish Nodes", IEEE Transactions on Wireless Communications, vol. 7, no. 2, pp. 697-704, February 2008.

[38] R. Kannan, S. Sarangi, and S.S. Iyengar, “Sensor Centric Quality of Routing in Sensor Networks”, IEEE Infocom, 2003.

[39] R. Kannan, S. Sarangi, and S.S. Iyengar, “Game-Theoretic Models for Reliable Path-Length and Energy-Constrained Routing with Data Aggregation in Wireless Sensor Networks”, IEEE Journal on Selected Areas in Communications, vol. 22, no. 6, August 2004.

[40] R. Kannan, S. Sarangi, and S.S. Iyengar, “Sensor-Centric Energy Constrained Reliable Query Routing for Wireless Sensor Networks”, Journal of Parallel Distributed Computing, vol. 64, pp. 839-852, 2004.

[41] R. Kannan, S. Sarangi, and S.S. Iyengar, “A Simple Model for Reliable Query Reporting in Sensor Networks Information Fusion”, Proceedings of the Fifth International Conference, July 2002.

[42] N.A. Kuznetsov, and V.N. Fetisov, “Enhanced-Robustness Dijkstra Algorithm for Control of Routing in the IP-Networks”, Automation and Remote Control, Springer Science+Business Media LLC, vol. 69, no 2, pp. 247-251, 2008.

# CHAPTER 6

# *Auction and Game-Based Spectrum Sharing in Cognitive Radio Networks*

## 6.1 Spectrum Sharing and Cognitive Radio: A Brief History

One of the main reasons behind the concurrent increase in the demand for and congestion of Radio Frequency (RF) spectrum is the rapid development of radio networks of all kinds in our world, which has defiantly changed the public feeling about radio. Nowadays, almost everybody has a mobile phone and radio stations are literary everywhere. Someone can argue that our world is becoming a radio world where waves are weaving everywhere around the Earth. What's more, this congestion has created a battle between the public, private and military sectors over frequency ownership and has put a premium on the cost of spectrum. According to a recent research introduced by the FCC (Federal Communications Commission) and Ofcom, it was found that most of the frequency spectrum was inefficiently utilized [1-2]. The existing spectrum allocation process, denoted as Fixed Spectrum Access (FSA), headed for static long-term exclusive rights of spectrum usage [3] and shown to be inflexible [4]. Studies have shown, however, that spectral utilization is relatively low when examined not just by frequency domain, but also across the spatial and temporal domains [5]. Thus, an intelligent device aware of its surroundings and able to adapt to the existing RF environment in consideration of all three domains, may be able to utilize spectrum more efficiently by dynamically sharing spectral resources [6 and 7]. Since the 19th century, when the laws of electromagnetic have been discovered and described by the set of Maxwell's equations and technical devices been invented to produce and use these electromagnetic waves predicted by theory, man has added his own man-made waves to the natural ones [7].

It is fair to say that, from the very beginning of wireless telephony, maritime radio systems has always used shared channels [7-8]. For example, 2,182 KHz is used as a calling frequency as well as emergency signalling frequency and other frequencies are used as working frequencies. If two ships want to communicate, one should identify a working frequency and make a call. By specifying a channel or channels, that ships keep watch on, both emergency and establishing connections between ships can be facilitative. In fact, channel sharing was necessary and effective because of the lack of sufficient channels offered to every single ship and due to the fact that, the typical ship will require far less than a full channel of capacity [7-8]. Around the mid of 1970's, the FCC permitted land mobile operation on some of the lower UHF channels in several large cities, in order to expand land mobile services. One group of channels was made available to Radio Common Carriers (RCCs) to provide mobile service on a common carrier basis. The FCC adopted rules permitting open entry for these channels and requiring carriers to monitor the channels and select unused channel to carry each conversation. In essence, exclusivity was provided on a first come, first-served basis one conversation at a time [7-9].

Another example of spectrum sharing is the second generation of cordless telephone (CT2), developed by the British industry and government in the mid of 1980's. CT2 was designed to be used in both in home and in public and uses a pool of 40 channels. To establish a call, any equipment will automatically identify a vacant channel or a channel with the minimum interference and begins operation on that channel [7-8]. No one can ignore one of the main advantages of the radio, it can be used anywhere, at any time, capable of building links at very short distances as well as on a cosmic scale. Radio is a unique tool to connect men and things without any material medium. It is a wonderful tool for social progress. Having said all these facts about spectrum sharing, spectrum management can now be seen as a major goal for telecommunications efficiency. It is necessary that this natural and public resource be utilized for the profit of as many users as possible, taking care of the largest variety of needs.

In order to explain Cognitive Radio (CR), then someone must mention Software Defined Radio (SDR), which is a transmitter in which operating parameters including transmission frequency, modulation type and maximum radiated or conducted output power can be altered without making any hardware changes. The sophistication possible in an SDR has now reached the level where a radio can possibly perform beneficial tasks that help the user, the network and help to minimize spectral congestion [7]. In order to raise an SDR's capabilities to make it known as a CR, it must support three major applications [7]:

1. Spectrum management and optimization.
2. Interface with a wide range of wireless networks leading to management and optimization of network resources.
3. Interface with human providing electromagnetic resources to aid the human in his and/or her activates.

To truly recognize how many technologies have come together to drive CR technologies, few of the major contributions that have led us to today's CR developments must be studied. The development of Digital Signal Processing (DSP) technologies arose due to the efforts of the research leaders [10-14], who taught an entire industry how to convert analog signal processes to digital processes. In the meantime, the simulation industry used in the radio industry was not only practical, but also resulted in improved radio communication performance, reliability, flexibility and increased value to the user [15-18].

The concept of CR emerged as an extension of SDR technology. Although, definitions of the two technology's are different, most radio expert agree with the fact that a CR device must have the following characteristic in order to be distinguished from an SDR one:

1. The named device should be aware of its environment.
2. The device must be able to change its physical behaviour in order to adapt to the changes of its current environment.
3. The device must be able to learn from its previous experience.
4. Finally, the device should be able to deal with situations unknown at the time of the device design. In another word, the device should be able to deal with any unexpected situations.

That being said, up to the authors knowledge, the idea of CR was first discussed officially in 1999 by [19]. It was a novel approach in wireless communications that the author describes it as "The point in which wireless personal digital assistants (PDA's) and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communications to detect user communications needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs.” [19]. What’s more, the work introduced in [19] can be considered one of the novel ideas which discussed CR technology. The work was based on the situation in which wireless nodes and the related networks are sufficiently computationally intelligent about radio resources and related computer-to-computer communication to detect the user communication needs as a function of use context and to provide resources and wireless resources most required. In another word, a CR is a radio that has the ability to sense and adapt to its radio environments. This work defined two basic characteristics of any CR device, which are cognitive capability and re-configurability. In order for the device to detect the spectrum parameters, the device should be able to interact with its environment. The spectrum needs to be analysed for spectrum concentration, power level, extent and nature of temporal and spatial variations, modulation scheme and existence of any other network operating in the neighbourhood. The CR device should be capable to adopt itself to meet the spectrum needs in the most optional method. The recent developments in the concept of software radios DSP techniques and antenna technology helped in this flexibility in CR devices design.

Finally, the intelligent support of CR’s to the user arises by sophisticated networking of many radios to achieve the end behaviour, which provides added capability and other benefits to the user.

## 6.2 Game Theory and Spectrum Sharing

Players in cooperative games try to maximize the overall profit function of everyone in the game in a fair fashion. This type of games has the advantage of higher total profit and better fairness. On the other hand, in non-cooperative or competitive games players try to maximize their own individual payoff functions. If such a game has a designer with preferences on the outcomes, it may be possible for the designer to decide on strategy spaces and the corresponding outcomes (*i.e.* the mechanism) so that the players' strategic behavior will not lead to an outcome that is far from desirable [20 and 21]. Recent studies have shown that despite claims of spectral insufficiency, the actual licensed spectrum remains unoccupied for long periods of time [8]. Thus, *cognitive radio* systems have been proposed [22] in order to efficiently exploit these spectral holes.

Previous studies have tackled different aspects of spectrum sensing and spectrum access. In [23], the performance of spectrum sensing, in terms of throughput, is investigated when the secondary users (SUs) share their instantaneous knowledge of the channel. The work in [24] studies the performance of different detectors for spectrum sensing, while in [25] spatial diversity methods are proposed for improving the probability of detecting the Primary User (PU) by the SUs. Other aspects of spectrum sensing are discussed in [26-27]. Furthermore, spectrum access has also received increased attention, e.g. [28-34]. In [28], a dynamic programming approach is proposed to allow the SUs to maximize their channel access time while taking into account a penalty factor from any collision with the PU. The work in [30] and [35-43] establishes that, in practice, the sensing time of CR networks is large and affects the access performance of the SUs. In [29], the authors model the spectrum access problem as a non-cooperative game, and propose learning algorithms to find the correlated equilibria of the game. Non-cooperative solutions for dynamic spectrum access are also proposed in [30] while taking into account changes in the SUs' environment such as the arrival of new PUs, among others.

Auctions of divisible goods have also received much attention [32] and [44-49]. Where the authors address the problem of allocating a divisible resource to buyers who value the quantity they receive, but strategize to maximize their net payoff (*i.e.* value minus payment). An allocation mechanism is used to allocate the resource based on bids declared by the buyers. The bids are equal to the payments, and the buyers are assumed to be in *Nash equilibrium*. When multiple SUs compete for spectral opportunities, the issues of fairness and efficiency arise. On one hand, it is desirable for an SU to access a channel with high availability. On the other hand, the effective achievable rate of an SU decreases when contending with many SUs over the most available channel. Consequently, efficiency of spectrum utilization in the system reduces. Therefore, an SU should explore transmission opportunities in other channels if available and refrain from transmission in the same channel all the time. Intuitively, diversifying spectrum access in both frequency (exploring more channels) and time (refraining from continuous transmission attempts) would be beneficial to achieving fairness among multiple SUs, in that SUs experiencing poorer channel conditions are not starved in the long run.

The objective of the work in this chapter is to design a dynamic mechanism that enables fair and efficient sharing of spectral resources among large number of SUs, as most of the current research consider relatively low number of SU’s in the model desgin. Firstly, a spectrum access model in cognitive radio networks as a repeated cooperative game must be designed. The theory and realization of cooperative spectrum sharing is presented in detail, where it must be assumed that there is one PU and several SUs. The case of dynamic games was also considered, where the number of SUs changes. The advantages of cooperative sharing are proved by simulation. Secondly, a discussion of the case of large number of SUs competing to share the offered spectrum is discussed and how the cooperative game will reduce the sellers and bidders revenue. Finally, a competitive auction and game-based mechanism is introduced to improve the overall system efficiency in terms of a better fairness in accessing the spectrum.

Throughout this chapter, an adaptive competitive second-price pay-to-bid sealed auction game is adapted as solution to the fairness problem of spectrum sharing between one primary user and a large number of secondary users in cognitive radio environment. Three main spectrum sharing game models are compared, namely optimal, cooperative and competitive game models introduced as a solution to the named problem. In addition, this chapter prove that the cooperative game model is built based on achieving Nash equilibrium between players and provides better revenue to the sellers and bidders in the game. Furthermore, the cooperative game is the best model to choose when the number of secondary users changes dynamically, but only when the number of competitors is low. As in practical situations, the number of secondary users might increase dramatically and the cooperative game will lose its powerful advantage once that number increases. As a result, the proposed mechanism creates a competition between the bidders and offers better revenue to the players in terms of fairness. Combining both second-price pay-to-bid sealed auction and competitive game model will insure that the user with better channel quality, higher traffic priority and fair bid will get a better chance to share the offered spectrum. It is shown by numerical results that the proposed mechanism could reach the maximum total profit for SUs with better fairness. Another solution is introduced in this chapter, which is done by introducing a reputation-based game between SUs. The game aims to elect one of the SUs to be a secondary-PU and arrange the access to other SUs. It is shown by numerical results that the proposed game managed to give a better chance to SUs to use the spectrum more efficiently and improve the PU revenue.

## 6.3 Assumptions and System Model

### 6.3.1 Primary Users and Secondary Users and Allocation Function

In the following sections, we consider a spectrum overlay-based cognitive radio wireless system with one PU and $N$ SU's (as shown in Figure 6-1). The PU is willing to share some portion ($b_i$) of the free spectrum ($F$) with SU $i$. The PU asks each SU a payment of $c$ per unit bandwidth for the spectrum share, where $c$ is a function of the total size of spectrum available for sharing by the SU's. The revenue (profit) of SU $i$ is denoted by $\mu_i$ per unit of achievable transmission rate. A simple example is shown in Figure 6-1.

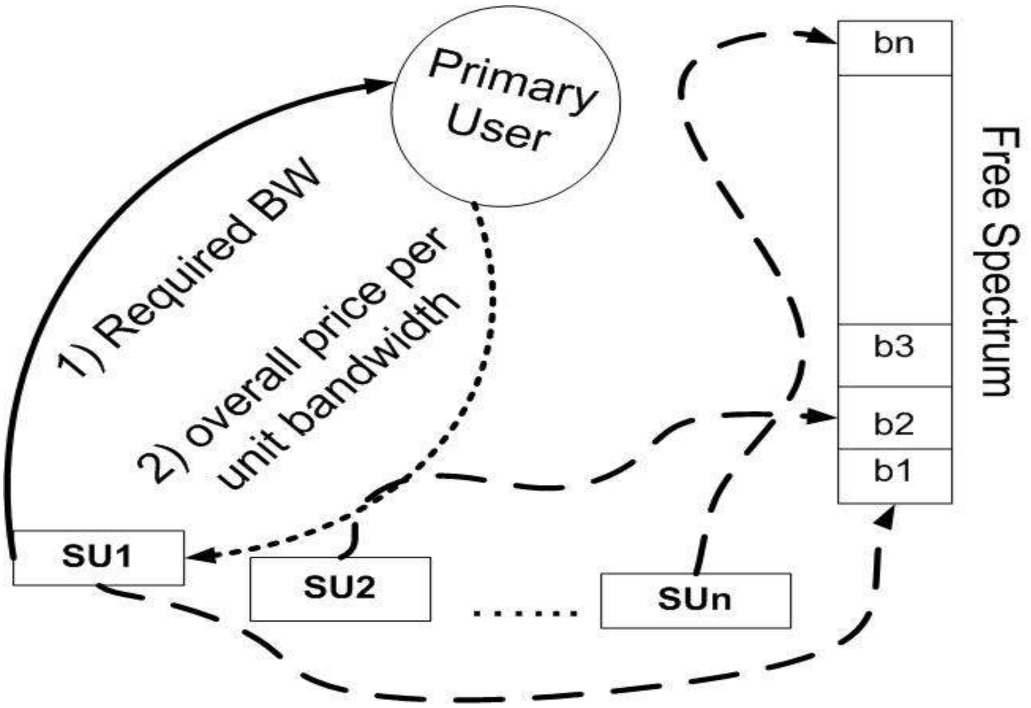


Figure 6-1: System model for spectrum sharing.

Both centralized and distributed decision making scenarios are considered in this work. In the former case, each SU is assumed to be able to observe the strategies adopted by other users (*i.e.,* either the users have the ability to discuss their shares between them, or the PU sends update of each SU share). In the latter case, the adaptation for spectrum sharing is performed in a distributed fashion based on communication between each of the

SUs and the PU only (*i.e.,* the secondary users are unable to observe the strategies and payoffs of each other).

### 6.3.2 Cost Function, and Wireless System Model

A wireless transmission model based on adaptive modulation and coding (AMC) where the transmission rate can be dynamically adjusted based on channel quality is to be assumed in this chapter. With AMC [16], the Signal-to-Interference Noise Ratio (SINR) at the receiver is denoted as $\gamma$ and equals to;

$$\gamma_i = \frac{p_i h_{ij}}{n_o + \sum_{j \neq i} p_i h_{i,j}} \qquad (6\text{-}1)$$

Where $h_{ij}$ is the channel gain from the user $j's$ transmitter to user $i's$ receiver, $p_i$ is the transmitting power of user $i$, and $n_0$ is the thermal noise level. The achievable transmission rate for user $i$ (in bits/sec) is given by;

$$r_i = log_2(1+\gamma_i) \qquad (6\text{-}2)$$

The spectral efficiency $I_s$ of transmission by a secondary user can be obtained from [16];

$$I_s = log_2(1+K\gamma_i) \qquad (6\text{-}3)$$

where $k=1.5/\ (ln0.2/BER^{tar})$, $BER^{tar}$ is the target bit-error-rate of the system. The pricing function [17] which the SU's pay is given by;

$$c(B) = y(b_1+b_2+\ldots+b_n)^z \qquad (6\text{-}4)$$

$y$ and $z$ are assumed to be positive constants and greater than one so that the function is convex (*i.e.*, the function is continues and differentiable), knowing that $Bid$ is the set of bids for all SU's (*i.e.,* Bid=$\{bid_1, bid_2, \ldots., bid_n\}$). Now let us denote $w$ as the worth of the spectrum to the PU ($w_i$ is the worth of each portion of the offered spectrum). Then, the condition $c(B) > w \times \sum_{b_j \in B} b_j$ must be satisfied in order to ensure that the PU is willing to share spectrum of size $B = \sum_{b_j \in B} b_j$ with the SU's (if it is equal, then PU will not gain any profit).

The overall revenue of any SU can be explained as the combination of the user revenue of achievable transmission rate, the spectral efficiency and the shared portion of the spectrum (*i.e.*, $r_i \times I_s \times b_i$). While the cost the user must pay is $b_i \times c(B)$. Then, the profit (revenue) of every SU can be represented as;

$$\mu_i = r_i \times I_s \times b_i - b_i \times c(B) \qquad (6\text{-}5)$$

The marginal profit ( $\frac{d\,\mu_i(B)}{d\,b_i}$) of SU *i* can be obtained from;

$$\frac{\partial \mu_i(B)}{\partial b_i} = r_i I_s - y\left( \sum_{b_j \in B} b_j \right)^z - yzb_i\left(\sum_{b_j \in B} b_j\ \right)^{z-1} \qquad \text{(6-6)}$$

Knowing that, the optimal size of allocated spectrum to one SU depends on the strategies other SU's are using. Nash equilibrium is considered as the solution of the game to ensure that all SU's are satisfied with it. By definition, Nash equilibrium of a game is a strategy profile with the property that no player can increase his payoff by choosing a different action, given the other players' actions. In this case, the Nash equilibrium is obtained by using the Best Response (BR) function, as shown in equation (6-7), which is the best strategy of one player given others' strategies. Let $ST_{-i}$ denote the set of strategies adopted by all except SU $i$ (i.e., $ST_{-i} = \{st_j\ | j=1, 2, \ldots, N; j\neq i\}$ and $ST = ST_{-i}\ \cup \{st_i\}$). The best response function of SU $i$ given the size of the shared spectrum by other SU's $b_j$, where $j\neq i$, is defined as follows;

$$BR_i = arg\ max_{b_i}\ \mu_i\,(\mathrm{ST}_{-i} \cup \{b_i\}) \qquad \text{(6-7)}$$

Then the game is in *Nash Equilibrium* if and only if the strategy of user *i* is his/her BR as compared to other users strategies, which means;

$$b_i = BR_i\,(\mathrm{ST}_{-i}),\ \forall_i \qquad \text{(6-8)}$$

## 6.4 Spectrum Sharing Strategies

Cognitive radio is an intelligent wireless communication system that is aware of its surrounding environment and can be used to improve the efficiency of frequency spectrum by exploiting the existence of spectrum holes [22]. Spectrum management in cognitive radio aims at meeting the requirements from both the primary user and the secondary users. There are three strategies in spectrum sharing optimal, competitive and cooperative models.

### 6.4.1 Optimal Spectrum Sharing Model

The objective of optimal model is to maximize the profit sum, which may make some secondary users have no spectrum to share [28, 32 and 50]. Therefore, it is unfair for all secondary users. From equation (6-6), the total marginal profit function for all the SU's can be denoted as follows:

$$\frac{\partial \sum_{j=1}^{N} \mu_i B(t)}{\partial b_i(t)} \qquad (6\text{-}9)$$

In order to get the solution of the biggest profit for all the secondary users, an optimal equation is built, as (6-10);

$$\textit{Maximize:} \sum_{j=1}^{N} \mu_i B(t) \qquad (6\text{-}10)$$

*Subject to:* $b_i \geq 0, \forall b_i \in B$

The assumption works as follow, the initial sharing spectrum is $b_i(0)$ for the SU $i$, which is sent to the primary user. The PU adjusts the pricing function *c*, and then it is sent back to the SU. Since all secondary users are rational to maximize their profits, they can adjust the size of the requested spectrum $b_i$ based on the marginal profit function. In this case, each secondary user can communicate with the primary user to obtain the differentiated pricing function for different strategies. The adjustment of the requested/allocated spectrum size can be modelled as a dynamic game [48] as follows:

$$b_i(t+1) = f\big(b_i(t)\big) = b_i(t) + \eta_i b_i(t) \frac{\partial \mu_i(B)}{\partial b_i} \qquad (6\text{-}11)$$

where $b_i(t)$ is the allocated spectrum size at time $t$ to SU *i* and $\eta_i$ is the adjustment speed parameter (*i.e.,* which can be expressed as the learning rate) of SU *i*. *f(.)* denotes the self-mapping function. The SU can estimates the marginal profit function in the actual system by asking the price for share a spectrum from the PU of size $b_i(t) \pm \pi$, where π is a small number (*i.e.,* π is 0.0001). Simply after that the SU observes the response price from the PU $c^-(.)$ and $c^+(.)$ for $b_i(t)-\pi$ and $b_i(t)+\pi$ , respectively. Then, the marginal profits for the two cases $\mu_i^-(t)$ and $\mu_i^+(t)$are compared and the marginal profit can be estimated from;

$$\frac{\partial \mu_i(.)}{\partial b_i} = \frac{\mu_i^+(.) - \mu_i^-(.)}{2\pi} \qquad (6\text{-}12)$$

The overall optimal profit can be estimated using equation (6-10).

### 6.4.2 Competitive Spectrum Sharing Model

The main objective of competitive model is to maximize the profits of individual SU's by a game [48-49 and 53-55]. The result is Nash equilibrium. In the distributed dynamic game, SU's may only be able to observe the pricing information from the PU; they cannot observe the strategies and profits of other SU's. The Nash equilibrium for each SU is built based on the interaction with the PU, similar to the case of the optimal sharing model. Since all SU's are rational to maximize their own profits, they can adjust the size of the requested spectrum bi based on the marginal profit function (i.e., equation (6-6)). In this case, each SU can communicate with the primary user to obtain different pricing function for different strategies. The adjustment of the requested/allocated spectrum size in competitive games show only a slight difference with optimal games, as each individual user is looking at improving his/her own profit. So equation (6-9) can be rewritten as;

$$\text{Maximize:} \mu_i(B) \qquad (6\text{-}13)$$

$$\text{Subject to: } b_i \geq 0, \forall b_i \in B$$

In a similar way to the optimal game, an SU can estimate its marginal profit using the following equation:

$$\frac{\partial \mu_i(B(t))}{\partial b_i(t)} = \frac{1}{2\pi}\{\mu_i(B_i(t)+\pi) - \mu_i(B_i(t)-\pi)\} \qquad (6\text{-}14)$$

when $b_i(t+1) = bi(t)$ is satisfied, the *Nash Equilibrium* points ($b_0, b_1, b_2, \ldots, b_N$) can be obtained.

### 6.4.3 Cooperative Spectrum Sharing Model

As explained in previous sections, in the model of competitive spectrum sharing, *Nash equilibrium* obtained at the maximum of the individual profit of SU. The result is not the best because they do not consider the interaction on other users [45-56]. For cooperative spectrum sharing, the SU's can communicate with the consideration on the behaviour to other users.

In this chapter, we assume that players can reach in common by communicating with each other. Decreasing the size of sharing spectrum a little for all the SU's on *Nash equilibrium*, (*i.e.,* a factor $\sigma_i$ $(0 < \sigma_i < 1)$ is multiplied on each SU strategy of *Nash equilibrium*). Although the size of shared spectrum has decreased, the cost which the PU charges to the SU decreases too, which results in the increase of the overall profit for all SU's and the total profits increase as well, but it might reduce the PU revenue.

SU's *Nash equilibrium* strategy can be got from equation (6-11). All SU's will negotiate and multiply $\sigma_i$, the cooperative strategy is obtained (*i.e.,* $\sigma_1 b_1, \sigma_2 b_2, \ldots, \sigma_N b_N$). $\sigma_i$ is chosen in such a way that both the overall and individual profit is maximized, which we called as the Nash state;

$$\textit{Maximize:} \sum_{j=1}^{N} \mu_i(B) \text{ and } \mu_i(B) \qquad (6\text{-}15)$$

*Subject to:* $b_i \geq 0, \forall b_i \in B$

However, the problem of instability of this model must be raised. It is possible that one or more SUs may deviate from *Nash equilibrium*. For example, suppose *u1* to be the first SU to share the spectrum and want to deviate, its profit may increase by setting its marginal profit function of equation (6-6) to zero. If another SU *u2* does not change its strategy, the profit of *u2* will decrease. Therefore, any SU has the motive to deviate from Nash state. In order to solve this problem, a mechanism needs to be applied to encourage the SUs not to deviate from the Nash state by computing the long term profit of the SU. Suppose SU *i* is looking deviate from the Nash state, while SU *j* ($j \neq i$) is still in the named state. Before SU *i* deviate, it will compute the long term profit. The mechanism will multiply the future profit of SU *i* (if decided to deviate) with a weight $\varepsilon_i$ ($0 < \varepsilon_i < 1$), which would make the profit in future stages are not higher than that of the previous stages, which means that the current profit is more valuable than future stages.

For any SU *i*, $\mu_i^{Ns}$, $\mu_i^{N}$, $\mu_i^{d}$ denotes the profits of Nash state, *Nash Equilibrium* and deviation, respectively. There are two cases: one is that they all in Nash at all stages, no SU to deviate from the optimal solution, the long term profit of any SU *i* is shown in equation (6-16). The other case is that SU *i* deviates from the optimal solution at the first stage, it will be in *Nash equilibrium* state in the following stages, and the long term profit of SU *i* is shown in equation (6-17).

$$\mu_i^{Ns} + \sigma_i \mu_i^{2Ns} + \sigma_i^2 \mu_i^{3Ns} + \cdots = \frac{1}{1-\sigma_i} \mu_i \qquad (6\text{-}16)$$

$$\mu_i^{d} + \sigma_i \mu_i^{N} + \sigma_i^2 \mu_i^{2N} + \cdots = \mu_i^{d} + \frac{\sigma_i}{1-\sigma_i} \mu_i \qquad (6\text{-}17)$$

The Nash state will be maintained if the long-term profit due to adopting the state is higher than that caused by deviation.

$$\frac{1}{1-\sigma_i}\mu_i > \mu_i^d + \frac{\sigma_i}{1-\sigma_i}\mu_i$$

*i.e.,*

$$\sigma_i \geq \frac{\mu_i^d - \mu_i^{Ns}}{\mu_i^d - \mu_i^N} \tag{6-18}$$

From equation (6-16), we know that the Nash state will be kept because of low long term profit for the SU who wants to deviate. The weights $\sigma_i$ are the vindictive factors to inhabit the motive of leaving the cooperative state.

## 6.5 Dynamic Cooperative Model

In reality, the number of SUs may change. Sometimes there are more secondary users to apply for the spectrum offered by the primary user, and sometimes the secondary users have finished the communication and drop out of the spectrum as it has taken up. For example, let us suppose that there are two SUs, which have been in Nash state. Now there is another (newcomer) SU to apply for the offered spectrum. We assume that the PU has no more spectrum to share. This will lead us to one solution, which is that the two SUs should make some of their spectrums exist to the newcomer.

During the process of reallocating, an adaptive method is applied with the following requirements. The total profit for all the SUs should be the biggest and it should be fair for the reallocation. Being prior users it is rational for them to have priority in spectrum allocation than those who comes later. In order to keep the total profit to maximum, those with better channel quality could take up more spectrum space. Therefore, the SUs with better channel quality could stop spectrum retreating earlier than those with worse channel quality. When the SUs reach optimal solution, the fairness will not be as good as the three SUs getting into Nash state directly. The reason is that these SUs coming at different time do not have the same priorities.

When SUs have finished the communication and exited the spectrum they had shared, an adaptive method is applied. A fixed part of the spectrum is allocated to the remaining

SUs for each step. It is possible for SUs with better channel quality acquire more spectrum in order to make the total profit bigger.

## 6.6 Simulation Results

### 6.6.1 Static Game (Two SU's only in the game)

In this section, a CR environment with one PU and two SUs sharing a frequency spectrum of 20MHz to 40MHz is to be considered. The system has the following settings; for the pricing function, $c(B)$, we use $y=1$ and $z=1$. The worth of spectrum for the PU is assumed to be one (i.e. $w=1$). The revenue of a SU per unit transmission rate is $r_i = 10, \forall i$ . The target average BER is $BER^{tar} = 10^{-4}$. The initial value is $b_i(0)= 2$ . The adjustment speed parameter $\eta_i = 0.09$. The SNR for SUs $u_1$ and $u_2$ are denoted by $\gamma_1$, $\gamma_2$ where $\gamma_1$ =11dB, $\gamma_2$=12dB.

#### 6.6.1.1 Optimal and Competitive Models

As explained in the previous section, the total profit is represented by $\mu(B) = \mu_1(B) + \mu_2(B)$ . In Figure 6-2, the total profits in optimal model arrived at its biggest value 228.7333 when $(b_1, b_2) = (4.1, 15.6)$.

The trajectories of optimal model and competitive model are shown in Figure 6-3, (with $\gamma_1$ =11dB, $\gamma_2$=12dB), the initial value is (2, 2) for the two models. In competitive model, the shared spectrum is determined by a game, where the two SUs have been in *Nash equilibrium*. In our simulation, the *Nash equilibrium* is at (13.8591, 24.1302). The sum of spectrum sharing is 37.9893 with the total profit of 228.2378.

It can be seen that the total profit for optimal model is higher than that of competitive model obviously. But one SU has no spectrum sharing for the optimal model, which means the lack of fairness. The advantage of competitive model is fair with a lower profit sum.

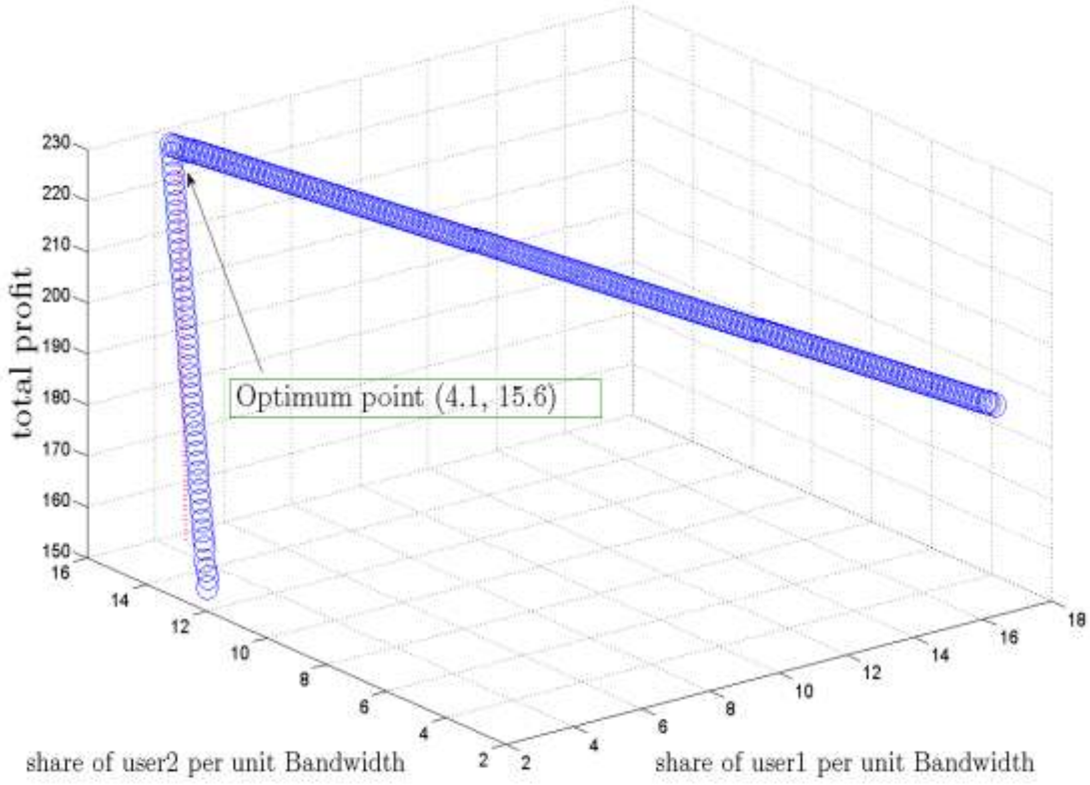


Figure 6-2: Total profit and spectrum share using optimal game.

### 6.6.1.2 Cooperative Spectrum Sharing Game

Based on the Nash equilibrium, we set the weight $\sigma_i$ in the range of [0.5, 1]. In order to keep the fairness, we assume $| \sigma_1 - \sigma_2 | \leq 1$ to guarantee the size of sharing spectrum is similar for both two SUs. Two SUs got their *Nash equilibrium* at (18.2591, 19.1302). At $\sigma_1 = 0.70$, $\sigma_2 = 0.80$, the total profit of 234.4963. Compared with the competitive model, we found that the shared spectrum in cooperative model is less than that of competitive model; it has a bigger total profit than that of *Nash equilibrium*, as shown in Figure 6-3.

The reason is that we set ($\sigma_1 b_1$, $\sigma_2 b_2$) as the strategies to share the spectrum, the price is lower, and the total profit will increase. Now, let us suppose the SU $u_1$ deviates from the optimal solution. The strategy of SU $u_2$ does not change. SU $u_1$ adopts the strategy based on the marginal profit function. The profit for the two SUs will change when SU $u_1$ deviated. The comparison of the individual profit in cooperative model, competitive model and deviation is shown in Figure 6-4. The total profit for the SUs is shown in Figure 6-5. $\gamma_1$ is a variable, which changes in the range of 8~11dB, $\gamma_2$ =12dB.

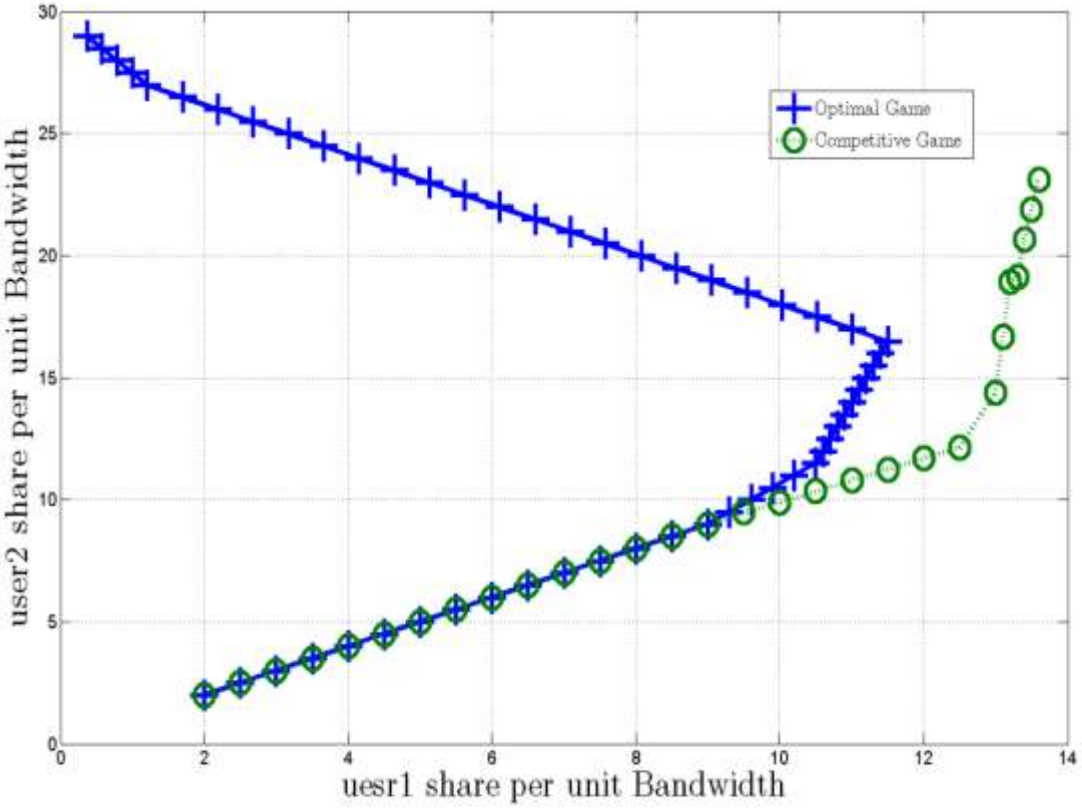


Figure 6-3: Optimal and competitive games.

It can be seen that $\mu_1$, $\mu_2$ are bigger in the cooperative model, compared with the competitive model. Therefore, the total profit is bigger too in the cooperative model. When SU *u1* deviates from the cooperative state, $\mu_1$ is higher, and $\mu_2$ is lower, and the total profit is lower (*i.e.* the amount of $\mu_1$ increasing is smaller than that of $\mu_2$ decreasing) as well.

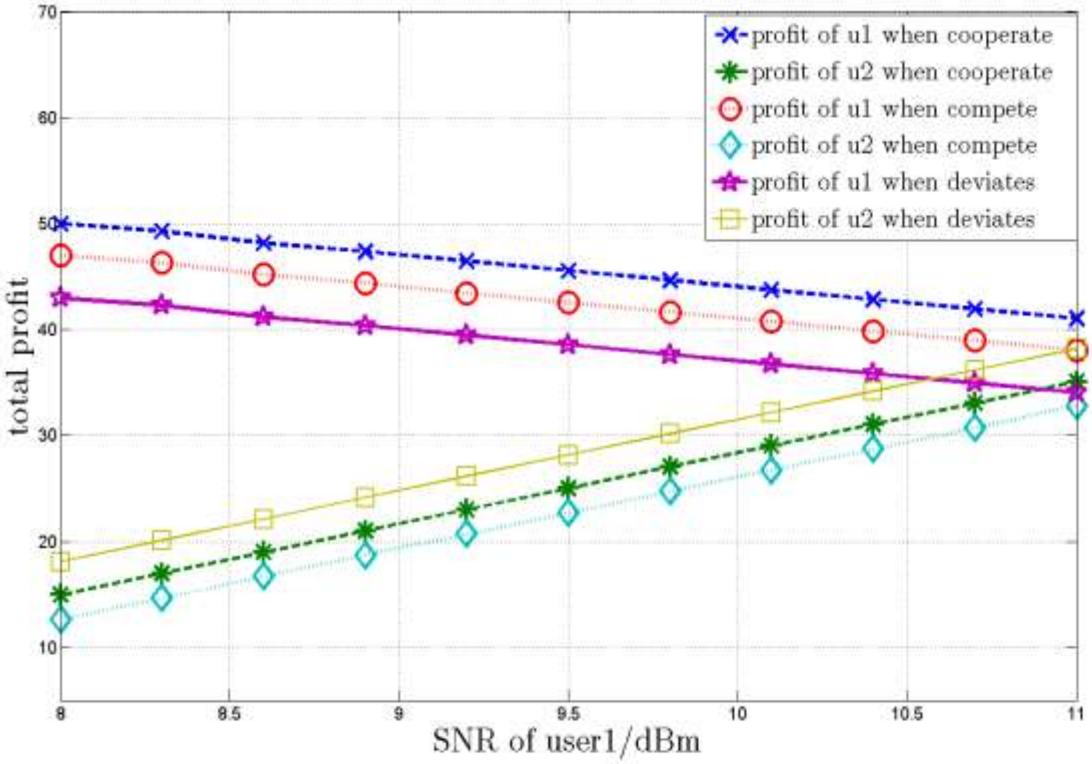


Figure 6-4: Total profit with different modes.

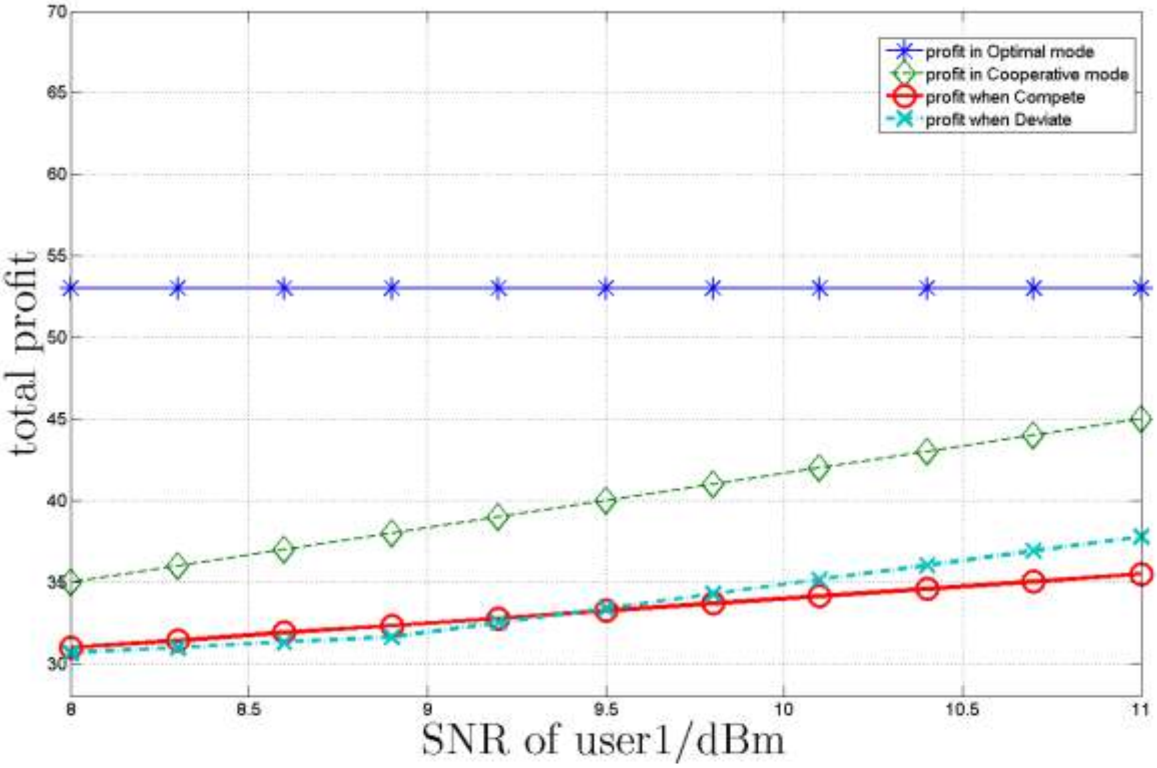


Figure 6-5: User Profit with different modes.

### 6.6.1.3 Dynamic Spectrum Sharing Game

The pervious results were based on two SUs. The analyzing method is similar for more SUs. In practice, the number of SUs may change. For example, there is another secondary user denoted by $u_3$ looking to apply for the offered spectrum. We assume that the channel quality for $u_3$ is the same with secondary user $u_2$ ($\gamma_1$ is a variable, $\gamma_2=\gamma_3$ =12dB). There is no more free spectrum for the primary user to share with others. The previously mentioned adaptive method is applied in the allocation of spectrum. First $u_1$ and $u_2$ exit a fixed ratio of spectrum to $u_3$, and the total profit is computed. If the total profit could increase, the process will go on. If the total profit decreases, the SU with a better channel state will stop the process of exit. The trajectory of the process is shown in Figure 6-6. In addition, the corresponding total profit is shown in Figure 6-7. When a new SU applies for spectrum sharing, it would converge to the point of (3.418948, 5.4642, 0.4936). The total profit is 62.3421, which is a little bigger than the case with two SUs. When the third SU exits the spectrum, an adaptive method is applied to reallocate the spectrum. The left two SUs converge to (2.2148, 5.9393) with a total profit of 73.9867, as shown in Figure 6-8.

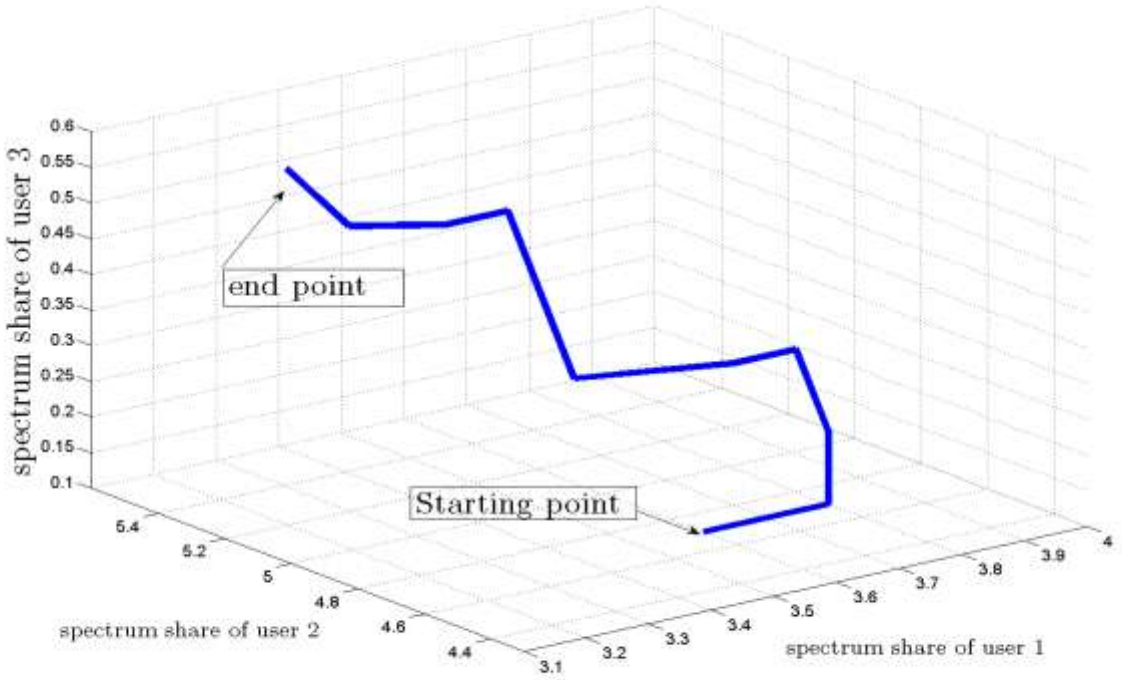


Figure 6-6: Spectrum sharing in dynamic game.

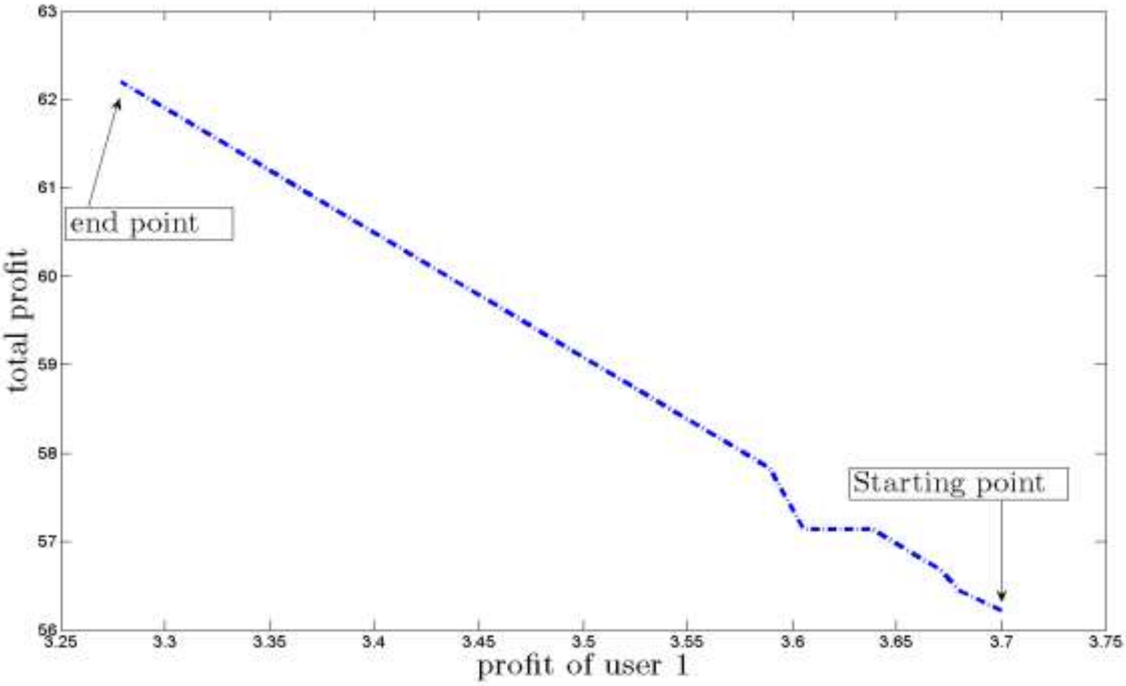


Figure 6-7: Dynamic game and user profit.

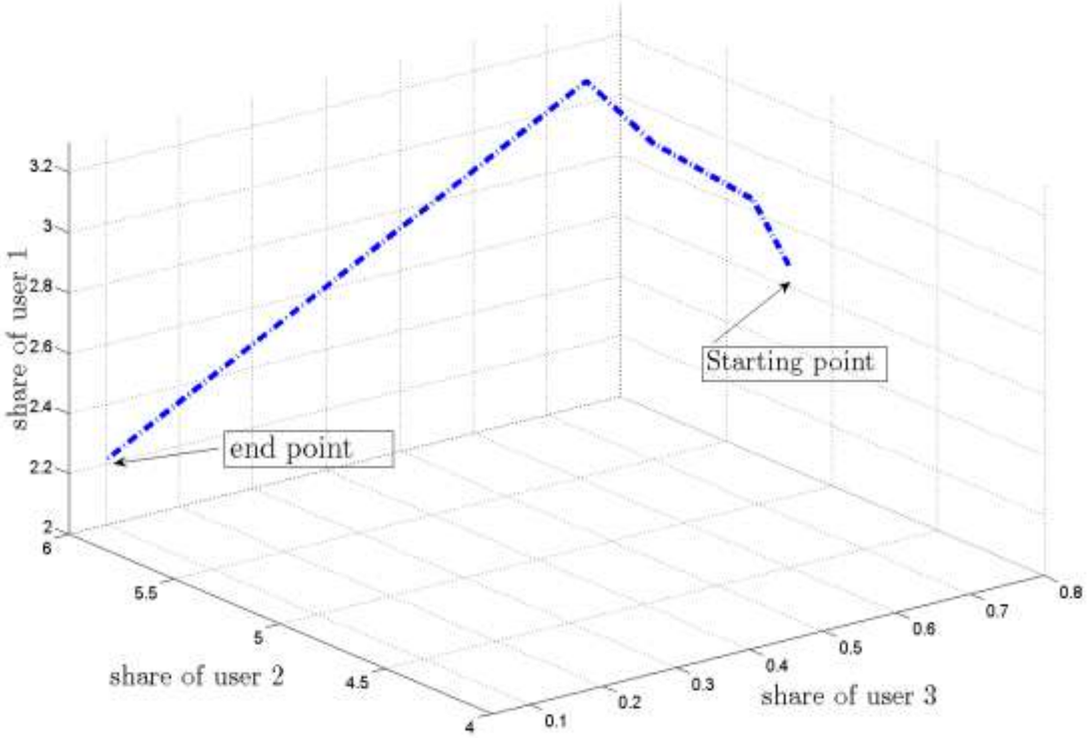


Figure 6-8: Spectrum Share when user retreats.

## 6.7 Is the Cooperative Game Visible?

So far we have discussed three game models to solve the problem of spectrum sharing in CR systems. We proved that the optimal game would improve the overall profit of the players in the game, which might lead to unfair distribution of the offered spectrum. The competitive game shows a lower overall profit, but gives a better share to the user with better channel quality, who ask for a share earlier and stays active for longer period (*i.e.,* a higher priority as compared to new comers). Finally, the cooperative game gives the best overall individual profit and it is the best way to insure a fair share between multiple users in any CR system. However, does the cooperative game model works in an actual CR system?

In practical CR environment, the communication between competitors (*i.e.,* players) is very hard to achieve. Individual users tend to contact the PU and ask for service [49], users can only observe the pricing function form the PU, but not the strategies and profits of other users. Nevertheless, achieving a cooperative scheme between the SUs (either, the PU forces the SU to get a fair share or using the model mentioned earlier) would improve both the seller and users revenue. Let us use the same assumption used in the previous section, where a PU have a 30MHz of free spectrum to offer to a group of users. The cooperative mode will work when the number of players is relatively small, so each player can discuss a fair share with the rest of the players. However, when the number of SUs increases, let say 20 or more SUs, the cooperative mode will not be useful anymore. If the PU or the users in such a scenario would decide to use the cooperative mode, the individual profit and share will be very low as compared to competitive game, taking into account the channel quality, user need and priority.

In order to solve such a problem, two solutions are proposed in the following sections. Firstly, a second-price pay-to-bid (or sometimes called as pay-as-bid) sealed auction mechanism is introduced to insure a fair competitive game between SUs. Secondly, reputation-based auction game is introduced as non-cooperative game to assign a SU to be a secondary-PU between other SUs. More details in the following sections:

### 6.7.1 Pay-to-Bid Competitive Auction

The allocation mechanism works as follows, let $W = [w_1, w_2, \ldots, w_n]$ be the non-negative bids (*i.e.,* user valuation) that the SU will pay in order to get a share of the offered spectrum and let $X = [x_1, x_2, \ldots, x_n]$ be the amount of the spectrum per unit bandwidth they are allocated as a result. We assume that the PU will announce the auction per unit bandwidth, for example the SUs will offer a bid for every 1MHz they will be allocated.

This allocation is made according to a cost-based allocation mechanism $\tau$, so that with the given payment $w$, the allocation to SU $i$ is given by $x_i = \tau_i(w)$, as shown in Figure 6-9. $r$ will be assumed to be the reserved price of the PU, any SU bidding less than that will be withdrawn from the auction.

In order to reflect user $i$'s valuation of the offered spectrum, a simple valuation function is proposed:

$$v_i = l_s \times up_i \tag{6-19}$$

where $v_i$ is user $i$'s valuation to the offered spectrum per unit bandwidth, $l_s$ is the spectral efficiency and $up_i$ defines how much the user needs to get the desired share of the spectrum, which is a function of user traffic priority ($tp_i$) and the channel SNR ($\gamma_i$);

$$up_i = tp_i \times \gamma_i \tag{6-20}$$

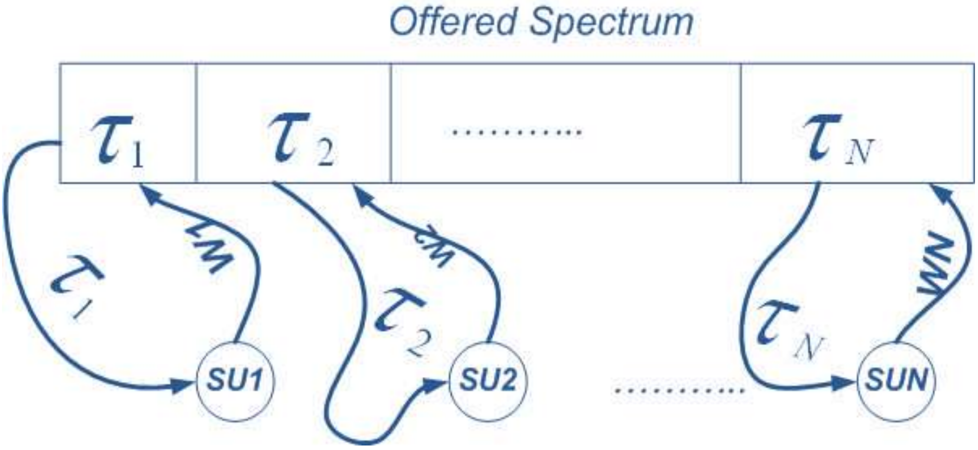


Figure 6-9: Pay-to-bid allocation mechanism.

The user valuation can be interpreted that user $i$ uses the importance of his traffic and the channel quality (already known to all users) as a ruler to set his bid in the auction.

This valuation measures the SU (if he wins the auction) capabilities to bid more for the offered spectrum keeping in mind the capacity of his channel. We can see that when the channel condition is good (according to equation (6-3)), the user will be more willing to increase his bid. As a result, a higher bid would be expected from him/her and vice versa.

It must be mentioned that the auction mechanism is designed in such a way that $v_i$ does not represent the real price that an SU has to pay during the auction. Simply it is an interpretation of the strategic situation that a node is facing. In fact $v_i$ reflects the relationship between the user valuation and the channel condition. The distribution of the valuation $v_i$ is also known (according to their relationship shown in equation (6-19)). This means that $v_i$ lies in the interval $[v_{min}, v_{max}]$. We defined *Bid* as the bid space in the auction, $\{bid_1, bid_2, \ldots, bid_N\}$, which represent the set of possible bids submitted to the PU. We can simply assign $bid_0$ to zero without loss of generality, as it represents the null bid. Accordingly, $bid_1$ is the lowest acceptable bid, and $bid_N$ is the highest bid. The bid increment between two adjacent bids is taken to be the same in the typical case. In the event of ties (i.e. two bidders offer the same final price), the object would be allocated randomly to one of the tied bidders.

To find the winner of the first-price sealed-bid pay-to-bid auction, a theoretical model is defined based on the work of [51]. The probability of detecting a bid $bid_i$ is denoted as $\xi_1$, the probability of not participating in the named auction will be denoted as $\xi_0$. Then the vector ξ, which equals to $(\xi_1, \xi_2, \ldots., \xi_N)$, denotes the probability distribution over *Bid*, where ( $\sum_i^N{}_{=0} \xi_i = 1$). Now we introduce the cumulative distribution function, which is used to find out whether a user $i$ will bid with $bid_i$ or less, $\sum_j^i{}_{=0} \xi_j = \xi$ , all of them are collected in the vector ξ.

Then, any rational potential bidder with a known valuation of $v_i$ faces a decision problem of maximizing his expected profit from winning the auction; *i.e.;*

$$\overset{max}{<bid_i \epsilon Bid>} (v_i - bid_i) Pr\ (winning|bid_i) \qquad (6\text{-}21)$$

The equilibrium probability of winning for a particular bid $b_i$ is denoted as $\vartheta_i$, and these probabilities are collected in $\vartheta$, $(\vartheta_0, \vartheta_1, \vartheta_2, \ldots, \vartheta_n)$. Using ξ, the elements of the vector $\vartheta$ can be calculated. We can easily find that $\vartheta_0$is known to be zero, as if any bidder submitted a null bid to the source, he is not going to win. We can calculate the remanning elements of $\vartheta$ as it can be directly verified that the following constitute a symmetric, Bayes-*Nash equilibrium* [52] of the auction game:

$$\emptyset_i = \frac{\zeta_i^n - \zeta_{i-1}^n}{n(\zeta_i^n - \zeta_{i-1}^n)} \quad \forall i = 0, 1, 2, \dots, n \tag{6-22}$$

The notation of Bayes-*Nash equilibrium* is used in this section as defined in [53], there approach is to transform a game of incomplete information into one of imperfect information, and any buyer who has incomplete information about other buyers' values is treated as if he were uncertain about their types. From equation (6-22), we can see that the numerator is the probability that the highest bid is exactly equal to $bid_i$, while the denominator is the expected number of users how are going to submit the same bid (*i.e.,* $bid_i$). For any user in the game, the best response will be to submit a bid which satisfies the following inequality;

$$(v_i - bid_i)\vartheta_i \geq (v_j - bid_j)\vartheta_j \qquad \forall\, j \neq i$$

The above inequality shows that user $i$'s profit is weakly beat any other user $j$'s profit. The above inequality is the discrete analogue to the equilibrium first-order condition for expected-profit maximization in the continuous-variation model [51], which takes the form of the following ordinary differential equation in the strategy function $\emptyset(v_i)$;

$$\acute{\emptyset}(v_i) + \emptyset(v_i)\frac{(n-1)f(v_i)}{F(v_i)} = v_i\frac{(n-1)f(v_i)}{F(v_i)} \tag{6-23}$$

Where $f(v_i)$ and $F(v_i)$ are the probability density and cumulative distribution function of each bidder valuation respectively. We assume that they are common knowledge to bidders along with $n$, the number of bidders in the system. The reserve price is denoted by *r*, (In many instance, sellers reserve the right not to sell the object if the price determined in the auction is lower than some threshold amount [52], say $c > 0$), and the above differential equation has the following solution;

$$\emptyset(v_i) = v_i - \frac{\int_r^{v_i} F(u)^{n-1}du}{F(v_i)^{n-1}} \tag{6-24}$$

In the case of the first-price sealed-bid auction, the bidder $i$ will submit a bid of $bid_i = \emptyset(v_i)$ in equilibrium and he will pay a proportional price to his bid if he wins. On the other hand, for the second-price sealed-bid auction, a user $i$ will submit his valuation truthfully. This is because the price a user has to pay if he wins the auction is not the winning bid but the second highest one. Therefore, there is nothing to drive a user to bid higher or lower than his true valuation to the data offered by the server. In this case, $bid_i = v_i$, shown in equation (6-19), and the payment process is the same as in the first-price auction. Once the winner has been announced, the PU will send an update message to all the SUs with the second highest price they need to pay in order to gain access. All SUs must pay the winning bid per unit bandwidth. To insure that the winner will get a higher priority than the rest of competitors, PU will send the winning bid to everyone and treat their replies according to the first bid was offered by the SUs in the first place.

This mechanism will offer a better competition in terms of fairness between players, the user with a better channel quality, a higher priority traffic and honest valuation will get a much better chance than other users to gain access to his/her desired share. Moreover, the named mechanism will improve the seller and winners revenue as compared to the optimal and cooperative game models.

Finally, the named mechanism is tested with similar scenario assumptions as in the previous section. We are comparing three models; first, when the spectrum is offered to the users using a cooperative game. Second, using a similar setting but with a competitive game and finally a competitive second-price pay-to-bid sealed auction. We will study the effects in two simple scenarios; one, a SU (named $u_1$) who is competing with other bidders to get a share of the spectrum since the PU announce the auction. Two, a new comer is joining the game (the newcomer will join the game as the eleventh user onward) and how the introduced mechanism will improve his/her revenue, taking into account that the new comer has an excellent channel quality and a fair bid.

Figure 6-10, proofs what have been discussed in section 6.6.1.3 in terms of individual user revenue. Although the cooperative games shows a better start (*i.e.,* when the number of bidders is low), the cooperative game tries to improve the player's revenue and keep a fair share between all bidders. This would cause a sharp decrease in the seller revenue when the number of bidders increases. On the other hand, the competitive game takes into account the channel condition and the user ability to grab his/her share before the others, that's why it shows better revenue when compared to the cooperative model.

For the second scenario, Figure 6-11 shows the dramatic improvement in the newcomers' revenue; keeping in mind that his/her priority is rather high. Clearly, the introduced mechanism helped in improving spectrum share in terms of fairness, massively improving the players' revenue when compared to the other models and gives the PU a better deal by using the second-price sealed-auction.

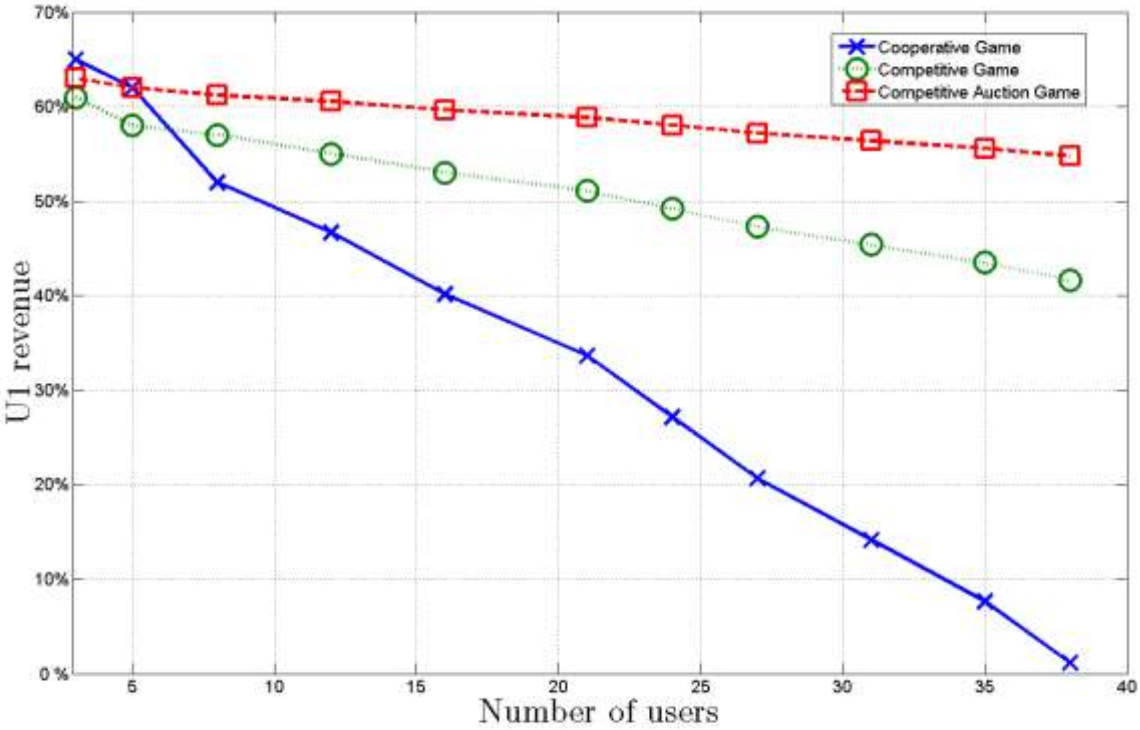


Figure 6-10: SU revenue vs. number of users with different models.

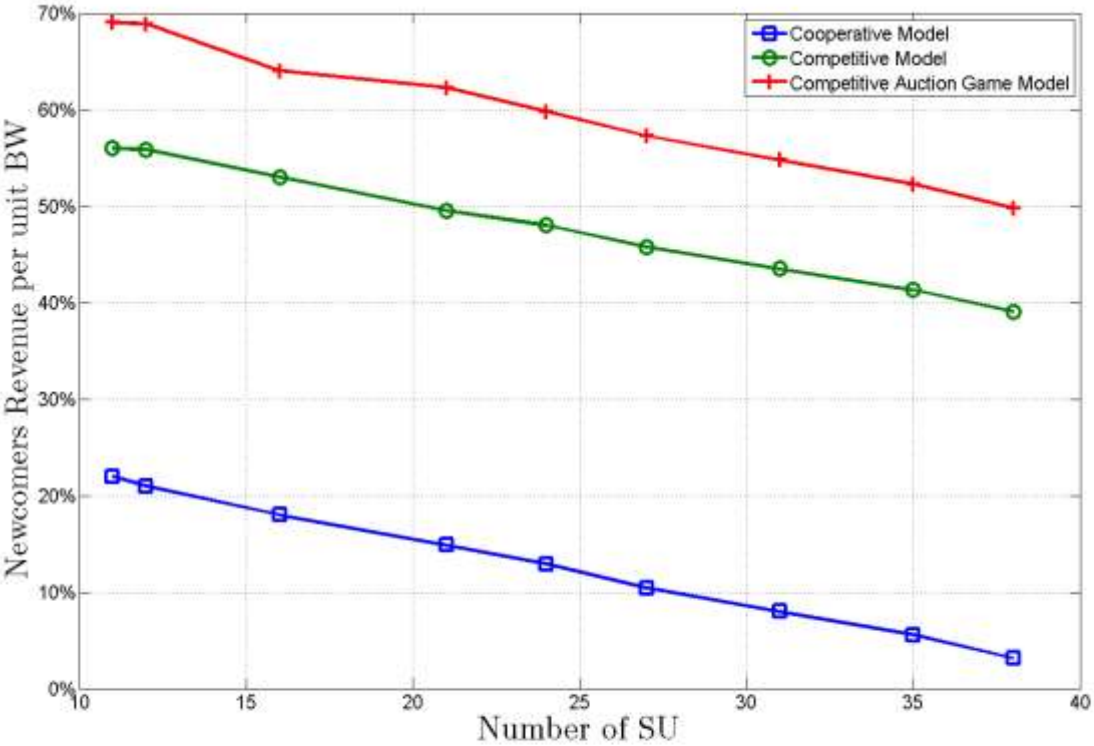


Figure 6-11: Newcomer revenue vs. number of users.

### 6.7.2 Reputation-Based Non-Cooperative Auction Games

With this game, PU will assign the spectrum to the winner of the second-price sealed-bid auction process. The revenue of the PU will not change, as using the second-price auction insures that all bidders will bid around the real value of the offered spectrum. The winner of the auction will be a new PU between the rest of the SUs, and will have the right to decide whether to share the spectrum with the rest or not. However, a penalty factor is introduced to insure that not only paying more will guarantee a share of the spectrum but also reputation will be combined with each bid. This factor will be forwarded to the PU and will show whether the winner of the last auction was popular or not, which is done by helping other SUs to share the offered spectrum.

In this section we will represent the infinitely repeated version of game $G$ by $G^{\infty}$ (*i.e. this is the case when $G$ is going to be played over and over again in successive time periods*). We are assuming that the PU is offering a single frequency band to be shared by other SU's. However, if the PU is planning to offer more bands then the proposed mechanism must be repeated for the other bands between the secondary users. We will define the user reputation as $R$ which will depends on user performance during any time period $t$ as well as in prior time periods. Reputation of player $i$ in some time period $t$ is denoted by $R_t^i$. Formally, we define node reputation as follows:

$$R_t^i = R_{t-1}^i\,(1-\propto) + w \times\propto \qquad 0 \leq\propto\leq 1, t \geq 2 \qquad\qquad (6\text{-}24)$$

where $\propto$ is the history of the user, it depends on the user reputation in the previous periods according to user behaviour. "$w$" is equal to "1" when player $i$ at time $t$ is interested in sharing the offered spectrum and "0" otherwise. Therefore, $0 \leq R_t^i \leq 1$, i.e. the reputation value of each player varies between "0" and "1" (including) ($R_t^i \in [0,1]$). Moreover, the reputation value of all players is equal to "0" when $t = 0$. A high value of $\propto$ means the more importance is assigned to a player's need in sharing the spectrum with the PU (higher priority) during the current period than its previous need record, and vice versa. Thus, when $\propto$ is high, a user with even low reputation value in the current time period $t$, can significantly improve his/her reputation when it realises that it needs a better share of the spectrum.

As the Nash equilibrium case has been defined earlier, the evaluation of the Nash equilibrium of the repeated game $G^{\infty}$ will be engaged. By finding the Nash equilibrium of

$G^{\infty}$ it leads to the deduction of the Nash equilibria of G. The proposed incentive mechanism is based on a player's links reputation $R$. The benefit of which is that a player draws from the system to its contribution, the benefit is a monotonically increasing function of a player's contribution. Thus, this is a non-cooperative game among the players, where each player with high priority traffic wants to maximize his/her utility. The classical concept of Nash equilibrium points a way out of the endless cycle of speculation and counter-speculation as to what strategies the players should use. The intent is to deduce a symmetric Nash equilibrium because all the players belong to the same population/network (i.e., assume the same role) and it is therefore easier (i.e., require no coordination among players) to achieve such an equilibrium. If the players in a game either do not differ significantly or are not aware of any differences among themselves (i.e., if they are drawn from a single homogeneous population) then it is difficult for them to coordinate and a symmetric equilibrium, in which every player uses the same strategy, is more compelling.

The argument of a single homogeneous population implies that all the peers in a CR network have equivalent responsibilities and capabilities as everybody else. We assume that if the player chooses the action $\{want\ to\ share\}$, this will assign him a probability of $p$, and if the player chooses the action $\{does\ not\ want\ to\ share\}$, this will assign one a probability of $1-p$.

It must be mentioned that in the action profile, a time and money saving Nash equilibrium case is defined, if all players choose the action $\{does\ not\ want\ to\ share\}$. As this will mean that, players are not interested in sharing the spectrum for the entire communication time. That is to say, users have low priority traffic and accessing the spectrum will be by chance, players will not compete to send their data and will not offer more money to the PU to get the spectrum. If any other player $i$ decided to switch to the action $\{want\ to\ share\}$, its payoff will be $-C$ which is less than a payoff of "0" that the node gets when decided not to share the spectrum. An undesirable Nash equilibrium case is generated, if all the players choose the action $\{want\ to\ share\}$. This is easy to see because all nodes will have to compete against each other again, this will waste time and the winner will be the PU, as one of the SU's should pay more to share the offered spectrum.

The expected payoff of any player in period $t$ when it selects the action $\{want\ to\ share\}$ is:

$$p\,(\,-C+\;R_t^{share}\;\times U) \qquad (6\text{-}26)$$

This payoff is denoted as $Payoff_{share}$, $U$ is the nodes utility. Similarly, the payoff for any player selects the action $\{does\ not\ want\ to\ share\}$ will be:

$$(1-p)(R_t^{dontshare}\;\times U) \qquad (6\text{-}27)$$

This will be denoted as $payoff_{dont\ share}$. It is easy to show that the term $R_t^{share}\;\times U$ captures the notation that the probability of SU becoming a secondary PU by sharing the offered spectrum is directly proportional to node's reputation.

$R_t^{share}$ is player $i$ reputation when he/she wants to share the offered spectrum at time $t$ (*i.e.* $w=1$ in equation (6-25)), and $R_t^{dontshare}$ is player $i$ reputation when he/she decides to take the action $\{does\ not\ want\ to\ share\}$ at the same time period $t$ (i.e. $w=0$ in equation (6-25)), from equation (6-25), the reputation value will be:

$$R_t^{share}\;=\;R_{t-1}\,(1-\propto)+\propto$$

and

$$R_t^{dontshare}\;=\;R_{t-1}\,(1-\propto) \qquad (6\text{-}29)$$

Generally, each player's expected payoff in equilibrium is his/her expected payoff to any of its actions that he/she uses with positive probability. The above useful characterization of mixed-strategy Nash equilibrium yields to:

$$payoff_{share}\;=\;payoff_{dontshare} \qquad (6\text{-}30)$$

Using equations (6-26), (6-27), and (6-28);

$$p\,(-C+(R_{t-1}(1-\propto)+\propto)\times U)=(1-p)(R_{t-1}(1-\propto)\times U) \qquad (6\text{-}32)$$

Solving equation (6-32) to get the final value of $p$;

$$p=\frac{R_{t-1}\times U\times(1-\propto)}{-C+2R_{t-1}\times U\times(1-\propto)+U\times\propto} \qquad (6\text{-}33)$$

It must be mentioned that the value $p$ obtained above is not a constant, but varies in each time interval depending upon a node's reputation at the end of the previous time interval $t-1$.

Finally, the mixed strategy pair $(p,1-p)$ for actions $\{want\ to\ share,$ $does\ not\ want\ to\ share\}$respectively, is a mixed strategy Nash equilibrium for the players (i.e. nodes in the network). Assuming no collusion among nodes, if all the other nodes follow the above strategy, then the best strategy for any node is to follow one of the above strategies. Actually, this is a symmetric mixed strategy Nash equilibrium for any $G$, as well as $G^{\infty}$. In fact, it is a more stable equilibrium than the one in which no node is interested in sharing the offered spectrum. This is caused by two reasons. First, when none of the SUs is interested in sharing the spectrum, the network is not useful to any user. Second, in real-time scenarios, users that derive finite utility from altruism would always send some messages irrespective of how much they obtain in return. Therefore, it is unlikely to have a scenario in which no node is looking to contact the PU to share the spectrum.

### 6.7.3 Properties of the proposed Nash Equilibrium

This section presents some of the interesting properties of the Nash equilibrium derived in the section above.

#### 6.7.3.1 Simplicity of Calculating the Nash Equilibrium

In section ‘6.7.2’, the probability of achieving the equilibrium point between the SUs has been calculated. This was based on which node will decide to share the spectrum with the PU and become a secondary PU. In each round of the game (or time period $t$) players decide whether they should ask to share the offered spectrum or not, based on their reputation at the end of the prior time period. This probability, as one can see, does not remain constant from one period to another. Moreover, it depends on a player’s reputation at the end of the last time period. Players can calculate their reputation using equation (6-25), since they know precisely their actions at each round of the game. Thus, determining the Nash equilibrium strategy is fairly straightforward for any player. However, it must be noted that there is an inherent assumption that nodes are serviced based on their current reputation.

Figure 6-12, shows how players’ reputations change in every time interval depending on their Nash strategy. At the beginning of the communication time, both, player 1 and 2 are competing with each other to guarantee access to the offered spectrum. However, player 1 uses the spectrum but at the same time managed to help player 2 (i.e. player 1 will be the secondary PU and will manage the access of players 2 and 3 to the offered spectrum). Player 3 shows his interest in the offered spectrum after the third time interval, and managed to use the spectrum once both player 1 and 2 finished using it or they are not interested anymore in sharing it. The figure shows the players (nodes) reputation values $0 \leq R_t^i \leq 1$ over ten time intervals.

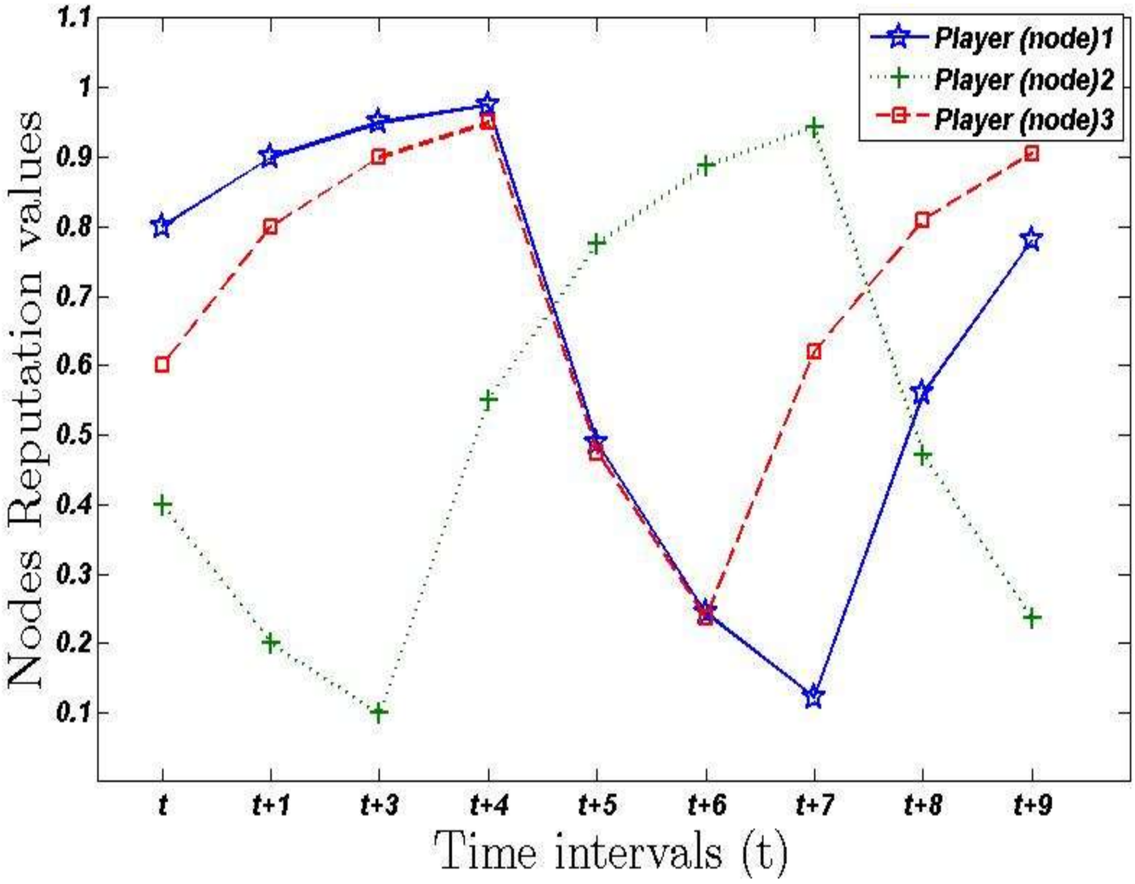


Figure 6-12: Change in player's reputation controlled by their Nash equilibrium strategies.

On the other hand, Figure 6-13 shows the same result but over a longer time period, around nine hundred time intervals. Similarly, three nodes are competing with each other, player one with the highest reputation and player three with the lowest. Player 1 will act as the secondary PU over the other two users (i.e. player 2 and 3). In this figure we used a random matrix generator to show different reputations when player 1 is interested to share the spectrum for 80% of the time, player 2 for 50% of the time and player 3 for 8% of the time only.

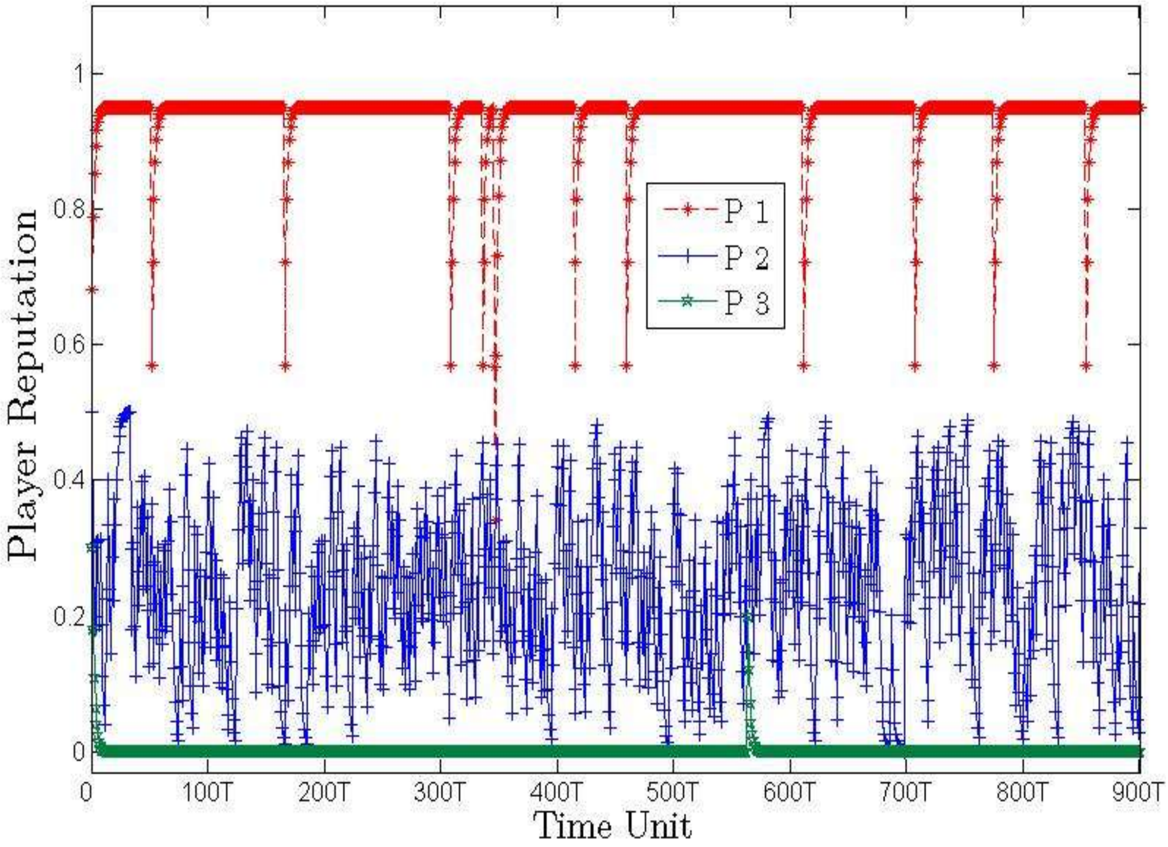


Figure 6-13: Changing player reputation over a longer time period.

### 6.7.3.2 Addressing the Spectrum to the right User

The simple game theoretic model presented in the previous sections, wherein node reputation is used as a basis for deciding who will share the offered spectrum, predicts that it is in every peer's best interest to serve others. This includes the nodes that are not interested to share the spectrum at the current time period. Our simulations support this behaviour as it was found that the total service received by a node is balanced by the total service that it has to offer to others, as shown in Figure 6-12.

### 6.7.3.3 Addressing the Problem of Competitive Sharing

An important property of the equilibrium emerges from equation (6-30) that predicts the probability with which one node will be a secondary PU and it should serve others. If we set the value of $C$ in away such that, $C \lll U$ (i.e. $C$ can be ignored from equation (6-30)), then equation (6-30) becomes:

$$p = \frac{R_{t-1}\,(1-\propto)}{2\,R_{t-1}\,(1-\propto)+\propto} \qquad (6\text{-}31)$$

That would lead us to the conclusion that $p < 0.5$. Then, Nash equilibrium of the proposed game predicts that players should help each other less than fifty percent of the time when PU offers the spectrum. This, although it appears to be very restrictive, is a consequence of the fact that all nodes are selfish and are better off trying to share the spectrum than serving others. Intuitively, if a node knows that everyone else in the network behaves selfishly, i.e., provide as little service as possible, then the best strategy for the named node cannot be to serve others most of the time (i.e., with probability greater than 0.5).

### 6.7.3.4 Fairness and Equal Sharing of Cost and Spectrum

From the previous section, it can be concluded that serving with a priority of less than 0.5 (i.e. when $C \lll U$) is an optimal point, the observer can notice that the overall system efficiency is severely reduced. This is because most of the nodes in the network act selfishly and at least half of the service requests from other nodes are not fulfilled. On the other hand, this equilibrium strategy provides fairness in the sense that the cost of system inefficiency is not burn by a single node (i.e. has one positive side), but it is shared among all nodes. This is because each node’s request is likely to be turned down by the serving node (i.e. selfish secondary PU). In this work, we assume that if a node’s request at one node is turned down, the node tries at some other candidate node capable of serving the request. On average, the probability that a node’s request is successfully served in a time period is proportional to its current reputation.

### 6.7.3.5 Decreasing α for a Better Share of the Spectrum

Figure 6-14 shows the effects of $\propto$ on the reputation probability of the nodes in the case where the node is not interested in sharing the spectrum. On the other hand, the node in Figure 6-15 is looking to keep its share of the spectrum (derived from equation (6-27)).

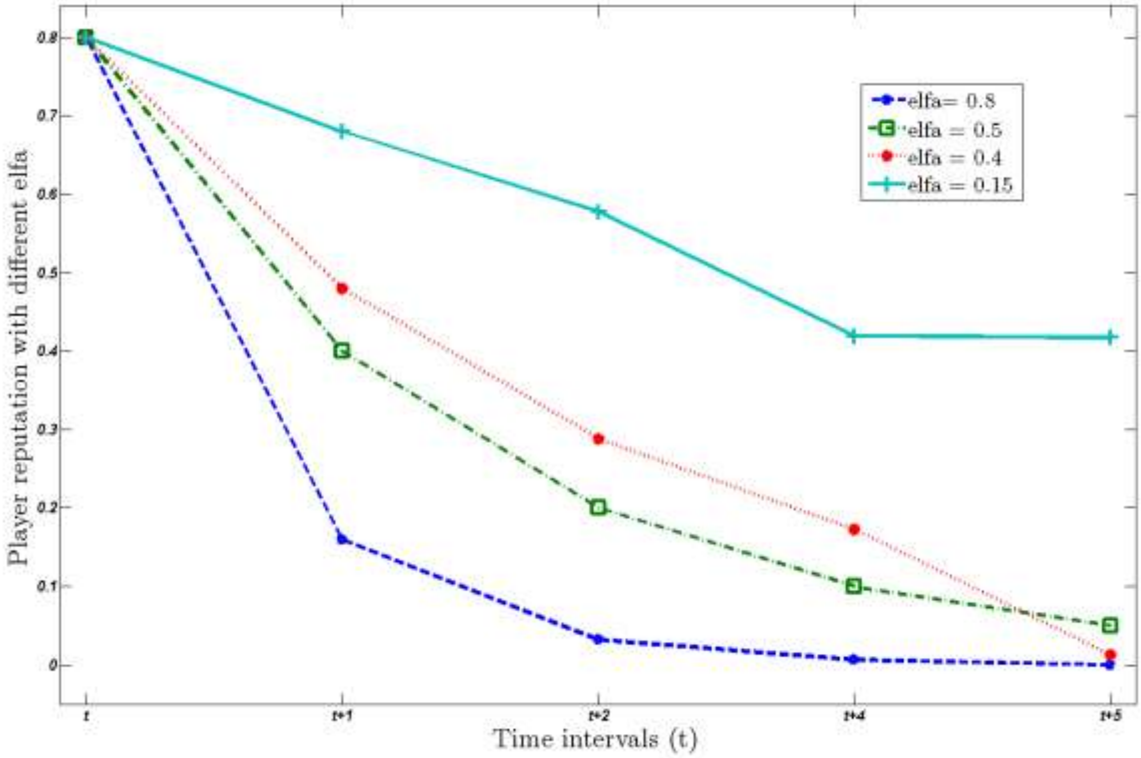


Figure 6-14: Players reputation with respect to α and the node is not interested in sharing the offered spectrum.

As can be seen from Figure 6-14, a lower value of α shifts the reputation probability curve upwards. However, that all depends on whether the node is interested in using the offered spectrum or not. If the node is looking to give its share of the spectrum to other nodes, a low value of ∝ will gradually help the node to lose its share, however a high value of ∝ will guarantee a faster release of the spectrum. This is true for Figure 6-15 as well, which is to be expected since ∝ determines how much importance is given to a node's current performance as compared to its past service record. A low value of ∝ (i.e., giving more importance to nodes past actions up to the current time period *t)* means that nodes need to continually provide service to be able to maintain high reputation and access spectrum offered from the PU. If however ∝ is high, nodes can easily increase their reputation in any period in which they provide service to other nodes. This is irrespective of how cooperative they have been in the past with regards to providing service to others. Therefore a simple way to improve the system efficiency is to set ∝ as low as possible.

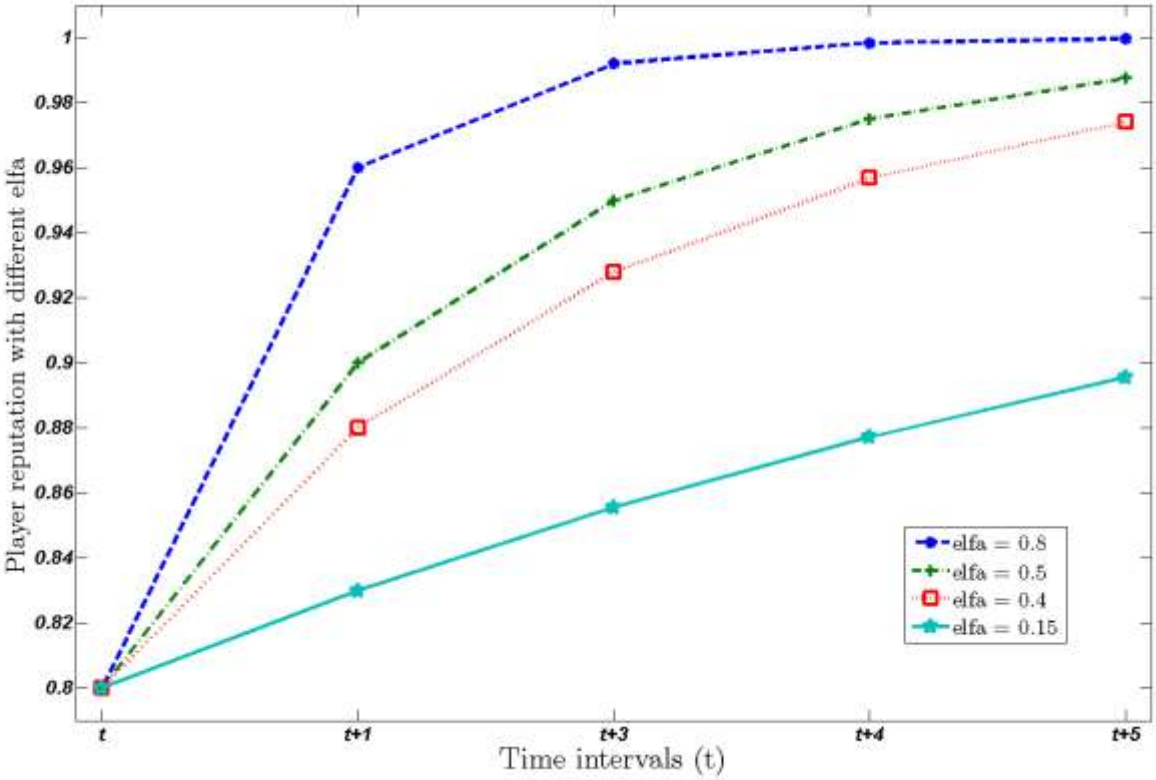


Figure 6-15: Players reputation with respect to α and the node is definitely interested in sharing the offered spectrum from the PU.

## 6.8 Summary

Cognitive radio is regarded as the key technology for next generation of wireless network. Dynamic spectrum sharing is one of the most important problems related to Cognitive Radio networks. We can summarize the key findings of applying game tools in dynamic spectrum sharing in cognitive radio networks by:

1. An adaptive dynamic competitive game and auction-based spectrum sharing mechanism is presented in this chapter.
2. The advantages over the optimal, cooperative and competitive static-models have been proved by simulation.
3. A general solution for the instability problem has been proposed and an adaptive method is used for the case when the number of secondary users is small by using cooperative game model.
4. Another solution for the same problem has been proposed as an adaptive competitive auction-based model to be used for the case when the number of secondary users (i.e. competitors) is large.
5. Another solution to the same problem is presented by using a non-cooperative reputation-based game model combined with second-price sealed-bid auction to choose a secondary primary user between group of secondary users. Such decision is based on user reputation and user’s valuation of the offered spectrum.

The above facts offer such solution aiming at improving the primary and secondary revenue and offer a better experience to the secondary users in terms of fairness. The introduced mechanism maintains the same results even when the number of competitors dynamically increases.

## 6.9 References

[1] FCC, "Spectrum Policy Task Force Report", ET Docket No. 02-135, pp. 35-53, November 7, 2002.

[2] S.S. Brave, S.B. Deosarkar, and S.A. Bhople, "A Cognitive approach to spectrum sensing in Virtual Unlicensed wireless network", International Conference on Advances in Computing, Communication and Control (ICAC3'09), pp. 668-673, 2009.

[3] M. Buddhikot, "Understanding Dynamic Spectrum Allocation: Models, Taxonomy and Challenges", Proceeding of IEEE DySPAN, 2007.

[4] T. Kamakaris, M. Buddhikot, and R. Iyer, "A Case of Coordinated Dynamic Spectrum Access in Cellular Networks", Proceeding of IEEE DySPAN, 2005.

[5] R. Axelrod, "The Evolution of Cooperation", Basic Books, reprint edition, New York, 1984.

[6] C. Ianculescu, and A. Mudra, "Cognitive Radio and Dynamic Spectrum Sharing", Proceeding of the SDR 05 Technical Conferences and Product Exposition, 2005.

[7] C. Jackson, "Dynamic Sharing of Radio Spectrum: A Brief History", Book chapter, July 2002. Available on line at: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=01542659 [Accessed March 2010].

[8] Federal Communications Commission, "Spectrum Policy Task Force Report", Report ET Docket, no. 02-135, Nov. 2002.

[9] 47 CFR 22.501 – Scope. Code of Federal Regulations-Title 47: Telecommunications (December 2005), Available online at: http://cfr.vlex.com/vid/22-501-scope-19849829 [Accessed March 2010].

[10] A.V. Oppenheim, W.R. Schafer, and R.J. Buck, "Discrete-Time Signal Processing", Prentice-Hall Signal Processing Series, 2nd edition, 1999.

[11] R.V. Cox, C.A. Kamm, L.R. Rabiner, J. Schroeter, and J. G.Wilpon, "Speech and Language Processing for Next-Millennium Communications Services", Proceedings of the IEEE, vol. 88, no. 8, pp. 1314-1337, August 2000.

[12] L. Rabiner, B.H. Juang and M.M. Sondhi, "Digital Speech Processing", Encyclopaedia of Physical Science and Technology, Third Edition, vol. 4, pp. 485-500, 2002.

[13] J.H. McClellan and C.M. Rader, “Number Theory in Digital Signal Processing”, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1979.

[14] J.H. McClellan, R.W. Schafer and M.A. Yoder, “Signal Processing First: A Multimedia Approach”, Upper Saddle River, NJ: Prentice-Hall, 1998.

[15] B. Schaller, “The Origin, Nature, and Implications of "MOORE'S LAW", the Benchmark of Progress in Semiconductor Electronics”, Spring 1996, available online at: http://research.microsoft.com/en-us/um/people/gray/Moore_Law.html [Accessed March 2010].

[16] D. Angel, “Restructuring for Innovation: The Remaking of the U.S. Semiconductor Industry”, (New York: The Guilford Press), 1994.

[17] E. Braun, and S. Macdonald, “Revolution in Miniature: The History and Impact of Semiconductor Electronics”, (Cambridge: Cambridge University Press), 1982.

[18] A. Dorfman, and S. Nancy,” Innovation and Market Structure: Lessons from the Computer and Semiconductor Industries”, (Cambridge: Ballinger), 1987.

[19] J. Mitola III, “Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio”, PhD Thesis, KTH Royal Institute of Technology, 2000.

[20] R. Axelrod, “The Evolution of Cooperation”, Basic Books, reprint edition, New York, 1984.

[21] P.K. Dutta, “Strategies and Games: Theory and Practice”, MIT press, 2001.

[22] S. Haykin, “Cognitive Radio: Brain-empowered Wireless Communications”, IEEE Journal in Selected Areas in Communications, vol. 23, pp. 201–220, Feb. 2005.

[23] K. Lee and A. Yener, “Throughput Enhancing Cooperative Spectrum Sensing Strategies for Cognitive Radios”, in Proceeding of Asilomar Conference on Signals, Systems and Computers, Pacific Grove, CA, Nov. 2007.

[24] D. Cabric, M. S. Mishra, and R. W. Brodersen, “Implementation Issues in Spectrum Sensing for Cognitive Radios”, in Proceeding Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, Nov. 2004.

[25] W. Zhang and K.B. Letaief, “Cooperative Spectrum Sensing With Transmit and Relay Diversity in Cognitive Networks”, IEEE Transactions in Wireless Communications, vol. 7, pp. 4761–4766, Dec. 2008.

[26] J. Unnikrishnan and V. Veeravalli, "Cooperative Sensing for Primary Detection in Cognitive Radio", IEEE Journal in Selected Topics in Signal Processing, vol. 2, no. 1, pp. 18–27, Feb. 2008.

[27] B. Wang, K.J.R. Liu, and T. Clancy, "Evolutionary Game Framework for Behavior Dynamics in Cooperative Spectrum Sensing", in Proceeding IEEE Global Communications Conference, New Orleans, LA, Dec. 2008.

[28] S. Huang, X. Liu, and Z. Ding, "Optimal Sensing-Transmission Structure for Dynamic Spectrum Access", in Proceedings International Conference on Computer Communications (INFOCOM), Rio de Janeiro, Brazil, Apr. 2009.

[29] M. Maskery, V. Krishnamurthy, and Q. Zhao, "Decentralized Dynamic Spectrum Access for Cognitive Radios: Cooperative Design of a Noncooperative Game", IEEE Transaction in Communications, vol. 57, no. 2, pp. 459–469, Feb. 2009.

[30] S. Subranami, T. Basar, S. Armour, D. Kaleshi, and Z. Fan, "Noncooperative Equilibrium Solutions for Spectrum Access in Distributed Cognitive Radio Networks", in Proceeding to IEEE DySPAN, Chicago, IL, Oct. 2008.

[31] M. Bloem, T. Alpcan, and T. Basar, "A Stackelberg Game for Power Control and Channel Allocation in Cognitive Radio Networks", in Proceedings ICST/ACM Game communication Workshop, Nantes, France, Oct. 2007.

[32] S. Sanghavi and B. Hajek, "Optimal Allocation of Divisible Good to Strategic Buyers", The 43rd IEEE Conference on Decision and Control, Paradise Island, Bahamas. December 2004.

[33] O. Raoof, Z. Al-Banna, and H.S. Al-Raweshidy, "Competitive Spectrum Sharing in Wireless Networks: A Dynamic Non-cooperative Game Approach", Springer. Boston, vol. 308/2009, pp. 197-207, August 2009.

[34] O. Raoof, Z. Al-Banna, and H.S. Al-Raweshidy, "A Dynamic Non-cooperative Game Approach for Competitive Spectrum Sharing in Wireless Networks", 15th EUNICE International Workshop - The Internet of the Future. Barcelona, Spain, September 2009.

[35] FCC, "Facilitating Opportunities for Flexible, Efficient, and Reliable Spectrum Use Employing Cognitive Radio Technologies, Notice of Proposed Rulemaking", 03-322A1, Dec 2003. Available online at: www.cs.ucdavis.edu/~liu/289I/Material/FCC-03-322A1.pdf [Accessed March 2010].

[36] Q. Zhao, L. Tong, A. Swami, and Y. Chen, “Decentralized Cognitive MAC for Opportunistic Spectrum Access in Ad Hoc Networks: A POMDP Framework”, IEEE Journal on Selected Areas in Communication (JSAC), April 2007.

[37] C. Peng, H. Zheng, and B. Zhao, “Utilization and Fairness in Spectrum Assignment for Opportunistic Spectrum Access”, ACM Journal of Mobile Networks and Applications (MONET), August 2006.

[38] R. Etkin, A. Parekh, and D. Tse, “Spectrum Sharing for Unlicensed Bands”, IEEE Journal on Selected Areas in Communication (JSAC), vol. 25, Iss. 3, pp. 517, April 2007.

[39] T. Alpcan, T. Bas¸ar, R. Srikant, and E. Altman, “CDMA Uplink Power Control as a Noncooperative Game”, Wireless Networks, vol. 8, pp. 659-670, 2002

[40] J. Huang, R. Berry, and M. Honig, “Distributed Interference Compensation for Wireless Networks”, IEEE Journal on Selected Areas in Communication (JSAC), May 2006.

[41] N. Nie, and C. Comaniciu, “Adaptive Channel Allocation Spectrum Etiquette for Congnitive Radio Networks”, 1st IEEE Conference on Dynamic Spectrum Access Network (DySPAN), Nov. 2005.

[42] M. Felegyhazi, M. Cagali, S. Bidokhti, and J. Hubaux, “Non-Cooperative Multi-Radio Channel Allocation in Wireless Networks”, 26th IEEE conference on Computer Communications (INFOCOM), May 2007.

[43] I. Hoang, and Y. Liang, “Maximizing Spectrum Utilization of Cognitive Radio Networks Using Channel Allocation and Power Control”, IEEE Vehicular Technology Conference (VTC), Sep. 2006.

[44] T. Basar, and G. Olsder, “Dynamic Noncooperative Game Theory”, Series in Classics in Applied Mathematics, SIAM, Philadelphia, 2nd Ed, 1999.

[45] B. Platt, J. Price, and H. Tappen, “Pay-to-Bid Auctions”, (July 9, 2009), Available at SSRN: http://ssrn.com/abstract=1432169 [Accessed April 2010].

[46] S. H. Chun, and R.J. La, "Auction Mechanism for Spectrum Allocation and Profit Sharing”, Game Theory for Networks, GameNets '09., pp. 498-507, 13-15, May 2009.

[47] W.W. Sharkey, F. Beltran, and M. Bykowsky, "Computational analysis of an auction for licensed and unlicensed use of spectrum", Game Theory for Networks, 2009. GameNets '09, pp. 488-497, 13-15, May 2009.

[48] D. Niyato, and E. Hossain, "Market-Equilibrium, Competitive, and Cooperative Pricing for Spectrum Sharing in Cognitive Radio Networks: Analysis and Comparison", IEEE Transactions on Wireless Communications, vol. 7, no. 11, pp. 4273-4283, November 2008.

[49] D. Niyato, and E. Hossain, "Competitive spectrum sharing in cognitive radio networks: a dynamic game approach", IEEE Transactions on Wireless Communications, vol. 7, no. 7, pp. 2651-2660, July 2008.

[50] D. Niyato, E. Hossain, and L. Long, "Competitive Spectrum Sharing and Pricing in Cognitive Wireless Mesh Networks", in Proceedings of IEEE WCNC 2008, Las Vegas, NV, 31 March-3, April 2008.

[51] S.L. Chen, W.A. Cui, Y.F. Luo, and X.H. Yang, "Optimal Design of Online Auctions with Shill Bidding and Open Reserve Price", WiCOM '08. 4th International Conference on Wireless Communications Networking and Mobile Computing, pp. 1-4, 12-14, October 2008.

[52] H.J. Parrsch and J. Robert, “Testing Equilibrium Behaivour At First-Price, Sealed-Bid Auctions With Discrete Bid Increments”, Scientific series, Montreal, June 2003.

[53] F.M. Menezes and P.K. Monteiro, “An Introduction to Auction Theory”, Oxford Scholarship Online, November 2004.

[54] M. Bennis, S. Lasaucle, and M. Debbah, “Inter-Operator Spectrum Sharing from a Game Theoretical Perspective”, Hindawi Publishing Corp. Network, US vol. 2009, pp. 1-12, 2009.

[55] L. Grokop, and D. Tse, “Spectrum Sharing between Wireless Networks”, IEEE INFOCOM proceedings, pp. 735-743, 2008.

[56] X. Wang, Z. Li, P. Xu, Y. Xu, X. Gao, and HH. Chen, “Spectrum Sharing in Cognitive Radio Networks-An Auction-Based Approach”, IEEE transactions on systems, man and cybernetics, vol. 40, Iss. 3, pp. 587-596, May 2010.

[57] J.E. Suris, L.A. Dasilva, Z. Han, and A.B. Mackenzie, “Cooperative Game Theory for Distributed Spectrum Sharing”. IEEE ICC proceedings, pp. 5282-5287, 2007.

# CHAPTER 7

# *Conclusions and Future Work*

## 7.1 Conclusions

The aim of this thesis was to resolve some of the issues in Cognitive Wireless Applications. This work introduced a green cooperative game-based vertical handover mechanism for heterogeneous multihomed wireless portable devices that improves the overall end-to-end QoS and offers a better experience the user during the communication time. The mechanism controls the power consumption in such devices and shows a better power saving architecture when compared to other mechanisms. Moreover, the thesis introduces a similar cooperative game to manage handovers in multi-interface fast handover MIPv6 wireless devices by introducing game-based multi-interface fast-handover MIPv6 protocol. Similar to the vertical handover model, this protocol provides an improved QoS experience for the user and consumes relatively the same amount of power when compared to single interface mobile node.

Applying cooperative games in the above two scenarios allow the user and/or application the ability to manage the handover process and control the node power consumption. Such a model help the node to easily define a dominate strategy (i.e. dominate access point or technology, based on the received QoS) that will help the game to reach its Nash equilibrium faster and improve the chance of keeping the node in the Nash state.

On the other hand, the thesis proposes competitive Auction game-based mechanisms to allocate resources in Ad-Hoc networks between competitors in a fairly manner and improve the overall routing reliability in such networks using competitive power and price-based routing games. This mechanism gives abetter allocation chance to users/nodes who value the data more. It applies both first and second-price sealed-bid auctions to announce the winner user and improve the source revenue. The mechanism gives the source the chance of improving the link reliability between the source and the winner of the bid by compensating the intermediate node in the Ad-Hoc network. The mechanism consider the nil strategy, where intermediate nodes might decide not to participate in forwarding packets if that will cost them more power and the source compensation is not enough.

Finally, the thesis proposes two competitive Auction game-based mechanisms aiming at offering a fare spectrum share between secondary users and improves primary and secondary users' revenue. The thesis adopts an adaptive dynamic competitive game and auction-based sharing mechanism that insurers any secondary user with high priority traffic, better channel quality and a reasonable valuation to the offered spectrum will have a better chance in gaining access to the offered spectrum. By using an adaptive auction games, the mechanism overcomes the disadvantages of previously static defined models, namely optimal, competitive and cooperative. The second mechanism adopted in this thesis is a competitive reputation-based Auction game model, which will propose a secondary primary user from a group of secondary users. Users will compete between themselves to win this position based on their reputation on previous time-periods added to the use of the second-price sealed-bid auction. These two mechanisms successfully shows a noticeable improvement in both primary and secondary user revenue and it insures a fair share of the spectrum when the number of competitors is changing dynamically during the time.

## 7.2 Future Work

### 7.2.1 Green Game-based Hybrid Vertical Handover Model for Heterogeneous Multihomed Wireless Portable Devices

The game-based green hybrid vertical handover model introduced in Chapter 3 serves as a game-based extension to the traditional vertical handover model used in heterogeneous wireless networks. Without this extension, portable devices with multiple wireless interfaces will suffer from what is called handover latency [1-2], which is the time the MN needs to establish a new point of attachment until the handover ends.

In order to reduce the handover latency effects, a few mobile host multi-homing protocols supporting handovers between interfaces have been proposed (3-8). The most advanced protocols are able to move single traffic flows independently of each other. However, the current solutions do not propose any means for the user to be able to dynamically influence the interface selection during operation. For example, different access technologies offer several types of price and quality, and a mobile user must be able to affect the interface selection so that the most suitable available interfaces are used. For this reason, HVHM was proposed, which is a game-based handover scheme that maintains the connectivity of all applications on the wireless mobile device when the handoff occurs. It aims to provide continuous end-to-end data service in the face of any link outages or handoff events, which should provide low latency and minimum packet loss.

In this model, the best network is chosen based on both static and dynamic factors. Static (fixed) factors are the channel capacity, service cost and power consumption. Dynamic factors include the RSS from the around AP and the speed of the MN.  The reason behind using game theory in this extension is that it is a mathematical concept that deals with the formulation of the correct strategy that will enable an individual or entity (i.e. player), when confronted by a complex challenge, to succeed in addressing that challenge. The game mechanism used in this model is not complicated and the winner AP can be easily calculated throughout a game-based score function. In order to control the size of any temporary files, which might be used to store the information of the APs the MN will visit during simulation time, a size 20 FIFIO matrix is used for this purpose. This will also reduce the complexity factor of calculating the winning AP.

However, so far all extensions that have been proposed managed the traffic flow between the nodes' interfaces and ignore the energy consumption caused from the use of all interfaces in the MN. In a multi-interface MN, all interfaces are kept 'ON' over the entire communication time, which will consume a massive amount of its battery life. In order to solve this problem, the GHVHM was proposed. In this model the MN's interfaces will be turned 'ON' only to check if there is a chance to switch to a better AP when a HO is needed. This mechanism works in the following steps; once the MN starts looking for connection, all the interfaces will be turned 'ON', the cost function will define the 'winner' AP, the communications start and the rest of the interfaces will be forced to switch 'OFF'. The main drawback of this model is that, while only the active interface is kept 'ON' and the rest are switched 'OFF', the MN might move across a network that offers a better service and the MN will not be able to switch to it as the compatible interface is switched 'OFF'. Yet, keeping the communication going with some acceptable QoS and saving a substantial amount of power is an advantage of this model.

The proposed game-based extension model, although proven to provide satisfactory results, has some issues which if addressed can further add to the improvement of proposed work.

1. As mentioned earlier, the simulation results compare four coverage technologies, namely UMTS, Bluetooth, GPRS and 802.11b wireless technologies. Different simulation scenarios and including more access technologies will give a better understanding of what the model can offer to the MN. This will include more interfaces to be taken into account in the game and a chance of a better service to the MN.

2. In this model, we used the RssONT point as a trigger to decide when to switch all interfaces in the MN. Another approach would be useful when using a QoS-based point to decide when the interfaces should be turned 'ON', taking into account the RSS from the around the APs.

3. In this model, we took into account the power consumed by the MN's interfaces during the communication time. The energy consumed by other applications working

in the MN was not considered. Taking into account the amount of power consumed by other factors would give a bigger picture of the advantages of the introduce model. This would be done by a real time measurement of what the MN will consume on different scenarios and multiple applications working in the background.

### 7.2.2 Green Game-Based Multi-Interface Fast-Handover MIPv6 Protocol

The MFMIPv6 protocol proposed [9] aims at reducing the reordering problem during handover when a MN has multiple wireless interfaces and multiple CoA registrations. In this protocol, the TCP throughput flow increases through avoiding unnecessary congestions. Moreover, the handover signalling performance would increase using this protocol as traffic is redirected to another interface during handover signalling. However, this protocol does not give the MN the ability to choose the right AP at the right point. Moreover, the protocol consumes a huge amount of the nodes' power as it keeps the MN's interface 'ON' all the time. For these reasons, game theory would be very useful to control the two interfaces and help the MN to decide which AP to go with. The game-based mechanism consists of two steps; first, the mechanism focuses on finding factors indicative of each network's weak points. Qualitative relations between the QoS parameters must be defined in this step in order to calculate the weight of each parameter and how it affects the overall QoS obtained. When this step is finished, priorities should be assigned to each parameter according to their weight. The higher a weight is, the higher the priority that should be given to the corresponding parameter. In the second step, the mechanism starts investigating all available networks in order to find the optimal choice. This game-based extension forms the GMFMIPv6 protocol, discussed in Chapter 4.

Another vital point needed to be fixed in the GMFMIPv6 protocol is energy consumption, as it uses two interfaces during the simulation time in order to get the full advantage of the MFMIPv6 protocol. This is solved using the RssONT point. In this method, one of the interfaces will be turned OFF until the RSS from the AP reaches a certain point "$\mathrm{R_{SS}}$ONT", which means that the MN is moving away from the AP and reaching the boundaries of its coverage. Once the MN reaches the named point, the game mechanism will work, as explained earlier, saving more energy to the MN by keeping the other interface 'OFF' most of the time. Yet, one drawback of this method will be the chance that the MN might lose handoff to a better network within the coverage of the bigger network. To solve this problem, the first interface will trigger the second interface once it receives any advertisement messages from the around the APs. The game mechanism will work to check whether a handover is needed or not; if so, the game process will proceed, if not, the second interface will be turned 'OFF' and wait for either the $R_{SS}$ONT point or to be forced by the other interface.

Similar to the work in Chapter 3, the proposed green game-based extension to the multi-interface fast-handover MIPv6 protocol shows pleasing results in terms of both TCP throughput performance and energy saving. However, there are some issues which if addressed can further add to the improvement of the proposed work. This includes taking into account the energy consumed by other applications working in the MN. This would be done by a real time measurement of what the MN will consume in different scenarios and multiple applications working in the background.

### 7.2.3 Auction and Game-Based Resource Allocation and Routing in Ad-Hoc Wireless Networks

In Ad-Hoc wireless networks, each node is capable of independently adapting its operation based on the current environment according to predetermined algorithms and protocols, and the nodes themselves provide networking services. Problems arise when nodes in such networks have their own authority; it is reasonable to assume that each node has the goal to maximize its own benefits by enjoying network services and at the same time minimizing its cooperation with other nodes. To this extent, Chapter 5 proposes a dynamic auction-based resource allocation mechanism in ad-hoc wireless networks. This auction-based mechanism works as follows: nodes will compete between each other to gain access to the data stored in the server node. The winner is the node that values the data the most. The server will try to compensate all intermediate nodes to improve the reliability of the route. The intermediate nodes will have the chance to decide whether they should participate in the named route or not, according to the amount of source compensation and how much energy is needed to forward packets to the next hop. This mechanism works in both first and second-price sealed-auctions. Finally, two types of sources have been defined: cooperative and selfish sources. The first will accept any positive payoff and will always keep the route more reliable by increasing the compensation provided to all intermediate nodes. Then again, the selfish source will try to maximize his/her own profit without paying any attention to the route quality.

In ad-hoc wireless networks, the establishment of multi-hop routes relies on nodes' forwarding packets for one another. Yet, if a selfish node decided to conserve its limited energy resources, it might decide not to participate in the forwarding process by switching off its interface. If all nodes decide to behave the same way, it may lead to the collapse of the network. Different game-based theoretic models have been proposed for analysing selfishness in forwarding packets [10-15]. Under general energy-constraint assumptions, the equilibrium solution for the single-stage game results in none of the nodes cooperating to forward packets.

The game-based mechanism proposed in Chapter 5 is mainly focused on keeping the defined path stable, where all the participating nodes are faithful to forward the packets to the next hop all time. A polynomial-time solution to find the Nash Equilibrium is shown by adding some suitable modifications to the well-known Dijkstra algorithm.

Simulation results prove the magnificence of the second-price sealed-auction mechanism in terms of improving the source revenue, especially when the number of competitors increases. The results compare both auction schemes with a random allocation mechanism, where the source offers the data to the first interested node and compensates all intermediate nodes in advance. Nonetheless, there are some issues which if addressed can further add to the improvement of the proposed mechanisms:

1. Applying the game-based routing mechanism on heterogonous wireless ad-hoc networks would show results that are more interesting, as using different technologies to forward packets between nodes might reduce the overall power consumption of the node; hence, more power to be saved in the entire network.

2. First and/or second-price open-auction mechanisms would increase the source revenue, as it will push the bidders to increase their bids. However, using such mechanisms would raise the chances of more complex mechanisms and might

require some time to decide the winner. Adding such mechanisms might need the addition of more restrictions to the mechanism such as the number of bidders in each round and the time of each round, keeping in mind that some nodes might require urgent information and cannot wait for a long time.

### 7.2.4 Auction and Game-Based Spectrum Sharing in Cognitive Radio Networks

The rapid development of radio networks of all kinds in our world, which have defiantly changed the public feeling about radio, is one of the main reasons behind the concurrent increase in the demand for and congestion of the Radio Frequency (RF) spectrum. However, according to recent research introduced by the FCC and Ofcom, it was found that most of the frequency spectrum was inefficiently utilized [16-17]. Chapter 6 of this thesis proposes an auction and game-based mechanism to improve the spectrum sharing in cognitive radio networks in terms of fairness. In fact, recent studies have shown that despite claims of spectral insufficiency, the actual licensed spectrum remains unoccupied for long periods of time [18]. Thus, *cognitive radio* systems have been proposed [19] in order to efficiently exploit these spectral holes.

The aim of the work presented in Chapter 6 is to design a mechanism that enables the fair and efficient sharing of spectral resources among secondary users. Throughout the chapter, a theoretical comparison is made between three spectrum sharing game models, namely optimal, cooperative and competitive models. The comparison is based on how much the named model will improve the primary user and the secondary users' revenue and fairness between secondary users themselves. The theory and realization of cooperative spectrum sharing is presented in detail, where it is assumed that there is one primary user and several secondary users. The case of dynamic games is also considered, where the number of secondary users changes. The advantages of cooperative sharing games are proved by simulation. Moreover, the case of large numbers of secondary users competing to share the offered spectrum and how the cooperative game will reduce primary user and bidders' revenue is also discussed in detail. Finally, a competitive auction and game-based mechanism to improve the overall system efficiency in terms of a better fairness in accessing the spectrum is introduced.

In addition, Chapter 6 proves that the cooperative game model is built based on achieving Nash equilibrium between players and provides better revenue to the sellers and bidders in the game. Furthermore, the cooperative game is the best model to choose when the number of secondary users changes dynamically, but only when the number of competitors is low. As in practical situations, the number of secondary users might increase dramatically and the cooperative game will lose its powerful advantage once that number increases. As a result, the proposed mechanism creates a competition between the bidders and offers better revenue to the players in terms of fairness. Combining both second-price pay-to-bid sealed auction and competitive game models will insure that the user with better channel quality, higher traffic priority and fair bid will get a better chance to share the offered spectrum. It is shown by numerical results that the proposed mechanism could reach the maximum total profit for secondary users with better fairness.

Throughout Chapter 6, we proved that the optimal game would improve the overall profit of the players in the game, which might lead to the unfair distribution of the offered spectrum. The competitive game shows a lower overall profit, but gives a better share to the user with better channel quality, who asks for a share earlier and stays active for a longer period (*i.e.* a higher priority as compared to newcomers). Finally, the cooperative game gives the best overall individual profit and it is the best way to insure a fair share between multiple users in any cognitive radio system. However, in a practical cognitive radio environment, the communication between competitors (*i.e.* players) is very hard to achieve. Individual users tend to contact the primary user and ask for a service [20]; users can only observe the pricing function from the primary user, but not the strategies and profits of other users. Nevertheless, achieving a cooperative scheme between the secondary users (either the primary user forces the secondary user to get a fair share or uses the model mentioned earlier) would improve both the seller's and users' revenue.

In order to solve such a problem, two solutions were proposed in Chapter 6. Firstly, a second-price pay-to-bid (or sometimes called as pay-as-bid) sealed auction mechanism is introduced to insure a fair competitive game between secondary users. Secondly, a reputation-based auction game is proposed as a non-cooperative game to assign a secondary to be a secondary-primary user between other secondary users.

Nevertheless, there are some issues which if addressed can further add to the improvement of the proposed solutions:

1. Looking at adding both first and second-price open-auctions, as it would increase the primary user's revenue. This option would be interesting for long-term contracts, where the primary user is looking to lend part of the spectrum for a long time. However, this option will not work in the case of short-term contracts or the case of using the spectrum whenever it becomes free.

2. Another approach would be looking at different scenarios of how secondary users can approach the primary user rather than the allocation function defined in the chapter.

3. Another auction scenario can be added for the game-based reputation model, where the secondary primary user can offer some of the shared spectrum to other secondary users. However, such modification requires changing the reputation model as the winning secondary user will not help others unless they pay for the service.

## 7.3 References

[1] A.S. Reaz, P.K. Chowdhury, M. Atiquzzaman, and W. lvancic. "Signalling Cost Analysis of SINEMO: Seamless EndtoEnd Network Mobility", San Francisco, California, MobiArch '06. ACM, New York, NY, link: http://doi.acm.org/10.1145/1186699 .1186712, pp. 37-42, 2004.

[2] N. Montavont and T. Noël, “Handover Management for Mobile Nodes in IPv6 Networks”, IEEE Communications Magazine, pp. 38-43, August 2002.

[3] V. Devarpalli, R. Wakikawa, A. Petrescu and P. Thubert, "Network Mobility (NEMO) Basic Support Protocol", RFC 3963. January 2005. Available online at: http://www.ietf.org/rfc/rfc3963.txt [Accessed Augest 2007].

[4] M. Inoue, K. Mahmud, H. Murakami, and M. Hasegawa, ”MIRAI: a Solution to Seamless Access in Heterogeneous Wireless Networks”, in Proceeding to IEEE ICC 2003, pp. 1033-1037, May 2003.

[5] J. Ylitalo, T. Jokikyyny, T. Kauppinen, A. Tuominen, and J. Laine, “Dynamic Network Interface Selection in Multihomed Mobile Hosts”, IEEE Computer Society, proceedings of the 36th Hawaii International Conference on System Sciences (HICSS’03), January 2003.

[6] A. H.zahran, B. Liang, and A. Saleh, “Signal Threshold Adaptation for Vertica handoff in heterogeneous wireless networks”, Mobile Network Application, Springer science, 2006.

[7] H. Wang, R. Katz, and J. Giese, “Policy-Enabled Handoffs Across Heterogeneous Wireless Networks”, Proceedings of Second IEEE Workshop on Mobile Computing Systems and Applications (WMCSA ’99), pp. 51-60, February 1999.

[8] L.Y. Chen, T. Sun, B. Chen, V. Rajendran and M. Gerla, “A Smart Decision Model for Vertical Handoff”, The fourth ANWIRE International Workshop on Wireless Internet and Re-configurability, Athens, Greece 2004.

[9] M.K. Park, J. Y. Lee, B.C. Kim and D.Y. Kim, “Design of Fast Handover Mechanism for Multiple Interfaces Mobile IPv6”, IEEE ISWPC2008, pp. 697-701, 2008.

[10] M. Urpi, Bonuccelli, and S. Giordano, “Modeling Cooperation in Mobile Ad-Hoc networks: a Formal Description of Selfishness”, Proc. of the 1st Workshop on Modeling and Optimization in Mobile, Ad-Hoc and Wireless Networks, March 2003.

[11] M. Felegyhazi, L. Buttyan, and J.-P. Hubaux, “Nash Equilibria of Packet Forwarding Strategies in Wireless Ad-Hoc Networks”, IEEE Transactions on Mobile Computing, vol. 5, Iss. 5, pp. 463-476, May 2006.

[12] P. Michiardi and R. Molva, “Analysis of Coalition Formation and Cooperation Strategies in Mobile Ad-Hoc Networks”, Journal of Ad-Hoc Networks, vol. 3, no. 2, pp. 193-219, March 2005.

[13] V. Srinivasan, P. Nuggehalli, C.F. Chiasserini, and R.R. Rao, “Cooperation in Wireless Ad-Hoc Networks”, Proceeding of IEEE INFOCOM, vol. 2, pp. 808-817, April 2003.

[14] M. Felegyhazi, L. Buttyan, and J.P. Hubaux, “Equilibrium Analysis of Packet Forwarding Strategies in Wireless Ad-Hoc Networks – the Dynamic Case”, Proceeding of the 2nd Workshop on Modelling and Optimization in Mobile, Ad-Hoc and Wireless Networks, March 2004.

[15] E. Altman, A.A. Kherani, P. Michiardi and R. Molva, “Non-Cooperative Forwarding in Ad-Hoc Networks”, INRIA, Sophia-Antipolis, France, Report no. 5116, February 2004.

[16] FCC, “Spectrum Policy Task Force Report”, ET Docket no. 02-135, pp. 35-53, released November 7, 2002.

[17] S.S. Brave, S.B. Deosarkar and S.A. Bhople, “A Cognitive Approach to Spectrum Sensing in Virtual Unlicensed Wireless Network”, International Conference on Advances in Computing, Communication and Control (ICAC3’09), pp: 668-673, 2009.

[18] Federal Communications Commission, “Spectrum Policy Task Force Report”, Report ET Docket no. 02-135, November 2002.

[19] S. Haykin, “Cognitive Radio: Brain-Empowered Wireless Communications”, IEEE Journal in Selected Areas in Communications, vol. 23, pp. 201–220, February 2005.

[20] D. Niyato, and E. Hossain, "Competitive Spectrum Sharing in Cognitive Radio Networks: A Dynamic Game Approach”, IEEE Transactions on Wireless Communications, vol.7, no.7, pp.2651-2660, July 2008.

# List of Papers

**Accepted papers:**

1. O. Raoof, G. Kamel, and H.S. Al-Raweshidy, “Differentiated and Integrated Service Mechanisms Used Under Network Mobility”, Mosharaka International Conference on Communications, Propagation and Electronics (MIC-CPE 2008) Jordan, Amman August 2008.
2. O. Raoof, and H.S. Al-Raweshidy, “Interface Selection Mechanisms in Multi-Homed Mobile Nodes using Game Theory”, IEEE Symposium on Computers and Communications (ISCC08), Marrakech, Morocco, pp. 616-623. July 6 - 9, 2008.
3. Z. Jerjees, O. Raoof, and H.S. Al-Raweshidy, “Cross-layer Optimization And Handover Managements In Next Generation Mobile Networks”, the fifth international Conference on Broadband Communications, Networks and Systems (BROADNETS), London, UK, pp. 366-370. September 8-11, 2008.
4. O. Raoof, and H.S. Al-Raweshidy, “Design an Interface/Network Selection Mechanism for Multi-Interface FMIPv6 Protocol”, IEEE 3'rd International Conference on Sensing Technology (ICST 2008), Tinan, Taiwan, pp. 348-353. Nov. 30 - Dec. 03, 2008.
5. O. Raoof, H. Radi, and H.S. Al- Raweshidy, “Dynamic Interface/Network Selection Mechanism Approach for Multi-homed Wireless Nodes”, The fifth IEEE GCC conference, Kuwait, 17-19 March 2009.
6. O. Raoof, and H.S. Al-Raweshidy, “Controlling the Handover Mechanism in Wireless Mobile Nodes Using Game Theory”, ICT-MobileSummit-2009, Santander, Spain, 10-12 of June 2009.
7. O. Raoof, and H.S. Al-Raweshidy, “Spectrum Sharing in Cognitive Radio Networks: A Dynamic Cooperative Game Approach”, IEEE WCNC 2010 Workshop, Sydney, Australia, 18 April 2010.
8. O. Raoof, Z. Al-Banna, and H.S. Al-Raweshidy, “Competitive Spectrum Sharing in Wireless Networks: A Dynamic Non-cooperative Game Approach”, Springer Boston Book series ’IFIP Advances in Information and Communication Technology’, Vol. 308/2009, pp. 197-207, August 2009.

9. O. Raoof, and H.S. Al-Raweshidy, “Pricing-based Resource Allocation in Ad-Hoc Networks Using Auction Theory”, Future Networks & mobile Summit 2010 (ICT-MobileSummit), Italy, 16-18-June 2010.
10. O. Raoof, and H.S. Al-Raweshidy, “Resource Allocation Auction and routing Game in Ad-hoc Networks”, Future Networks & mobile Summit 2010(ICT-MobileSummit), Italy, 16-18 June 2010.
11. O. Raoof, and H.S. Al-Raweshidy, “Cooperative Spectrum Sharing in Cognitive Radio Networks”, The 7th IEEE, IET International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP) 2010. Newcastle, UK, 21-23-July 2010.

**Papers currently under-review/ in press:**

1. O. Raoof, and H.S. Al-Raweshidy, “Auction-Based Routing Games in Wireless Ad-Hoc Networks”, Submitted to Wireless Communications and Mobile Computing Journal-Wiley. **Major revision**, under revision since March 2010.
2. O. Raoof, and H.S. Al-Raweshidy, “Green Game-Based Multi-interface Mobile IPv6 Protocol”, Submitted to Wireless Communications and Mobile Computing Journal-Wiley. **Major revision**, under revision since May 2010.
3. O. Raoof, and H.S. Al-Raweshidy, “Spectrum Sharing in Cognitive Radio Networks: An Adaptive Game Approach”, Submitted to IET Journal in Communications. **Major revision**, under revision since May 2010.
4. O. Raoof, and H.S. Al-Raweshidy, “Green Hybrid Vertical Handover Model for Heterogynous Wireless Networks”, Submitted to International Journal of Communications Systems-Wiley. Under revision since January 2010.

**Book Chapters:**

1. O. Raoof, and H.S. Al-Raweshidy (**Accepted**), “Introduction to Game Theory”, For publishing in the book under the working title "Game Theory", 978-953-7619-X-X, available on line by October 2010 at: http://www.sciyo.com
2. O. Raoof, and H.S. Al-Raweshidy (**Accepted**), “Game Applications in MIPv6 Protocol”, For publishing in the book under the working title "Game Theory", 978-953-7619-X-X, available on line by October 2010 at: http://www.sciyo.com
3. O. Raoof, and H.S. Al-Raweshidy (**Accepted**), “Game Applications in Ad-Hoc Wireless Networks”, For publishing in the book under the working title "Game Theory", 978-953-7619-X-X, available on line by October 2010 at: http://www.sciyo.com
4. O. Raoof, and H.S. Al-Raweshidy (**Accepted**), “Game Applications in Cognitive Radio Networks”, For publishing in the book under the working title "Game Theory", 978-953-7619-X-X, available on line by October 2010 at: http://www.sciyo.com