Fair Relay Selection in Wireless Rural Networks Using Game Theory

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To my loving parents and my most supportive siblings. . . .

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text.

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Abstract

Access to Internet is the key to facilitate the economic growth and development of the rural communities and to bridge the digital-divide between the urban and rural population. The traditional broadband access technologies are not always suitable for the rural areas due to their difficult topography and sparsely populated communities. Specialized relay stations can be deployed to extend the coverage of a wireless rural network but they come with an inherited increase in the infrastructural cost. An alternative is to utilize the in-range users as relays to enhance the coverage range of the wireless rural network.

In this thesis, the in-range ordinary users termed as primary users (PUs) are used to act as relays for the out-of-range users called the secondary users (SUs). Two relay selection solutions, the Fair Battery Power Consumption (*FBPC*) algorithm and the Credit based Fair Relay Selection (*CF-RS*) protocol have been proposed with the aim of providing fair chance to every PU to assist the SUs, thus resulting in fair utilization of battery power of all relays along with the coverage extension. The *FBPC* algorithm uses the concept of proportional fairness as the relay selection criterion. However, if only proportionally fair consumption of battery power is taken as the relay selection parameter, the *FBPC* algorithm may result in selecting relays with poor channel conditions. The rural network may also consist of selfish PUs which need to be incentivized to use their resources for the SUs. The *CF-RS* protocol is developed which takes into account both the achievable data rate and consumption of battery power for selection of a relay. The *CF-RS* protocol is formulated using Stackelberg game which employs a credit-based incentive mechanism to motivate the self-interested PUs to help the SUs by providing instantaneous as well as long term benefit to the PUs.

A basic network model consisting of PUs and SUs has been simulated and the performance of the *FBPC* algorithm and the *CF-RS* protocol have been evaluated in terms of data rate and utility achievable at the SUs, dissipation of battery power of the PUs and Jain's fairness index to determine fairness in utilization of battery power. The results obtained show that the *FBPC* algorithm achieves approximately 100% fairness for utilization of battery power of relays but compromises the data rate attainable by the SUs. Thus the *FBPC* algorithm shall be viewed as a trade-off between the fair battery power dissipation of relays and the data rate achievable by the SUs. Whereas, the *CF-RS* protocol provides 55% better utility and longer service time to the SUs without harming the attainable data rate and achieves 80% fairness. When the *CF-RS* protocol is used for relay selection, it is advantageous even for the self-interested users to participate in the relaying process to earn some benefit to utilize it when needed to buy assistance from other users.

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List of Acronyms and Symbols

Acronyms

ACK: Acknowledgement

ACO: Ant Colony Optimization

AF: Amplify and Forward

ANN: Artificial Neural Network

AP: Access Point

AWGN: Additive White Gaussian Noise

BANT: Backward Ant

BER: Bit Error Rate

CDMA: Code Division Multiple Access

CF-RS: Credit Based Fair Relay Selection

CF: Compress and Forward

CPE: Customer Premise Equipment

CSE: Channel Estimation Error

CSI: Channel State Information

CSS: Credit Clearance Service

CTS: Clear to Send

D2D: Device to Device

DF: Decode and Forward

DGP: Digital Gangetic Plain

EF: Estimate and Forward

FANT: Forward Ant

FBPC: Fair Battery Power Consumption

FCC: Federal Communication Commission

FF: Filter and Forward

FIR: Finite Impulse Response

FORS: Fair Opportunistic Relay Selection

GA: Genetic Algorithm

GMP: Geometric Programming

GRG: Generalized Reduced Gradient

GTFT: Generous TIT-FOR-TAT

HANET: Hybrid Ad-hoc Network

HGA: Hybrid Genetic Algorithm

ICSI: Instantaneous Channel State Information

ICT: Information and Communication Technologies

IEEE: Institute of Electrical and Electronics Engineers

ISM: Industrial Scientific Medical

ITU: International Telecommunication Union

KSBS: Kalai-Smorodinsky Bargaining Solution

LF: Linear Process and Forward

LP: Linear Programming

M2M: Machine to Machine

MAC: Medium Access Control

MANET: Mobile Ad-hoc Network

MAP: Mobile Access Point

MDP: Markov Decision Process

MGM: Maximum Generalized Mean

MHM: Maximum Harmonic Mean

MINLP: Mix Integer Non-Linear Programming

MLP: Multi-layer Perceptron

MRC: Maximal Ratio Combiner

MRS: Multiple Relay Selection

NACK: Negative Acknowledgement

NBS: Nash Bargaining Solution

nLF: Nonlinear Process and Forward

NLOS: Non Line of Sight

NLP: Nonlinear Programming

OFDM: Orthogonal Frequency Division Multiplexing

OFDMA: Orthogonal Frequency Division Multiple Access

OP-PFS: Outage Priority based Proportional Fair Scheduling

OSI: Open Systems Interconnection

PER: Packet Error Rate

PFS: Proportional Fair Scheduling

PMSE: Program Making Special Events

PN-BS: Primary Network Base Station

PSO: Particle Swarm Optimization

PU: Primary User

QoS: Quality of Service

RBF: Radial Basis Function

RTS: Request to Send

SER: Symbol Error Rate

SINR: Signal to Interference and Noise Ratio

SN-BS: Secondary Network Base Station

SNR Signal to Noise Ratio

SRS: Single Relay Selection

SU: Secondary User

TVWS: TV White Space

UAV: Unmanned Aerial Vehicle

UHF: Ultra High Frequency

VANET: Vehicular Ad-hoc Network

VHF: Very High Frequency

VoIP: Voice over Internet Protocol

WiFi: Wireless Fidelity

WiMAX: Worldwide Interoperability for Microwave Access

WLAN: Wireless Local Area Network

WMN: Wireless Mesh Network

WRAN: Wireless Regional Area Network

WSN: Wireless Sensor Network

Symbols

β_j	Budget of SU_j
$\forall$	For all
$\frac{\partial}{\partial P_{ij}}$	Partial derivative with respect to power
$\frac{\partial}{\partial p_{ij}}$	Partial derivative with respect to price
$\mathbb{R}$	Set of real numbers
$\mathbb{Z}$	Set of integers
$\overline{CBP_i}$	Cumulative battery power consumption of PU_i
σ^2	Noise power
$\sum$	Summation
B_k	Overall benefit
BP_i	Battery power of PU_i
BP_{th_c}	Critical threshold of battery power
BP_{th}	Battery power threshold
c	Cost
C_k	Overall cost experienced by PU_k
CBP_{ij}	Instantaneous battery power consumption of PU_i for current transmission to SU_j
CR_i	Credits of PU_i
d_{Ai}	Distance between AP and PU_i
d_{ij}	Distance between PU_i and SU_j
$f\left(p_{ij}\right)$	Pricing function
G_{Ai}	Channel gain of AP and PU_i link
G_{ij}	Channel gain of PU_i and SU_j link
I	Relay satisfying the utility condition
k	Node exchanging its role in network

L	Number of iterations/ Simulation duration
$M\,where\;\; j \in [1,2,...,M]$	Set of Secondary user
$N\,where\;\; i \in [1,2,...,N]$	Set of Primary user
n_{Ai}	Additive white Gaussian Noise with zero mean and variance σ^2 on AP and PU_i link
n_{ij}	Additive white Gaussian Noise with zero mean and variance σ^2 on PU_i and SU_j link
p	Price
P_A	Transmission power of AP
P_i	Transmission power of PU_i
P_{ij}	Transmission of PU_i for SU_j
P_{max}	Maximum allowed transmission power
PU_i	Primary User i
R	Data rate in bits per second
SU_j	Secondary User j
T_A	Transmission range of AP
T_i	Transmission range of PU_i
U	Utility function of system
U_i	Utility of PU_i
U_j	Utility of SU_j
W	Bandwidth in Hertz
x	Transmitted signal with unit energy
$y_{A,i}$	Signal received at PU_i
$y_{i,j}$	Signal received at SU_j

Chapter 1

Introduction

This chapter provides a brief description of the problem under study, a concise overview of the proposed solutions and the main contribution of the work presented in this thesis. In the end, section 1.3 provides the organization of the thesis.

1.1 Overview

With the advance in technology across the world, Internet access is becoming a necessity. Whether one lives in urban area, sub-urban or a rural environment, in order to cope with the fast moving world, it is essential to have connectivity to the Internet. In urban areas, it is easier to provide Internet access to a large number of users by deploying base stations for each locality, since users are located in close vicinity to one another. Similarly hotspots can be easily identified to pool in more resources for the users. In rural settings, the Internet users are located over a large geographical area with sparsely populated communities and unfavourable topography. The characteristics of rural population and the difficult physical terrains make the provision of Internet access quite challenging in rural areas. The communication technologies which are widely used in urban settings are not very efficient in rural areas due to lack of infrastructure, cost of service and transportation of necessary equipment for network deployment [4–6] and [7].

The wireless technologies provide a viable solution for bridging the digital divide between the urban and the rural populations. However, considering the remoteness, the diversity in the location of users and the topographic terrains, there still will be users who will not be in the transmission range of any base station/ access point. It is economically as well as managerially infeasible to deploy separate base stations/ access points for a small group of users [8] whose positions may not be stationary. In such circumstances, usually specialized relay stations are used to extend the coverage area of the base station [5]. Deployment of specialized relay stations comes with inherited increase in infrastructural cost as well as challenges in selection of a suitable location for the relay station deployment.

An alternative to extend the coverage range of base stations is to utilize the in-range ordinary mobile users to provide relay services to the out-of-range users. This helps in saving both the deployment and the operational cost incurred when specialized relay stations are used. The literature on cooperative wireless networks mostly emphasizes on fair allocation of bandwidth [9, 10], optimal allocation of power [11–14] and [15], or energy efficiency of the network [16, 17]. However, the physical layer fairness which focuses on fair dissipation of battery power of the relays taking part in the cooperation hasn't been thoroughly addressed [18, 19] and [20]. Most of the relay selection algorithms choose nodes with better Signal to Interference and Noise Ratio (SINR), the ones situated close to either the end users or the source, as relays, which means that some nodes spend much of their battery power providing relaying service while others located a bit far spend nothing at all which results in unfair usage of battery power of the relay nodes.

In cooperative wireless networks, it is usually assumed that all the users in the network are obedient i.e. whenever they will be asked to provide relaying service for out-of-range users , they will obediently follow the request. However, this is not always true because a wireless network is also composed of self-interested users who will always act to maximize their own benefit. Providing a relaying service means consumption of extra battery power and sharing of resources with other users. Thus the self interested users need to be given incentives in order to make them act as relays for out-of-range users. The incentives can be either tokens or credits paid to self-interested users which they can utilize when they have moved out of coverage range or as monetary benefits.

Earning monetary benefits or credits may not be sufficient to encourage the in-range users to generously and willingly utilize their battery power for the out-of-range users unless there is a possibility of in-range users ending up in situations when they themselves require assistance to access their own data. Considering mobile in-range users, there will be scenarios when an in-range user moves out of the transmission range of an access point, then it can utilize the credits it has earned as a relay to purchase relaying service for itself. The higher the credits it had earned, the more the service it can buy from other in-range users when it becomes an out-of-range user.

The motivation of this research is to extend the coverage area of a rural wireless network without deployment of extra infrastructure and deteriorating the achievable data rate and ensuring fair utilization of battery power of relay nodes. The aim is to utilize the ordinary mobile users which are in transmission range of the access point to serve as relays for the out-of-range users.

1.1.1 Proposed Approach

Two relay selection solutions, the Fair Battery Power Consumption (*FBPC*) algorithm and the Credit based Fair Relay Selection (*CF-RS*) protocol have been proposed with the aim of providing a fair chance to every in-range user to assist the out-of-range users, thus resulting in fair utilization of battery power of all relays. The *FBPC* algorithm uses the concept of proportional fairness as the relay selection criterion instead of SINR. However, if only proportionally fair consumption of battery power is taken as the parameter for choosing relays, the *FBPC* algorithm may result in selecting relays with poor SINR. Therefore, the *CF-RS* protocol is developed which takes into account both the achievable data rate and consumption of battery power required for selection of a relay. The *CF-RS* protocol is formulated using the Stackelberg game which employs a credit based incentive mechanism to motivate the in-range users to help the out-of-range users by providing instantaneous as well as long term benefit to the in-range users.

A basic network model consisting of both in-range and out-of-range users has been simulated and the performance of the *FBPC* algorithm and the *CF-RS* protocol have been evaluated in terms of data rate and utility achievable for the out-of-range users, dissipation of battery power of the in-range users and Jain's fairness index to determine fairness in utilization of battery power. The results obtained show that the *FBPC* algorithm achieves approximately 100% fairness for utilization of battery power of relays but compromises the data rate attainable by the out-of-range users. Thus the *FBPC* algorithm shall be viewed as a trade-off between the fair battery power dissipation of relays and the data rate achievable by the out-of-range users. However, the *CF-RS* protocol provides better utility and longer service time to out-of-range users without harming the attainable data rate and achieves 80% fairness.

The *CF-RS* protocol is capable of handling high data demand from the out-of-range users and the proposed pricing function for the *CF-RS* protocol gives more flexibility to the in-range users for selection of price for their services, thus giving incentives to the self-interested in-range users to help the out-of-range users. In terms of utility gained by the in-ranger users, compared to an algorithm which uses SINR as the relay selection criteria, the *CF-RS* algorithm provides 45% better utility to the in-range users. Even in extreme network configurations i.e when the in-range users are located far from the out-of-range users, there is only one nearby in-range user or when the out-of-range users are located at the edge of the extended coverage area, the *CF-RS* protocol achieves 70-90% fair utilization of battery power. When the *CF-RS* protocol is used for relay selection, it is advantageous for the self-interested mobile users to participate in the relaying process to earn some benefit to utilize it when needing to buy assistance from other users.

1.2 Research Contribution

The contributions of this work are:

- Formulation of the *FBPC* algorithm based on proportional fairness using the ratio of cumulative to instantaneous battery power consumption as the relay selection criterion.
- Formulation of the *CF-RS* game highlighting the set of strategies available to both in-range and out-of-range users at every stage of the game. The unique feature of *CF-RS* game is the way the cost for providing relay service is calculated. Instead of keeping cost constant, unlike [21, 22], cost is updated according to the consumption of battery power.
- Development of a relay selection protocol utilizing the *CF-RS* game for fair consumption of battery power of relays i.e. the in-range users.
- Mathematical analysis of *CF-RS* game, determining the optimal power the out-of-range user shall buy from the in-range user and the optimal price the in-range user shall advertise for its service.
- Formulation of a pricing function considering the cost incurred by the in-range users for providing the data forwarding service.
- Introduction of a credit based system focusing on long-term benefit gained by the in-range users by assisting in relaying data for the out-of-range users.

1.3 Structure of Thesis

The reminder of the thesis is organized as follows;

Chapter 2 provides an overview of the challenges of wireless rural networks, technologies applicable for the provisioning of Internet to the rural communities and usage of cooperative communication to bridge the digital divide between rural and urban population. Literature on relay selection techniques addressing selection among the obedient relays, the self-interested users and the physical layer fairness are also discussed.

The network scenario and the system model for the wireless rural network is presented in Chapter 3. A mathematical model with constraints imposed by the wireless rural networks is also developed, the available mathematical tools to solve relay selection problem and the one most suitable for the network model studied in this thesis are discussed.

Chapter 4 describes the *FBPC* relay selection algorithm, utilization of cumulative to instantaneous battery power as relay selection criterion and calculation of Jain's fairness index to measure fair consumption of battery power of the in-range users. Credit based relay selection game addressing the self-interested users using the extensive form of Stackelberg game is developed and the mathematical analysis of the *CF-RS* game and derivation of the pricing function is performed. The *CF-RS* protocol, based on the *CF-RS* game, is also discussed from the perspective of providing long term benefit to the in-range users, specially when the in-range and the out-of-range users exchange their roles.

Performance evaluation of the *FBPC* relay selection algorithm and the *CF-RS* protocol is provided in chapter 5, and chapter 6 concludes this thesis by discussing the performance gains achieved through the proposed solutions and direction for future work.

Chapter 2

Research Background

This chapter gives an overview of wireless rural networks, the challenges they pose to the broadband service providers and the technologies being used to address them. It also provides a brief summary of cooperative relaying and the advantages of collaborative communication. General relay selection techniques considering obedient relays and self-interested users are discussed, followed by literature focusing on equal power consumption of relays participating in the cooperative communication.

2.1 Wireless Rural Networks

Living in a digital age makes the broadband access an important and favorable means of providing information, content and public services. Broadband access is becoming increasingly essential for the development of businesses, provisioning of health, government related services and recreation as well as a means of delivering education and providing employment and social support. In urban and sub-urban environments, both wired and wireless technologies can be used to provide broadband services to users. The cost associated with deployment of wired broadband access is dependent on distance to the end users, remoteness of the locality and the population density of the targeted area [23]. Therefore, wireless technologies are preferred over wired technologies considering the evident infrastructural cost. In urban and sub-urban areas, it is easier to provide Internet access to a large number of users by deploying base stations or access points for each locality since users are closely located and are easily accessible. Similarly hotspots can be conveniently identified to pool more resources for the users.

However, the rural communities pose completely different challenges which are unlike the ones experienced by the broadband service providers in wireless urban and sub-urban area networks [4, 5] and [6]. These are discussed in detail in the following subsection 2.1.1. In a typical rural community, unlike urban and sub-urban living, users are scattered over a large geographical area, the natural environment and/or mountainous terrains make it impossible to provide coverage to large number of users with few resources (base stations).

2.1.1 Challenges Posed by Rural Communication Networks

The main challenges of a rural communication network are listed below:

- Features of rural population: Sparsely populated areas
- Reachability considering the topography of rural areas
- Available services to rural communities
- Service cost in rural environment: High deployment and maintenance cost
- Technologies applicable to rural settings
- Self Sustainable systems: Lack of grid power sources

In most of the developing countries, more than 70% of the population is located in rural areas [24]. Moreover, the rural communities are scantily populated which means the users of broadband services are spread over a large geographical area which makes the provision of service quite difficult. Also the demand for broadband services in rural areas is low due to lack of awareness and competence as stated in [4] and [7]. Thus in order to bridge the digital divide between the urban and rural communities, rural communities need to be given education and awareness. This in turn will also result in facilitating the economic growth and development of rural communities. Another major difficulty that the rural communities present are the geographical constraints and the harsh climatic conditions (specially in extreme environment rural areas). The topography of rural areas restrains the easy transportation of necessary equipment for deployment of wireless Information and Communication Technologies (ICT) [6].

Other factors that the service providers need to consider are the type of services rural communities will be interested in to use. Tele-education, e-healthcare and e-administration are beneficial services for the rural communities [4]. However, with advancement in Smart phone technologies, services like audio and video streaming, Voice over Internet Protocol (VoIP) and social media services are also gaining popularity among rural communities. There is a cost associated with all these services. Lack of infrastructure and high deployment and maintenance cost of infrastructure promotes the usage of ad-hoc wireless technologies in rural areas [6]. Two important aspects needs to be considered for the deployment of an ad-hoc network in rural settings:

- Network reliability
- Quality of Service (QoS)

Both reliability and QoS depend upon the availability of users i.e. the ad-hoc nodes and the links between the nodes [8], which can be affected by the following factors:

- Hardware reliability: The harsh climatic conditions may result in hardware failure, affecting the network connectivity.
- Power reliability: Considering the physical terrains of the rural areas, it is very difficult to power ad-hoc nodes using grid power. Thus the network nodes are required to be

Table 2.1 Coverage of data services across UK ([1])

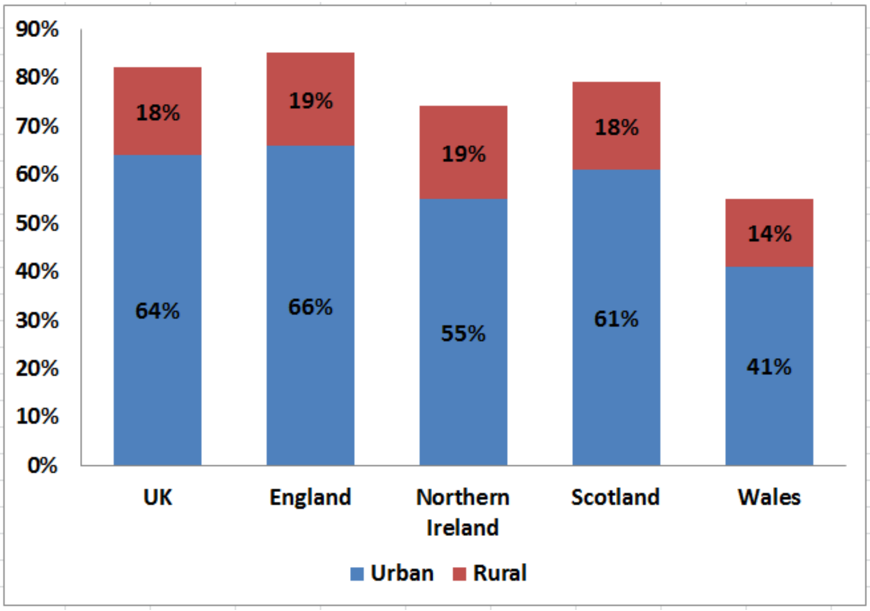
	Indoor Coverage, % Premises	**Outdoor Geographic Coverage, % Landmass**	**Motorways, % Road Network**
UK	85%	63%	91%
England	87%	82%	91%
Northern Ireland	75%	76 %	81%
Scotland	82%	31%	88%
Wales	73%	52%	96%

self-sustainable utilizing renewable energy sources like solar panels to recharge their batteries. Power reliability also necessitates the controlled power consumption by the ad-hoc nodes.

- Software reliability and security: The software installed on network nodes is required to be robust and self-reconfigurable in order to withstand node failure due to power outage as well as due to temporary hardware failure. Node should also be able to detect intra and inter network attacks.
- Link performance: The climatic changes and environment conditions can make the link quality between nodes highly fluctuating.

When it comes to the provisioning of broadband access to rural living, developing and developed countries are not quite different, they present the same challenges. Even in a developed country like the United Kingdom (UK), 1.1 million homes and businesses are not getting a decent broadband access, mostly located in rural areas. 17% of premises in rural areas of UK with 23% of rural Northern Ireland and 27% of rural Scotland do not have access to broadband services [1]. Table 2.1 presents the coverage of data services across the UK and Figure 2.1 shows indoor 4G coverage in urban and rural areas of UK. Even though it is widely accepted that broadband access is essential for rural communities to enable them to actively participate in digital economy as well as to overcome the physical and social isolation, rural communities are most often excluded from fast broadband expansion [25] and [26]. The features of rural communities impose technological and economical

Figure 2.1 Indoor 4G coverage in rural and urban UK ([1])

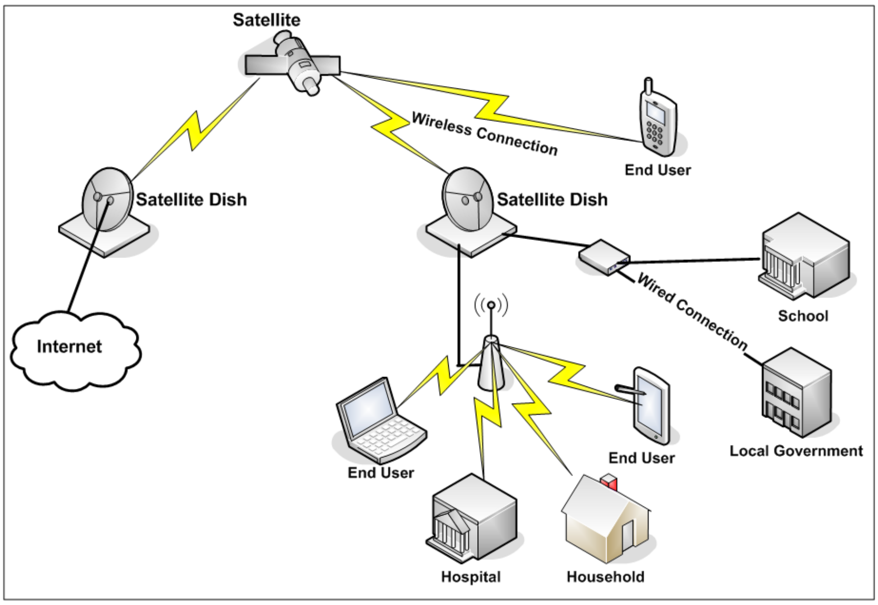


constraints. However, according to [4, 23] and [7] the major limiting factor for the broadband providers to invest in rural areas is the low adaption rate to broadband services among rural communities. Incentives need to be taken by governments, regulatory authorities and by social welfare organizations to educate and promote the benefits of broadband access among rural communities to speed up the adaption rate, specially in developing countries.

2.1.2 Technologies Available for Providing Broadband Access

The poor bandwidth efficiency of copper cables and the cost associated with them makes them an unsuitable candidate for providing Internet access to rural living [23]. Similarly optical fiber is also not a good choice for rural areas owing to the topographic remoteness of rural environment. Satellite communication can be used to provide broadband coverage to hard-to-reach areas and unlike wired and cellular networks; it does not require backhaul capacity to be available at each location as can be seen in Figure 2.2. Figure 2.2 presents a satellite communication network in which the users either directly access the network using specialized equipment like a satellite phone or indirectly via a satellite dish utilizing wired

Figure 2.2 A Satellite communication network



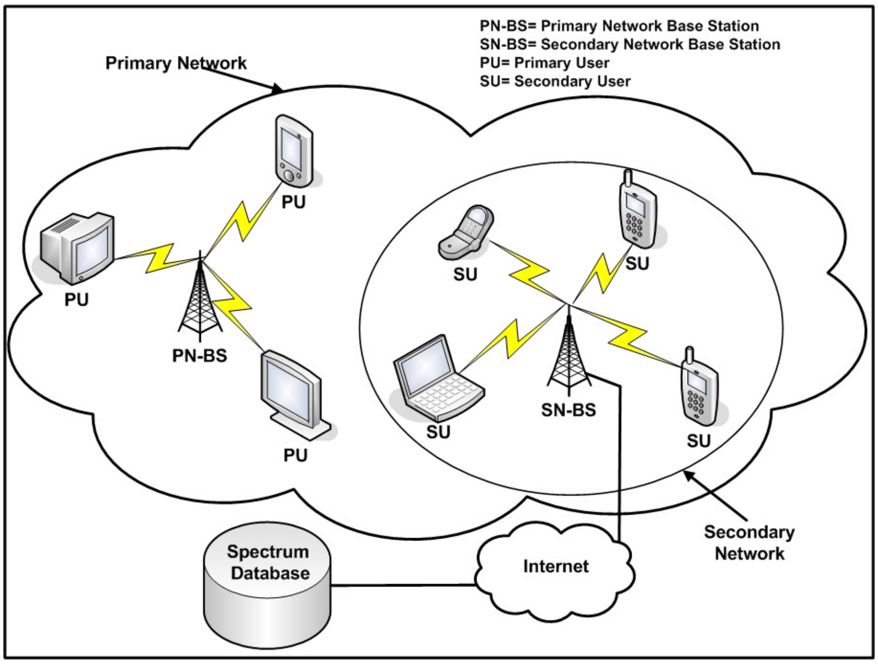
and/or wireless communication link. However, for the same speed satellite access has a higher cost as well as a higher delay which is problematic for interactive applications [23].

IEEE 802.11 [27], because of its low cost, comparatively high bandwidth, its operation in license free Industrial, Scientific, Medical (ISM) band and ease of maintenance, is a suitable candidate wireless technology for rural areas relative to satellite and cellular technologies [24] and [28]. IEEE 802.11, WiFi, technologies has been exploited in the Digital Gangetic Plain (DGP) and Ashwini projects [28] to provide connectivity to rural areas of India. Highly directional antennas have been mounted on tall structures and IEEE 802.11 protocols have been tuned to achieve a much longer coverage range around 30 km [24]. Although the radio used in long distance WiFi networks, deployed in rural communities, is of low cost, the cost of other components of the system especially the batteries required to power the system, is substantial which needs to be optimized to make WiFi a viable solution for rural settings [29]. Minimizing the power consumption as well as providing the right type of services to the rural living is also important for installing a profitable broadband access network.

WiFi has been also used to provide services like e-health, tele-education, remote monitoring for disaster management and e-administration to more than 150 towns and villages in rural and remote areas of Japan [4]. The International Telecommunication Union's (ITU) pilot projects in Bulgaria, Uganda and Yemen also chose WiFi as the suitable technology to enable the rural communities of these countries to have access to the Internet. Wray Wireless Mesh Network using IEEE 802.11b as backbone technology was implemented by Lancaster University to provide Internet access, for multimedia applications and online gaming to village schools ([6, 30] and [31]). AirJaldi network in Dharamasla India is another example of deployment of Wireless Mesh Network (WMN) extending coverage to schools, offices and hospitals over long distances of 10km to 41km. [6] presents a brief summary of various IEEE 802.11 mesh deployments in different rural areas of Africa, Asia, Scotland and Ireland. IEEE 802.16 standard WiMAX [32] and [33] was another candidate technology for providing last mile broadband access to rural communities. However, it was not clear if it would be able to achieve the same cost scale as WiFi [28].

Another candidate solution for rural Internet access is usage of the TV broadcast bands (TV white space) operating in the high VHF (156-174 MHz) and low UHF (300 MHz- 3 GHz) bands. Due to their large coverage, good propagation characteristics for non-line of sight (NLOS) communication, practicable antenna size, low levels of industrial noise and no constraints on dedicated spectrum requirement, the TV white space bandwidth is ideal for providing broadband access to sporadically populated rural communities [34]. A large number of vacant TV channels, also called TV white space (TVWS), are available in rural areas which can be opportunistically utilized to bridge the digital divide on non-interfering basis i.e. not causing harmful interference to the licensed users of TV band. It has been indicated by Federal Communications Commission (FCC) that fixed broadband access systems can leverage the TV channels 5-13 in VHF band and 14-51 in the UHF band. According to UK's communication regulation authority Ofcom's classification of TVWS

Figure 2.3 IEEE 802.22 Wireless Region Area Network



channels, channels 31 to 37 and 61 to 69 are termed as cleared spectrum which Ofcom aims to license through auction. Channel 38 is reserved for wireless microphones and PMSE (Program Making Special Events) equipment, while channels 21 to 30 and 39 to 60 are available for secondary usage [35]. Utilization of TVWS for provision of broadband access promotes economic growth as well as efficient usage of the highly valuable, scarce and useful spectral resource.

IEEE 802.22 Wireless Regional Area Network (WRAN) standard [36] has been developed to regulate and facilitate the usage of TVWS for broadband access in rural living as well as to coexist with other wireless technologies. Figure 2.3 presents a WRAN where secondary users utilize the vacant licensed spectrum of a primary network to access the Internet. IEEE 802.22 WRAN standard typically provides a coverage of 17-30 km in radius with maximum coverage range of 100 km from the base station and can serve up to 255 fixed Customer Premise Equipment (CPE) with outdoor directional antenna located nominally 10 m above ground level. The minimum throughput achievable at the CPE situated at the end of the coverage is 1.5 Mbps in downlink and 384 kbps in uplink, thus enabling video-conference services. However, specialized equipment i.e base stations and CPE are needed for employment of 802.22 technology. Also all devices in the WRAN are required to be deployed in a fixed location and the base station is required to know its location with a precision of 15 m radius as well as the location of all of its associated CPEs within a 100 m radius.

In addition to the standarised network technologies, researchers around the world have worked on various solutions to improve network access. Pentland *et al.* [37] proposed a store and forward asynchronous mode of communication for providing broadband access to rural communities of developing countries and argued that asynchronous non-real time ICT services are adequate to fulfill the needs of a rural community. Their proposed technique called DakNet is basically an electronic postman which physically moves around the villages to provide wireless transfer of data extending the connectivity of the access point. DakNet requires specialized public booths to be installed in each village and a portable storage device called the Mobile Access Point (MAP) is deployed on a bus, a motorbike or a bicycle. MAP is powered by a small generator and is responsible for data transfers between the public booths and user's private devices as well as between the public booths and the access point. The MAP equipped vehicle gathers requests from the villagers using the public booth, when it comes in coverage range of access point retrieves or uploads data to Internet, stores the requested data and on its visit back to village provides the requested data and information to the villagers. However, with advancement in technology and awareness among rural communities, their demand for real time data is increasing.

Table 2.2 summarizes the salient features of wireless technologies applicable to rural areas. However, the most important aspect to be considered for deployment of broadband wireless networks in rural areas is not the superiority of technology but the costs linked with operation, installment and maintenance of wireless networks [7]. The technique proposed in this thesis aims at providing broadband access to rural communities using a semi ad-hoc

Table 2.2 Comparison of wireless technologies applicable to rural areas

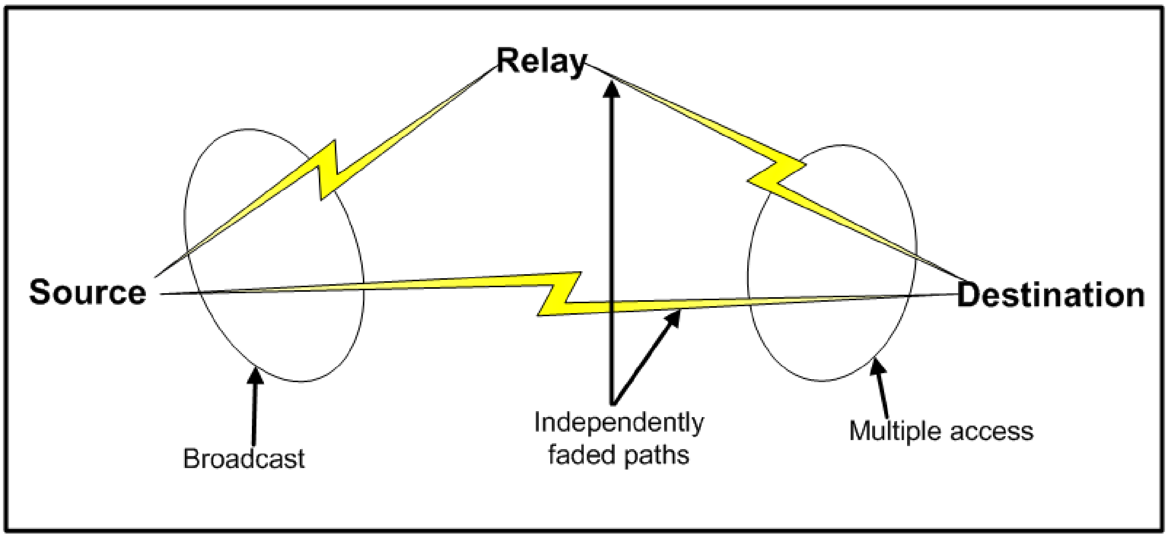
Technology	Data Rate	Spectrum	Frequency Band	Coverage
Satellite Communication	$<$ 2 Mbps	Licensed	12-18 GHz	50 km
WiFi	11 & 54 Mbps	Unlicensed ISM	2.4 & 5 GHz	0.1-1 km
802.16	70 Mbps	Licensed	2-11 & 10-66 GHz	50 km
802.22	1.5 Mbps	Unlicensed	54-862 MHz	17-30 km

semi infrastructure based method (Implementation of WiFi Direct technology). Basically the proposed solution is an extension of an already existing rural wireless network to reach a large number of users, by utilizing the in-range users to serve as relays for out-of-range users. This relaying among users requires cooperation among the rural users and their willingness to help each other. Chapter 3 and chapter 4 provide details of our proposed technique.

2.2 Cooperative Communication

An alternative to installing a new infrastructure to provide Internet access to rural communities is to extend the coverage range of already existing wireless networks in rural areas utilizing cooperative communication among users. Cooperation in rural wireless networks basically implies receiving data and information from the source node and forwarding to the destination node or passing/relaying the data to the intermediate nodes in order to reach the destination or sink node. Figure 2.4 depicts a basic three node cooperative communication model employing a relay node. Cooperative communication has emerged as an enabling technique to gain the benefits of spatial diversity without deploying multiple antennas per node. The diversity advantages attainable via cooperative communication can boost network reliability, improve spectral and energy efficiency, decrease the probability of outage and enhance reachability to the isolated users of the network [38] and [39]. Cooperative communication is the key element in empowering the device to device (D2D) or machine to machine (M2M) communication [40, 41] and [42]. The characteristics of cooperative communication that

Figure 2.4 Basic three node cooperative communication model using relay node



differentiate it from traditional non-cooperative systems are: 1) utilization of resources of multiple users for data transmission of a single source and 2) at destination node combining signals received from multiple collaborating users.

Cooperative communication using the relay nodes is also a cost effective method of enhancing the network coverage. Cellular networks, wireless mesh networks e.g. Vehicular Ad-hoc Networks (VANETs), Mobile Ad-hoc Networks (MANETs) and other ad-hoc networks and Wireless Sensor Networks (WSN), all employ cooperation among nodes/users to enhance the achievable data rates and the overall network performance. Multi-hop communication beyond point to point and point to multi-point was made possible by coordination among network users [39]. Some network performance gains achievable via cooperation are pathloss gain, diversity gain and multiplexing gain.

Before defining pathloss gain, lets first understand pathloss.The loss in signal's power as it transverses the channel between the transmitter and receiver is called pathloss and is measured in decibels as the ratio of the transmitted and received power. The mathematical expression of pathloss is given by equation(2.1).

$$\Gamma_{dB} = 10\alpha \log\left(\frac{d}{d_0}\right) + c \tag{2.1}$$

where Γ_{dB} is the pathloss, α is the pathloss co-efficient, d the distance between the transmitter and the receiver, d_0 the distance to the reference point where measurements are being taken and c is a constant. The pathloss co-efficient can take values between 2 and 6 depending on the environment where the transmitter and the receiver are located, whether it is an urban micro or macro cell or rural locality. Since the value of pathloss is mainly dependent on the distance between the transmitter and the receiver, it is deterministic in nature [43].

Pathloss gain is one of the gains associated with wireless channel which is the outcome of cooperative communication i.e. using intermediate nodes to assist the signal transmission between the source and the destinations and dividing the total available transmit power between the source node and the relay node. With the help of a relay node, distance to the destination is reduced and so is the pathloss experienced by the transmit signal. Pathloss gain is given by equation 2.2, where P_D^1 and P_D^2 are the received power at destination using direct and cooperative link respectively,and K_1 is the gain at relay.

$$\frac{P_D^2}{P_D^1} = 2^{\alpha-1}\left[\left(\frac{2}{d}\right)^{\alpha} K_1 + 1\right] \tag{2.2}$$

Diversity gain is obtained by employing intermediate nodes to provide additional copies of the signal to the destination which results in lower probability of outage and thus improves the overall network performance [44]. Other than using multiple intermediate nodes, diversity gain can also be achieved using time, frequency and spatial diversity. In time diversity, multiple copies of the signal are transmitted at different time instances whereas in frequency diversity, different frequency channels are used for signal transmission. In case of spatial diversity, more than one transmit and/or receive antennas are employed for source destination communication [45] and [44]. The usage of the intermediate node as relay in cooperative communication also provides another channel between the source and destination, thus cooperative communication also achieves multiplexing gain. However, cooperative communication presents additional challenges as well [46], some of which are listed below:

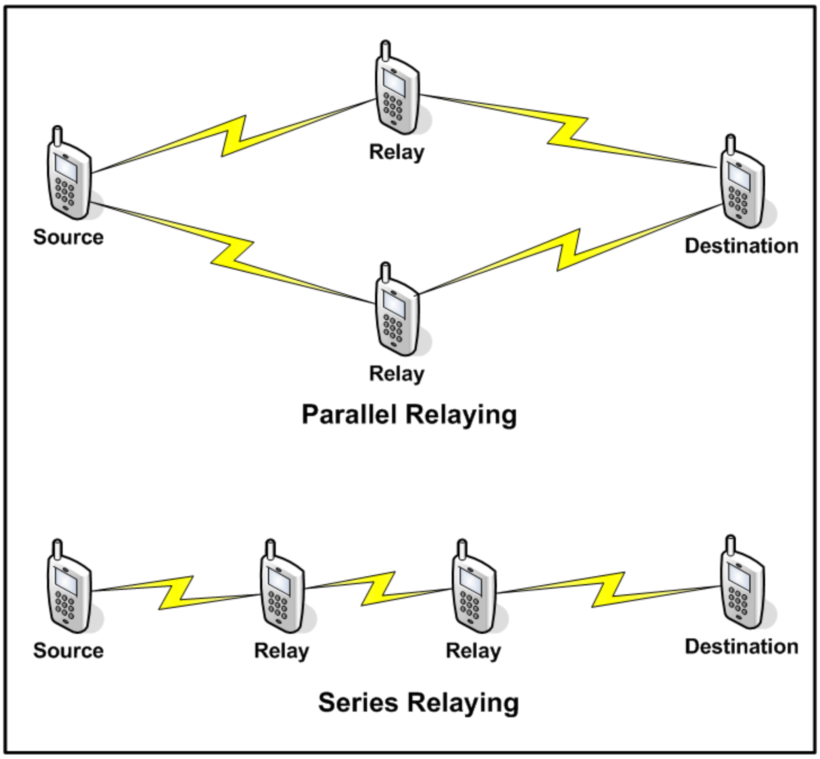
- Analysis of capacity gain achievable via cooperative communication and implementation of cooperation protocols considering practical constraints.
- Careful selection of immediate nodes as relays and allocation of power.
- Formulation of routing protocols since multi-hop cooperative communication is a special case of routing.
- In cooperative communication, individual nodes have only local information thus distributed resource allocation techniques are required.
- Cooperative communication protocols designs shall also accommodate energy efficient transmission.

However, the main focus of this thesis is the selection of intermediate relay in cooperative communication and the other challenges are not discussed in details.

2.2.1 Relay Selection Techniques

The idea of cooperative communication, which is that several nodes can collaborate and share their resources to successfully transmit data [47], gives rise to two important questions: 1) how network performance is affected by cooperation? 2) how to determine signal/ data relaying node for source-destination pair in order to optimize network performance? The performance gains offered by cooperative communication depend on selection of intermediate

Figure 2.5 Parallel and series relaying in a cooperative network



node between the source and the destination. The techniques used for relay selection can be broadly classified into two categories; centralized and distributed schemes:

- **Centralized Schemes**: In centralized schemes, a single central controlling entity is in charge of selecting one or more relay nodes for each pair of source and destination. Centralized relay selection schemes find application in cellular networks.

- **Distributed Schemes**: In distributed schemes, there is no central controlling entity and each node is capable of selecting the relay for collaboration. Distributed relay selection protocols are more suitable for ad-hoc networks.

The number of nodes that help the source destination pair also has impact on network performance. Thus on the basis of number of selected relays, distributed relay selection schemes are further divided in Single Relay Selection (SRS) techniques and Multiple Relay Selection (MRS) techniques [48], which is also called parallel relaying. The parallel and series relaying are shown in Figure 2.5. Sections 2.3, 2.4 and 2.5 provide a detailed summary of various relay selection methods. Nodes working as relays consume their battery power to retransmit source node's signal to destination node, thus in order to minimize the overall power consumption, nodes need to identify with whom they shall cooperate and how to participate in cooperative relaying [49].

The adverse effects of wireless channel impairments e.g. fading, shadowing and pathloss can be mitigated by careful relay selection which in turn can achieve spectral efficiency and diversity without requiring significant decoding or synchronization. Decision on whether to employ a single relay or multiple relays to assist the source destination communication needs to be made by analyzing the achievable diversity gain as well as the added complexity [2].

2.2.2 Design Parameters for Cooperative Relaying

The design requirements which are crucial for the performance of cooperative relaying schemes are:

- **Power Allocation**: In wireless networks the distance between the source node and the destination node is dynamically changing and transmit power is the key parameter to control path loss and signal fading. Therefore, a restriction on transmit power is required, with the power ideally being equally shared between the source and the relay node whenever a cooperating node is needed for better reception. However, when the distance between the relay node and destination is large, or channel between the relay and destination is of poor quality, then more power can be assigned to the relay node [2].

- **Interference**: Interference mitigation strategies need to be considered in order to minimize the harmful effect of interference produced by the signal transmission from the source and relay node.

- **Feedback**: Existence of a feedback channel between the transmitter and receiver can greatly enhance the performance of cooperative systems. Either complete Channel State Information (CSI) or incomplete/ partial CSI is fed back to the transmitter.

- **Synchronization**: In order to achieve adequate system performance synchronization is required from physical layer to the network layer. At hardware level, carrier frequency is used to synchronize cooperating nodes whereas suitable protocols are needed for nodes synchronization at medium access and network level.

- **Channel Estimation**: An essential requirement for designing cooperative relaying schemes is good channel estimation. Errors that occur while carrying out wireless channel estimation is referred as Channel Estimation Error (CSE) and is one of the most performance degrading factors in wireless communication.

- **Selection of Relaying Stages**: In a wireless network, sometimes there is no direct link available between the source-destination pair due to limited system capacity or coverage, and the communication between the source-destination pair completely relies on the cooperative link. Thus selection of relaying stages i.e. to utilize dual hop or multiple hop cooperative communication between the source destination pair is an important design parameter for cooperative relaying. Increasing the number of relaying stages (Figure 2.5 number of relays in series) takes advantage of the pathloss gain but it comes with increased complexity and a trade-off needs to be made.

2.2.3 Performance Evaluation Parameters for Cooperative Relaying

Following parameters are commonly used to evaluate the performance of cooperative systems:

- **Error Rates**: Error rate is a measure used to determine the proportion of incorrect transmissions occurring over a specific time interval. The commonly used error rates are Bit Error Rate (BER), Symbol Error Rate (SER) and Packet Error Rate (PER), which are unit-less performance criteria usually expressed as a percentage. Noise, interference and distortion synchronization errors are the main factors contributing towards erroneous transmission. These error rates depend on channel condition and it is important to make decisions on error rate measurements utilizing the available channel conditions [2].

- **Outage Probability**: The channel suitability for transmission between the source and destination is greatly affected by shadowing and channel fading. The outage probability is the measure used to determine channel suitability and is calculated over the duration of the transmission. Though outage probability is computed over channel realizations, error rates e.g BER, SER and PER can also be utilized to determine outage probability.

- **Channel Estimation Error**: CSE being an important design parameter is also an essential measure for performance evaluation of cooperative systems.

2.2.4 Cooperative Relaying Strategies

Depending on the type of signal processing taking place at the relay node, cooperative relaying can be classified into two broad categories; transparent relaying and regenerative relaying.

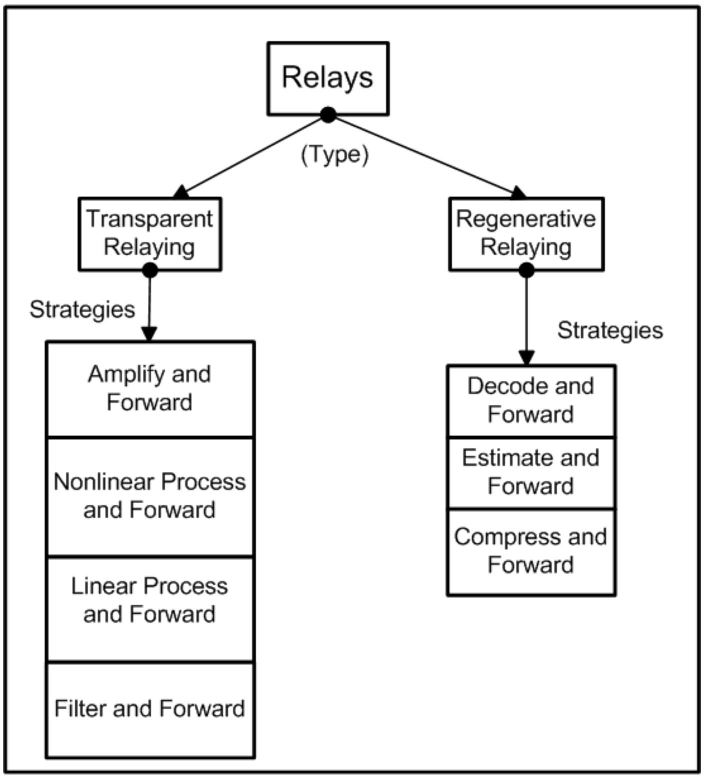
- **Transparent Relaying**: In transparent relaying no modification is performed by the relay on the information embedded in the received signal, other than simple operations like amplification or phase rotation. No conversion of analog signal to digital domain is required and the signal received at the relay is retransmitted to the destination after performing amplification and frequency translation. Common relaying strategies that fall under the category of transparent relaying are:

- **Amplify and Forward (AF)**: In amplify and forward method, the intermediate relay node receive data/signal from the source node, simply amplifies the received noisy signal and relays the amplified signal to the destination node [50] and [51].
- **Linear Process and Forward (LF)**: In this strategy, after amplification of the analog signal, linear phase shifting is performed before retransmission [52].
- **Nonlinear Process and Forward (nLF)**: This strategy is basically nonlinear AF in which a nonlinear operation is performed on the analog signal received at the relay node. This strategy is useful for minimizing the end-to-end error rate caused by the amplification of the noisy signal [53].
- **Filter and Forward (FF)**: The received analog signal is filtered using Finite Impulse Response (FIR) before being forwarded to the destination. It reduces the inherent processing complexity of the Orthogonal Frequency Division Multiplexing (OFDM) system and has been designed for OFDM transmission [54].

- **Regenerative Relaying**: Regenerative relaying modifies the information encapsulated in the received signal, performing a complex operation before retransmission and thus requiring powerful hardware. Some of the common relaying strategies belonging to regenerative relaying are:

  - **Decode and forward (DF)**: The decode and forward method first decodes the received signal, which is encoded again before forwarding the received signal to the destination node [50]. DF is better than all other relaying strategies in terms of minimizing outage and error probability [55].
  - **Estimate and Forward (EF)**: The received signal is first amplified and is then converted to baseband by the relay node. Signal detection algorithm is then used to obtain the signal for a particular modulation order. Similar or a different modulation order is employed to transmit the estimated signal [56].

Figure 2.6 Relaying taxonomy on the basis of relaying strategies [2]



– **Compress and Forward (CF)**: In this relaying strategy, EF is used to first detect the signal and then the detected signal is compressed and encoded again before retransmission. CF performs better when the relay is located closer to the destination node or has a better channel state to destination [57].

The taxonomy of cooperative relaying on the basis of relaying strategy is summarized in figure 2.6. Depending on the nature of collaboration among nodes, the users of a wireless communication network can be categorized into two types:

- **Obedient User**: In a fully cooperative network, users/ nodes are always willing to utilize their resources to relay data for other users of the network. Such users are termed as obedient users.

- **Self-interested User**: Self-interested or selfish nodes are the users which only take part in cooperation when they receive something in return. They need to be given incentive in order to make them relay data for other users of the network [21].

2.3 Relay Selection Techniques in Cooperative Wireless Networks

This section provides an overview of some of the techniques proposed for relay node selection in cooperative wireless network. The methods that utilize ordinary users/ nodes to relay data for other users of the network and do not require specialized relay stations have been discussed.

Sadek *et al.* [58] devised a relay allocation algorithm considering the spatial distribution of users to expand the coverage area of a wireless network using cooperative communication. An uplink data transmission in wireless local area network (WLAN) is considered and a modification of incremental relaying protocol is proposed. The incremental relaying protocol employs simple amplify and forward technique, however in the modification proposed in [58] the base station sends a negative acknowledgement (NACK) when the packet is lost. On receiving the NACK, the relay alloted to the source node retransmits its copy of the packet to the base station, on the condition that the relay had correctly received its copy of the packet in the first place. Their relay selection algorithm chooses the intermediate node which is the nearest to the user/ source node when transmitting data towards the base station or the access point. The distance between the source node and the intermediate nodes is determined by sending 'Hello' messages and calculating the arrival time of the response from the neighbouring nodes. The main drawback of this scheme is that it only considers distance between the source node and the intermediate nodes when appointing the relay irrespective of the channel conditions. Thus this approach may result in picking a relay with poor channel conditions and affecting the overall network throughput.

Bletsas *et al.* [59] analyzed a distributed relay selection algorithm, exploiting the concept of opportunistic relaying i.e. selecting the best relay among the available relays. Unlike previous works which used the topology and distance information for relay selection irrespective of channel conditions, a relay is chosen for data forwarding by taking into account the instantaneous end to end CSI between the source and the destination. Their method requires signal strength calculation for relay selection and these signal strength measurements are performed within the channel coherence time. Coherence time is defined as the time duration in which the channel conditions remain static.

Medium Access Control (MAC) protocol *Ready-to-Send (RTS)* and *Clear-to-Send (CTS)* messages are used to estimate the channel conditions between the source and the destination nodes. Each relay node calculates a timer value employing the Instantaneous Channel State Information (ICSI) and timer of the relay with best channel conditions expires first.

Chen *et al.* [18] improved the work of Bletsas *et al* [59] by proposing relay selection solutions that integrated power awareness in relay selection technique to maximize the life time of wireless ad-hoc networks. The lifetime of the network has been defined as the time when the first node in the network runs of out of power. Their solutions consist of optimum power assignment and three power-aware relay selection measures. The purpose of the optimal power allocation is to minimize the overall transmission power required for the source to destination communication whereas the relay selection parameters are used to extend the lifetime of the network.

Chen *et al.* [18] have considered a basic network scenario in which all nodes are in transmission range of each other and can listen to each other. 802.11b MAC protocol has been utilized and *RTS* and *CTS* messages are exchanged between the source and the destination to estimate the channel conditions. These messages are overheard by the potential relay nodes and a timer value is set by each potential relay. Unlike Bletsas *et al.*, the initial timer value is determined using the residual battery power of the source node, the residual power of the relay node and the transmission power requirement of the source and the relay node for cooperation and the relay with the best channel conditions has the smallest timer value. The source node also sets its own timer, calculated using the transmit power required for direct transmission to the destination node and its residual battery power. If the timer of the source node expires first, then the source node goes for the direct communication with the destination node.

Three relay selection criteria are proposed by Chen *et al.* [18]. The first method chooses the transmission mode and the relay which minimizes the overall transmission power and the timer values are dictated by the required transmit powers. While the second and the third methods use the current transmission power used by the relay and the source node as well as the residual power of both the source and the relay node and select the relay which maximizes the minimum residual power, utilizing the principal of *max-min* fairness.The second criteria focuses on maximizing the minimum difference between the residual power and the required transmit power whereas the third criteria tends to maximize the minimum ratio of residual powers. However, [59] and [18] both considered obedient relays who are always willing to cooperate.

The opportunistic relaying technique has also been utilized in [60] for designing a relay selection criterion which they named as Max-Generalized-Mean (MGM) criterion for choosing the best relay in cooperative communication. MGM criterion incorporates both the max-min and the Max-Harmonic-Mean (MHM) relay selection measures.The max-min criterion focuses on maximizing the minimum of the channel gain of the source-relay link and the relay-destination link. However, the MHM criterion aims at maximizing the harmonic mean of gains of the source-relay channel and the relay-destination channel. Chen *et al* formulated a generalized mean using the channel gains of the source-relay link and the relay-destination link and the relay with maximum generalized mean is selected as the 'best' relay for cooperative communication between the source and the destination. If the best relay is successfully able to decode the received signal, then it forwards the re-encoded signal to destination, otherwise it remains silent. [60] does not discuss the energy/ battery consumption of the relay node and the benefit the relay will obtain by participating in the cooperative communication.

Saghezchi *et al.* in [16] addressed the problem of energy efficiency in a Hybrid Ad-hoc Network (HANET) which is an infrastructure network having the functionality of multi-hop communication. The main advantages of HANET is the extension of network coverage and the overall throughput improvement. Their framework utilizes the ordinary mobile terminals to function as relay nodes. In their model, a mobile station can only act as a relay when it is in idle state and can relay data for only one user. A two-hop relaying network in uplink direction has been considered. Wimedia air interface is used for the communication between the source mobile station and the relay mobile station, whereas the transmission between the relay and the AP is supported by WiFi link. They proposed a centralized optimization algorithm run by the AP to decide when mobile user should directly communicate with the AP and when to use relay nodes to maximize the energy saving.

The energy required to transmit one bit of information/ data has been used by Saghezchi *et al.* in [16] as the metric to evaluate the performance of their proposed algorithm. The source mobile station communicates with the mobile stations situated in its vicinity to acquire the information regarding CSI, their current battery levels and their willingness to help and form a cooperative cluster with the nearby mobile stations. The source mobile station then passes all this information to the AP to determine whether source mobile station shall go for direct communication or cooperative communication and if cooperative communication then the selection of optimal relay among the available candidate relays is performed. The AP formulates a linear programming problem with the objective of maximizing the energy saving of the data transmission between the source mobile station and the AP. If the cost of cooperative communication is less than that of the direct communication, then cooperative mode is selected for data transmission. The cost of the cooperative link has been determined using transmission cost of source to relay link, the reception cost of source and relay link and the transmission cost of relay to AP communication.

However, Saghezchi *et al.* [16] didn't discuss how the willingness of intermediate mobile station is determined and what benefit the intermediate mobile station will gain by relaying data for the source mobile station. Their work only focuses on extending the lifetime of the source mobile station's battery.

Summary: The relay selection techniques discussed in this section either used the distance and network topology information or the timer value based on either CSI or residual battery power to determine the best relay for a source-destination pair. In MGM technique [60], the channel gains between the source-relay and the relay-destination links are used for choosing the best relay. Saghezchi *et al.* [16] emphasised on extending the source node's battery lifetime. However, all these techniques are only applicable to obedient relays and expect [18] , the literature didn't consider the fair utilization of battery power of relays.

2.4 Relay Selection Techniques considering Self-Interested Users

Section 2.3 discussed the relay selection techniques for obedient relays. However, a public network may also comprise of selfish users who are not always willing to cooperate and are interested in their own benefit. The factors that contribute towards selfishness of users are ([61]): 1) lack of resources, e.g low battery power, available memory or computational capability 2) security concern of receiving malicious information from other users of the network 3) No incentive to collaborate with other users. These self-interested users need to be given proper incentives in order to make them use their resources for providing relay service to the other users of the network. This section describes the relay selection methods for self-interested users.

Lam *et al.* [62] introduced the idea of deploying pricing to be an incentive technique to motivate self-interested users to participate in relaying data for other users of a public wireless mesh network. They proposed a game-theoretic mechanism for collaboration in single-hop and multi-hop wireless mesh networks. Each intermediate user asks for a price to provide relaying service. However, Lam *et al* considered a star topology for their analysis which means there is a single link to the access point and the user wanting to reach the access point can either accept the price the intermediate user is asking for or reject the help and be deprived of the service.

Saghezchi *et al.* [17] employed Coalitional game theory for relay selection to expand the lifetime of mobile users and improve the overall energy efficiency of a HANET. Mobile users share information about their channel conditions and available battery power and when it is advantageous for them, they cooperate with one another in relaying data to the base station. In the Coalitional game, all players cooperate to follow a group strategy that maximizes their overall utility/ benefit. A Coalitional game has an ordered pair $< N, v >$, where $N = \{1, \ldots, n\}$ is the set of players which are rational players i.e. they always look to maximize their benefit and v is the characteristic function or utility function. Any subset of players is called a coalition and the utility gained as a result of forming a coalition is distributed among the players.

In [17], Saghezchi *et al.* used linear optimization to determine the best matching for mobile station and relay in order to maximize the energy efficiency and the benefit users can achieve through the coalition. The utility or characteristic function of coalition has been defined in terms of the energy being saved by using the relay node and the extension in battery lifetime of the mobile station. Energy saving is calculated by subtracting the energy consumed when the relay is utilized from the energy consumed via the direct link. For cooperative link energy consumption, transmission power of mobile station and energy used by relay for reception and transmission have been considered. Battery lifetime extension is the difference of remaining battery levels after cooperation and when no cooperation has been used i.e. when the direct communication is deployed.

However, Saghezchi *et al.*'s work focuses on maximizing the overall utility of forming a coalition, not the utility of individual users which means unfair battery power dissipation of users acting as relays. Khayatian *et al.* [13] also used the coalition game for relay selection and optimal power allocation in cooperative networks. Users located in close vicinity form a coalition. Their scheme first chooses the best relay within a coalition in a decentralized manner and then assigns the optimal transmission power to the source and relay nodes. The relay selection process comprises of two steps; first step remove the users which are not capable of supporting the source node's transmission and in second step the best relay is chosen. Two algorithms are used to pick the best relay. The first algorithm is based on characteristic function which is defined as the gain in data rate obtained via coalition formation considering the power consumption of source node and relay node. Whereas the second algorithm uses the Shapley vaule which is a fairness measure for distributing the benefit of coalition among member forming the coalition. A Coalition game considers the overall benefit rather than the individual benefit of the relay and the source node.

Mastronarde *et al.* [21] devised a token based system to incentivize self-interested users to act as relays in cellular networks and have used Markov Decision Process (MDP) to predict when it is beneficial for a user to provide relay services to other users present in the network. Each user tends to maximize its long term benefit i.e. its utility which is defined as the difference between the energy it consumes for relaying data of other users and the advantage in terms of data rate it receives through other users who relay its data. The utility is actually the level of satisfaction of a user [63]. They have also considered that each user has energy budget which is the minimum battery power a user is willing to utilize to relay data for other users and below this battery level a user cannot provide relay services until it gets its battery charged again. A user gains a token when it relays data for others users and spends a token when it receives relaying service from other users. The user with no token can neither avail nor provide relaying service.

A simple two-hop AF relaying policy is considered in [21] and a user can always use the direct transmission link to the base station if no user is willing to provide data forwarding service or if the direct link is better than the relay assisted link. The relay with minimum required transmission power is sent a request asking for its assistance. The decision on whether to provide relay service or not is dependent on relay's utility, its energy budget and its token state. Their findings advocate that users have higher motive to collaborate with other users in a network having users with high battery power budget, users with high mobility and when the network has average number of tokens i.e. not too many nor too few.

However, in [21] the cost experienced by the relay only depends on its instantaneous transmission power, which implies some users will be providing relay services more often than other users and their battery power will consumed more quickly. Mastronarde *et al.* [21] didn't address the fair battery power utilization of relays.

Stackelberg game has widely been used to address the relay selection problem in wireless networks comprising of self-interested users [22, 64, 11, 65] and [66]. Wang *et al.* [22] used game theory to model the relay selection and power control mechanism for cooperative communication networks. A seller buyer game has been developed using the Stackelberg game considering the benefits of both the source node and the relay nodes. The relay nodes are the seller of the game while the source node is the buyer. The relay nodes are also termed as leader of the game since they advertise the price for providing data forwarding service and the source node is the follower in the game. The communication between the source and the destination is divided into two phases: in phase 1 the source node transmits to both the destination and the relay node while in phase 2 the relay node employs an amplify and forward technique to send the data to the destination node. Their algorithm determines the optimal number of the required relays and which relay nodes should be selected by the source node and the amount of service i.e the transmission power to buy from each selected relay node. They also analyzed the optimal price that a relay node should advertise in order to be chosen by the source as well as to earn some benefit itself for providing the relaying service. Utility of the source node is defined as the difference between its benefit in terms of the achieved data rate and the price its pays to the relay node. While the utility of the relay node is the difference between its price and cost.

In [22], each relay node determines its price considering the channel conditions on the source-relay link and the relay-destination link as well as the price announced by other relays. Initially each relay will set its price same as the cost it will incur while providing data forwarding service and then will update its prices accordingly. If the cost experienced by the relay is higher than the price for its service, then it will not participate in the seller-buyer game. When the relay node is located close to the source node, it asks a smaller price for its services, which means the source node will buy more power from the relay, resulting in better utility for both source node as well as the relay node. However, Wang *et al.* [22] have considered a fixed cost per unit power for providing the relay service, which is independent of power consumption of the relay node as well as the distance between the relay and the end user. The assumption of having a fixed cost will result in unfair battery power consumption of relay nodes.

Cui *et al.* [64] also utilized Stackelberg game to devise a cooperative MAC for Ad-hoc wireless networks considering the effects of interference. A leader follower game is developed to determine the appropriate relay node for each source node, taking into account the revenue of both source node and the relay node. A relay node can serve only one source destination pair in order to avoid interference. The source node and available relay nodes will be continuously sensing the channel without triggering any harmful interference and will attempt to access the channel whenever it is unoccupied.

Cao *et al.* [11] have also used game theory to model the interaction of users and relay nodes in a multi-user single relay network. They have also deployed Stackelberg game to determine the optimal price of a relay formulating a leader-follower game and Kalai-Smorodinsky Bargaining Solution (KSBS) has been used to fairly distribute relays power among users. Their work focuses on how the relay's power should be allocated among the users, instead of maximizing the overall network power efficiency. Convex optimization is used to construct the problem of power assignment.

A bargaining game is basically a cooperative negotiation between the players of the game [11]. Each player of the bargaining game has a ideal utility which is the maximum attainable utility as well as a minimum utility which the player can achieve without entering the bargaining game. If the ideal utility a player can reach with cooperative negotiation is the same as its minimum utility, then the player will not participate in the bargaining game. KSBS is a solution to the bargaining game which maximizes the ratio of actual net utility gain and the maximum utility gain of a player. The actual utility gain is the difference between the utility obtained through negotiation and the minimal utility. Whereas the maximum utility gain is the ideal utility minus the achievable utility gained by taking part in bargaining game. KSBS is an equality/ equilibrium point that balances the attainable utility and fairness among players.

Cao *et al.* [11] have considered a high mobility scenario where the relay has perfect information of channel conditions and a single relay, which is a specialized node, assists the communication between all source and destination nodes. Cao *et al.* have used the concept of pricing to limit the amount power each user can buy from the relay, thus promoting fair access to the system resources. Their work poses a competition among users, rather than among relays i.e. relay's power distribution among users rather than fair consumption of battery power of relays.

Summary: A detailed summary of some of the literature addressing the relay selection problem in wireless networks comprising of selfish users has been presented in this section. A Game theoretic approach and pricing based schemes are commonly used to motivate the self-interested users to help the neighbouring users in the network. A Coalition game focuses on the overall benefit accomplished through cooperation and Stackelberg game emphases on the individual utility of the users participating in the game. Whereas bargaining game deals with the fair distribution of utility among the users. However, all the approaches discussed in this section did not take into account the fair utilization of battery power of these self-interested users.

2.5 Relay Selection Techniques Considering Fair Battery Power Utilization

Most of the literature on cooperative wireless networks focuses on fair allocation of bandwidth [9, 10], optimal allocation of power [11–13] or energy efficiency of the network [16, 17]. Very little attention has been paid towards the fair battery power dissipation of the relays participating in the cooperation process [18]. Mostly nodes with better SINR, the ones located close to the end users are selected as relays, which implies that some nodes spend much of their battery power relaying data while others located a bit far spend nothing at all. This results in unfair battery power utilization of relay nodes. This section highlights some of the relay selection methods that aim at fair or equal consumption of battery power of relays present in a cooperative wireless network.

Michalopoulos and Karagiannidis [19] studied the physical layer fairness in cooperative networks with AF cooperative mode. Physical layer fairness is defined as the fair utilization of battery power of relays and to equally distribute the consumed energy among the collaborating intermediate nodes. A centralized system model is considered to comprise of a single source and destination node and a number of intermediate nodes to provide relay service to the source and destination nodes. The average channel conditions are known to the central controlling unit. The source node uses both the direct link as well as the cooperative link to communicate with the destination node and the destination node then employs Maximum Ratio Combiner (MRC) to retrieve the received signal.

In [19] the relay selection technique chooses a relay ensuring that the average energy consumption of all relays in the network remains equal. Each relay has a weight coefficient associated with it whose value depends on relay's instantaneous Signal to Noise Ratio (SNR) taking into account the end-to-end source-destination link and a positive constant dependent on the average channel quality. This positive constant plays the decisive role in controlling the average selection duration of a relay as well as its power consumption. Information about this positive constant is conveyed to the relays by the central controlling unit which is the destination node in this case. Relays then in a distributed manner determine the best relay to forward the signal to the destination. The best relay is chosen by assigning a timer value to each relay. The relay with the highest weight coefficient has the smallest timer value, since timer value is inversely proportional to the weight coefficient. On expiry of the timer, the best relay informs its neighbors by sending a flag message and if it can not directly liaise with other relays then the control unit transmits the flag message. The network performance has been evaluated using the probability of outage and the average symbol error probability for the proposed relay assignment technique.

Liu *et al.* [20] also addressed the unequal power consumption of relays in cooperative networks. They have complemented the work of Michalopoulos and Karagiannidis [19] by developing a distribution algorithm for path selection imposing the constraint of equal power consumption for the DF cooperative mode. They have also examined a network model having a single source and a destination node with multiple available relays. Each relay has information about the channel state between itself and the destination and uses this information to determine the value for its timer. The timer value is also dependent on a parameter which in turn (gives the author the opportunity to) controls the probability of selection of a relay and hence result in equal power consumption of all relays. However, both [20] and [19] have not provided any incentive to the relays to participate in the cooperative transmission.

Ahmed *et al.* [67] have analyzed relay selection and fair power assignment problem considering generic noise and interference instead of assuming Additive White Gaussian Noise (AWGN). Their work promotes the idea of forming relay subset which is the pre-selection of a group of relay nodes among all available relays and then choosing the best relay from the subset of relays. The relay subset is formed using the average CSI which is acquired through average SNR and noise levels at the relay, rather than using the instantaneous channel measurements. Acquisition of instantaneous channel measurements poses excessive overhead specially in a network comprising of large number of relay nodes. [67] utilized the instantaneous CSI only for selecting the best relay. A constraint on energy consumption of relays and source node has been imposed to control the energy consumption of all nodes in the network. This constraint will result in fair utilization of battery power of relays. However, they have also assumed that relay nodes are always willing to collaborate with the source and destination nodes to support their transmission, which is not the case in a public network comprising of self-interested users.

YuBo *et al.* [68] also studied a wireless network consisting of a source and a destination node with a number of relays available to provide cooperative communication. There is no direct link between the source and destination owing to poor channel quality. Perfect channel information is obtained using RTS and CTS messages between the source and destination node and the DF cooperative mechanism is examined. The opportunistic DF approach is generally is divided into two phases, in the first phase the source broadcasts its signal to all relays present in the network. In the second phase, the best relay among the relays which were successfully able to decode the source's signal forwards the re-encoded signal to the destination. In opportunistic DF mode, the appointment of the best relay is done by fixing a timer value for each relay which is inversely proportional to the SNR between the relay and the destination. The timer of best relay lapses first.

YuBo *et al.* in [68] have argued that the opportunistic scheme performs well in terms of achieving optimum outage probability but relay nodes suffer unfair energy consumption as a result of this scheme. A relay node situated in mid-way between the source and destination has a higher probability of being designated as the best relay and thus its battery power being dissipated rapidly. This in turn affects the lifetime of the whole network with good relays running out of battery quickly. YuBo *et al.* have proposed an Outage Priority-based Proportional Fair Scheduling (OP-PFS) approach to improve fairness among relay nodes at the same time as not degrading the network performance in terms of probability of outage. OP-PFS is a balance between Proportional Fair Scheduling (PFS), which has a strict condition on fairness i.e. all relays should be elected with equal probability, and no fairness at all. OP-PFS urges that it is not necessary to always employ the best relay, the one having best channel conditions, to support the source destination communication. In OP-PFS, the relays with the ability to correctly decode the source's signal make a candidate set. The best relay among the candidate set is also chosen using a timer but here timer value depends on channel quality of both source-relay and relay-destination channels. The relay's timer is then multiplied by a weighted value to increase the probability of selection of the relay with mediocre channel quality.

[68] further enhanced fairness by designing a cross-layer opportunistic scheme in which destination assigns an energy counter to each relay node. Initially the counter value of each relay is set to zero. At the start of each cooperation cycle, the relay nodes provide their

counter values to the destination and the destination picks the relay with smallest counter. If more than one relay has the same counter value then the destination randomly chooses a relay. The selected relay then forwards the source's signal to destination and updates its energy counter by one. However, YuBo *et al.* have also assumed obedient relays and there is no mechanism proposed to motivate the self-interested relays to take part in cooperation process. By only taking into account the fair depletion of battery power of relays while selecting the relay will make the network suffer in terms of achievable data rate and throughput.

Afghah and Adedi [14] developed a non-cooperative game to balance the efficiency and fairness while allocating power in a system constituting of parallel relay assisted source-destination links. They emphasized fair allocation of power rather than fair utilization of the power assigned to the relays. Shen *et al.* [15] also formulated a distributed algorithm for relay selection and allocation of power to the relay nodes. AF cooperative mode is considered and they have used Nash Bargaining Solution (NBS) to fairly assign power to relays.

Zhao and Pan [69] have proposed a distributed strategy for selection of relays considering the physical layer fairness. Simple AF cooperative technique is used to evaluate the performance of their Fair Opportunistic Relay Selection (FORS) method. The FORS ensures that equal dissipation of battery power of all relays which is achieved by assigning weights to the channel fading coefficients and altering the probabilities of selection of relays using the proportional fair scheduling. Zhao and Pan have advocated that by increasing the probability of choosing relays with poor channel conditions as well as decreasing the probability of picking the relays with good channel quality, fairness in terms of battery power consumption can be achieved.

The network model consists of a source node, a destination node and a number of relays available to assist the source-destination communication [69]. A static channel state has been assumed within the coherence time and relays only require local CSI. A fixed power allocation between the source node and the relay node has been considered as well as an equal transmit power for both the source node and the chosen relay node. Each relay sets a timer whose value depends on the weight alloted to the relay and the channel gains of source-relay link and the relay-destination link. The relay whose timer lapses first is chosen as the best relay. The chosen best relay then informs the other competing relays either directly by sending a flag message or by the help of destination node. The destination node receives the transmitted signal from both the source node on direct link and the relay node on cooperative link and uses MRC to decode the received signal.

The weight efficients are calculated in [69] by using the equal average power consumption assumption for all relays and that the probability of selection of all the relays is equal to 1. Zhao and Pan have derived that the values of weight efficients depend on channel statics only. The main focus of Zhao and Pan's work ([69]) is fair selection of relay node resulting in equal cumulative power consumption of relays' battery, rather than the optimum power allocation. However, by increasing the probability of selection relay with poor channel condition will greatly affect the performance of wireless system in terms of achievable data rates and throughput. There should be a balance between fair battery power utilization of relays and the achievable data rate. Also there is no incentive for relays in FORS to help the source-destination communication, relays are still consuming their battery power though fairly but without gaining any benefit.

Summary: In short, the relay selection techniques discussed in this section stress on the fair distribution of the consumed energy among all the participating immediate nodes. Their aim is to ensure that the average energy dissipation of all relay remains equal. This is achieved by using timer values to select the best relay. The timer value is determined either using the weight coefficients assigned to relays on the basis of channel conditions or using parameters which control the probability of selection of relays. Another proposed way to achieve equal energy utilization is employ an energy counter for each relay and the relay with smallest counter value shall be selected to assist the source-destination communication.

However, all these methods have considered obedient relays, which are willing to help the source-destination communication without asking for anything in return.

2.6 Research Problem

The research problem studied in this thesis is the extension of coverage range of an already existing wireless network in a rural area, utilizing the ordinary self-interested users. The considered rural wireless network comprises of two kinds of users, the in-range users and the out-of-range users. Cooperative relaying is the enabling technology to achieve this infrastructure-less coverage expansion. Since the in-range users are selfish users, they require incentives in order to encourage them to collaborate with the out-of-range users. This cooperation will enable the out-of-range users to access the Internet to send and receive their data. These selfish in-range users also have concerns regarding the utilization of their battery power for signal and data transmission and reception of the out-of-range users. If only few in-range users are repeatedly chosen as relays to assist the out-of-range users, this will result in unfair consumption of battery power of relays causing dissatisfaction among the in-range users. Thus a mechanism is needed that motivates the selfish in-range users by giving incentive to help the out-of-range users as well as ensuring fair dissipation of battery power of these in-range users.

The relay selection techniques discussed in section 2.3 have considered obedient in-range users who are obliged to help the source-destination communication or in other words the out-of-range users. Different game theoretic approaches, some of which have been described in section 2.4, have been used to incentivize the self-interested users to utilize their resources for other users and gain some benefit for themselves. The methods summarised in section 2.5 also addressed the relay selection problem focusing on equal battery power consumption of the participating obedient relays. However, none of the techniques presented in sections 2.3, 2.4 and 2.5 have addressed the fair utilization of battery power of the self-interested users. Therefore, a relay selection technique both giving incentives to the selfish users to encourage them assist the out-of-range users and at the same time guaranteeing the fair consumption of their battery power is needed. Thus this thesis aims at developing a relay selection algorithm providing incentives and fair opportunities to the selfish in-range users to help expand the coverage range of a wireless rural network to the out-of-ranges users, establishing fair utilization of battery power of the in-range users.

Chapter 3

Mathematical Tools for Wireless Network Modeling

The mathematical formulation of the relay selection problem for the network model of rural communities and the detailed analysis of the mathematical tools commonly used to model and solve relay selection problem in wireless networks are described in this chapter.

3.1 System Model

The network model considered in this research as presented in Figure 3.1 comprises of two types of users in wireless rural environment. The first type of users is in transmission range of the base station/ access point (AP) and can directly transmit and receive desired data from the AP. The second type of users is located outside the coverage range of AP and cannot communicate with AP without help from the in-range users. The in-range users are termed as primary users (PUs) of the network whereas the out-of-range users are the secondary users (SUs) as shown in Figure 3.1.

The system model employs the simple AF technique for providing relay service to the secondary users. Since no direct link exists between the AP and the secondary users, a

Figure 3.1 Network model containing two types of users; in-range and out-of-range users

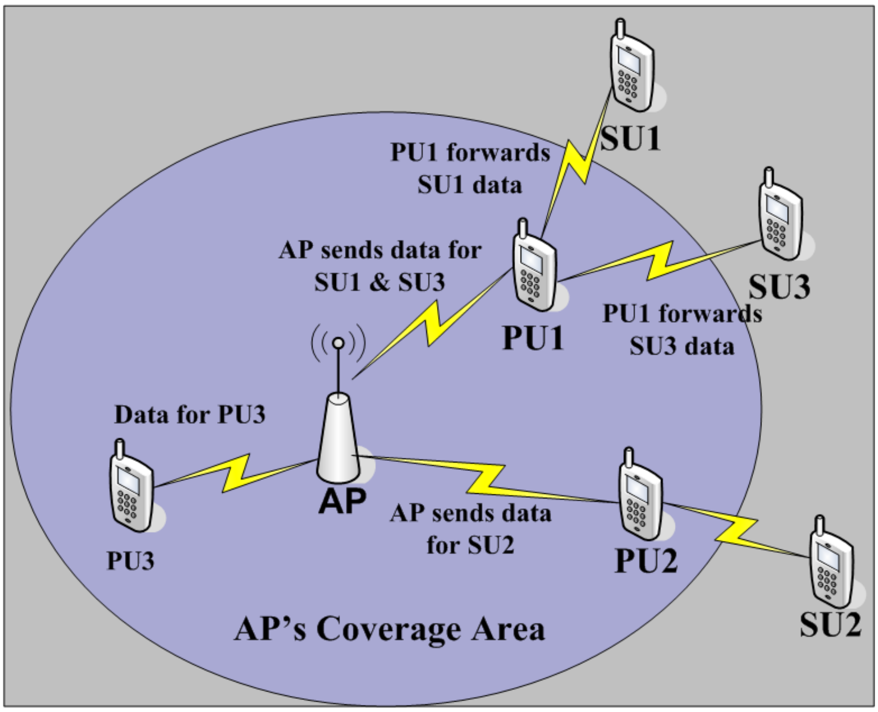
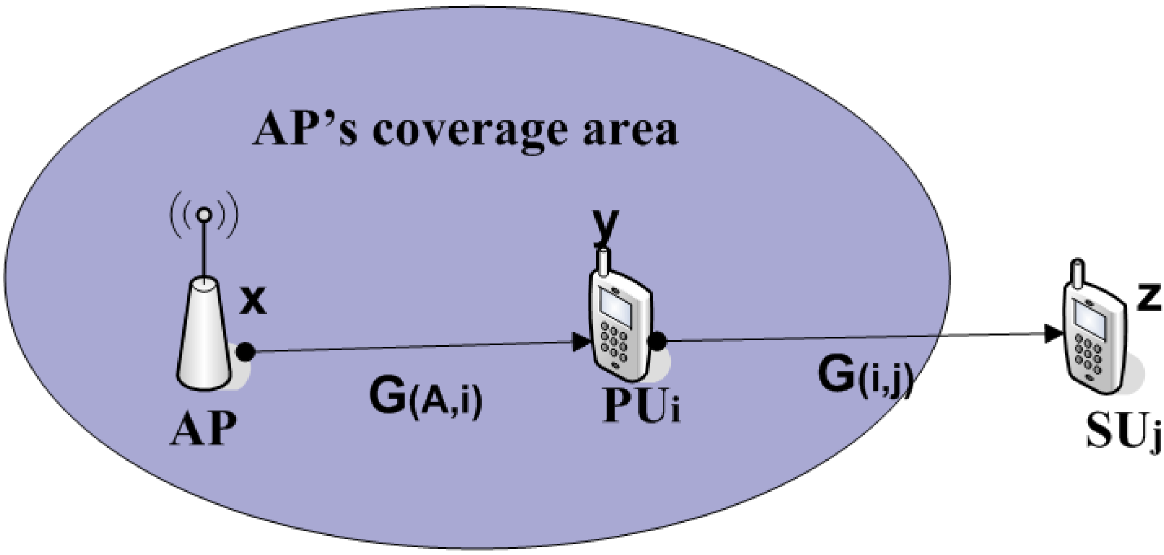


Figure 3.2 System model, data transfer between AP and secondary user via primary user



secondary user can only access the AP with the help of the in-range primary users acting as relays, see Figure 3.2. The system model described in [22] has been modified according to the considered network model depicted in Figure 3.1. Let N be the set of primary users and M be the secondary users in the system model under study, where $i \in \{1,2,...,N\}$ and $j \in \{1,2,....,M\}$. The primary user i receives data from the AP for the secondary user j. The signal received at the primary user i is given by equation(3.1)

$$y_{A,i} = \sqrt{P_A G_{A,i}}\, x + n_{A,i} \tag{3.1}$$

where P_A is the transmission power of AP, $G_{A,i}$ is the channel gain between the AP and the primary user i, x is the transmitted signal with unit energy and $n_{A,i}$ is AWGN with zero mean and variance σ^2 on AP and PU_i link. The primary user i amplifies the received signal and forwards to the secondary user j. Equation(3.2) represents the signal received at the secondary user.

$$y_{i,j} = \sqrt{P_i G_{i,j}}\, x_{i,j} + n_{i,j} \tag{3.2}$$

where

$$x_{i,j} = \frac{y_{A,i}}{|y_{A,i}|} \tag{3.3}$$

In equation(3.2), P_i is the transmission power used by the primary user i to forward the signal $y_{A,i}$, $G_{i,j}$ is the channel gain between primary user i and secondary user j and $n_{i,j}$ is the AWGN on the link $\{i,j\}$. Substituting equation(3.1) and equation(3.3) into equation(3.2), we get the final signal received at the secondary user j as

$$Z = \frac{\sqrt{P_i G_{i,j}}\left(\sqrt{P_A G_{A,i}}\, X + n_{A,i}\right)}{\sqrt{P_A G_{A,i} + n_{A,i}^2}} + n_{i,j} \tag{3.4}$$

The SINR and the achievable data rate at the secondary user j can be obtained using equation(3.5) and equation(3.6)

$$SINR = \frac{P_A P_i G_{A,i} G_{i,j}}{\sigma^2 \left(P_A G_{A,i} + P_i G_{i,j} + \sigma^2\right)} \tag{3.5}$$

$$R = \frac{W}{l} \log_2 (1 + SINR) \tag{3.6}$$

where σ^2 is the noise power, which is assumed to be same on both links $\{A,i\}$ and $\{i,j\}$, W is the bandwidth and l, $l \in \{1,2,....,M\}$, is the number of secondary users the primary user i is assisting at any given time.

Equation(3.6) is actually the Shannon-Hartley capacity theorem which gives the tightest upper bound on the channel capacity, which is the theoretical maximum date rate at which information can be transmitted over a channel of a specified bandwidth in the presence of noise [70]. Though the real communication networks cannot achieve this theoretical upper bound on data rate, the Shannon-Hartley theorem has been widely used in literature ([21, 15, 22, 64] and [66]) to calculate the data rate provided by a network. Therefore, the Shannon-Hartley theorem has also been utilized to determine the achievable data rate at the secondary user.

3.2 Problem Formulation

The aim is to utilize the ordinary mobile users which are in the transmission range of access point/ base station (the primary users) to serve as relays for the out-of-range users (the secondary users). The deployment of ordinary mobile users as relays gives rise to two important questions; that are:

1. What should be the relay selection criteria?

2. Why should a mobile user act as relay and use its battery power to forward data for other users?

An out-of-range user will prefer a relay having a good channel quality, hence providing the highest data rate. On the other hand, a relay needs to be motivated to serve a secondary user by incentives like earning some benefit and without consuming too much of its battery power for assisting the out-of-range user's communication. The benefit for the relay can be a monetary benefit or tokens/credits earned that can be utilized later when the relay moves out of the transmission range. Also each relay present in the network will want a fair chance to be selected by the secondary user to earn some benefit and be assured that the battery power of all relays is utilized fairly. Fair utilization of the battery power of relays can be achieved using the concept of proportional fairness [71] and [72] i.e. by minimizing the cumulative to instantaneous battery power consumption of each relay. Thus the relay selection problem in wireless rural networks can be formulated as a multi-objective problem given by equations (3.7), (3.8) and (3.9). Detailed explanation along with the definition of the terms used to formulate multi-objective optimization is given in section 3.3.

$$\max U_j = \left[R_{ij} - p_{ij}P_{ij}\right]\alpha_{ij} \qquad \forall\ i,j \tag{3.7}$$

$$\max U_i = \left[p_{ij}P_{ij} - c_{ij}\right]\alpha_{ij} \qquad \forall\ i,j \tag{3.8}$$

$$\min \left[\frac{\overline{CBP_i}}{CBP_{ij}}\right]\alpha_{ij} \qquad \forall\ i,j \quad \text{and} \quad CBP_{ij} \propto P_{ij} \tag{3.9}$$

where U_j is the utility of the secondary user j, U_i is the utility of the primary user i, $\overline{CBP_i}$ and CBP_{ij} are the cumulative and the instantaneous battery power consumption of primary user i and the ratio $c_{ij} = \frac{\overline{CBP_i}}{CBP_{ij}}$ is the cost incurred while providing relaying service. Thus equation(3.9) then becomes:

$$\min\ c_{ij}\,\alpha_{ij} \qquad \forall\ i,j \quad \text{and} \quad CBP_{ij} \propto P_{ij} \tag{3.10}$$

The optimization problem at the secondary user is to find the optimal primary user PU_i and the amount of power P_{ij} to buy from PU_i that maximizes the utility of the secondary user SU_j as well as minimizes the cost $c_{ij} = \frac{\overline{CBP_i}}{CBP_{ij}}$. Minimizing c_{ij} is required to achieve fair utilization of battery power of all primary users. The optimal price p_{ij} needs to be advertised by the primary user considering the cost c_{ij} of its relaying services in order to maximize its utility and earn credits. The price advertised by the primary user is the controlling parameter governing the relay selection process. α_{ij} is a binary variable taking values

$$\alpha_{ij} = \begin{cases} 1 & PU_i \text{ serving } SU_j \\ 0 & \text{otherwise} \end{cases}$$

whereas $p_{ij} \in \mathbb{R}$ and $P_{ij} \in \mathbb{Z}$.

Each wireless network has certain limitations which need to be considered while modeling the network and the aim of the network operator is to maximize or minimize a certain parameter to optimize the performance of the whole network. Our relay selection problem is subject to the following system constraints:

- A secondary user can communicate with the access point/ base station only with the help of a primary user

$$\sum_{i=1}^{N} \alpha_{ij} = 1 \qquad \forall j \tag{3.11}$$

- Battery power of a primary user to be selected as relay should be greater than a predefined threshold

$$\sum_{j=1}^{M} BP_i \, \alpha_{ij} > BP_{th} \qquad \forall i \tag{3.12}$$

- A primary user should be in the transmission range of AP as well as that of the secondary user in order to be selected as relay

$$\sum_{j=1}^{M} d_{Ai} \, \alpha_{ij} \leq T_A \qquad \forall i \tag{3.13}$$

$$\sum_{j=1}^{M} d_{ij}\ \alpha_{ij} \leq T_j \qquad \forall i \tag{3.14}$$

where d_{Ai} is the distance between the AP and the primary user i, T_A transmission range of the AP, d_{ij} distance between the primary user i and the secondary user j and T_j is the transmission range of the secondary user j.

- The budget of secondary user j should be greater than the price p_{ij} advertised by the primary user i.

$$\sum_{i=1}^{N} \beta_j\ \alpha_{ij} > p_{ij} \qquad \forall j \tag{3.15}$$

The relay selection problem in rural wireless networks is then a multi-objective non-linear programming problem with binary x_{ij}, integer P_{ij} and real variable p_{ij}.

Two methods are frequently used to mathematically model the relay selection problem in wireless networks ([73–76, 22, 11, 64] and [66]. These methods are:

- Multi-objective Optimization
- Game Theory

A detailed description of each of these methods is given in the following sections.

3.3 Multi-objective Optimization

Multi-objective optimization is a field of multiple criteria decision making which deals with mathematical optimization of problems involving one or more than one objective functions. An objective function is basically the criterion which the decision maker aims to either maximize or minimize to improve or optimize the performance of the system and to obtain the desired results. The variables used to define a problem mathematically are termed decision variables. There are some limitations imposed by the problem or the system which are expressed as system constraints. Both objective functions and system constraints are modeled in terms of the decision variables along with some constant terms. A system may impose conflicting objective functions e.g. maximizing the profit as well as minimizing the production cost. Depending on the existence of the system constraints, the optimization problem is classified as constrained or unconstrained problem. The optimization problem can be static if it involves dealing with one instance of the problem or it can be dynamic if long term planning and decision making is required. Similarly it may be deterministic if all relevant data is known with certainty or it may be stochastic or probabilistic if probability distribution of random data elements is required [77].

An optimization problem is also called a mathematical programming problem. Optimization problem can be categorized in four types:

- **Linear Programming Problem (LP)**: All objective functions and constraints are linear functions.
- **Non-Linear Programming Problem (NLP)**: At least one of the objective functions or constraints is non-linear.
- **Geometric Programming (GMP)**: A programming problem in which the objective function and constraints are expressed as posynomial functions. A function is called a posynomial if it can be expressed as the sum of power terms. For example equation(3.16) is a posynomial function.

$$h(X) = c_1 x_1^{a11} x_2^{a12} ... x_n^{a1n} + ... + c_N x_1^{aN1} x_2^{aN2} .. x_n^{aNn} \tag{3.16}$$

- **Quadratic Programming Problem**: A nonlinear programming problem in which objective function is quadratic with linear constraints.

If decision variables are constrained to belong to a set of integer values only, the optimization problem is called an integer programming problem. However, if all the decision variables are allowed to take any continuous real value, the optimization problem is called a real-valued programming problem. Lagrange multiplier approach is used to solve an optimization problem if the problem has equality constraints and in case of inequality constraint the Kuhn-Tucker conditions are used to find the optimal solution. However, both of these approaches lead to a set of simultaneous nonlinear equations which are difficult to solve [78].

3.3.1 Linear Programming (LP) Problem

In an LP problem, the objective function as well as the constraints are linear in their nature. Simplex algorithm is commonly used to solve LP problems. Simplex algorithm comprises of two steps. In the first step artificial variables are added to the standard form of LP problem to find a basic solution and the basic solution is obtained by setting n-m constraints equal to zero, where m is the number of equality constraints in a problem with n variables given that $n > m$. The features of the standard form of LP problem are: 1) minimization of the objective function, 2) all constraints are defined as equality equations and 3) all decision variables are non-negative. In the second step, the basic solution obtained using artificial variables is used to find the optimal solution of the original LP problem. [78] and [79] provide a detailed explanation of the Simplex algorithm.

A solution of the LP problem using the Simplex algorithm requires a large amount of storage and computational time. Other techniques, which are less expensive in terms of storage and computational time, have been developed to handle LP problems. With every LP problem, called the primal, there is an associated LP problem called the dual [71]. If the optimal solution to the primal is known, the optimal solution to the dual can be easily obtained. The advantage of this primal-dual property of LP problem is that we can find a solution to the one which is more simple to solve. The dual of the LP problem is formulated by taking the transpose of the rows and columns of the constraints and for the objective function, the inequalities are reversed and maximization is performed instead of minimization.

The decomposition method can also be used to solve an LP problem encompassing a large number of variables and constraints. In the decomposition method, the problem is split into smaller sub-problems and these sub-problems are then independently solved. Detailed analysis of the decomposition method and the LP problems which can be solved using this technique is given in [78].

Karmarkar's interior method [80] can also be utilized to find the solution to large size LP problems. In contrast to the Simplex algorithm, in which search is performed along the boundary of the feasible space, i.e. moving from one vertex to the adjacent feasible vertex to locate the optimal point, in the interior method the search is carried out in the interior of the feasible region.

3.3.2 Non-Linear Programming (NLP) Problems

If an optimization problem is composed of at least one non-linear function, either one of the objective functions or the constraints, such an optimization problem is called a Non-Linear programming (NLP) problem. As described in section 3.2, the relay selection problem for the system model defined in section 3.1 is a NLP problem. Numerical methods can be used to solve optimization problems in which objective function or constraints cannot be explicitly expressed in terms of the decision variables. However, numerical methods are suitable for solving one-dimensional minimization problems [78] and our optimization problem comprises of more than one decision variable.

Methods available to solve constrained non-linear optimization problems with more than one decision variables are generally divided into two categories; direct methods and indirect methods. In the direct methods, the constraints are handled in an explicit manner, whereas in most of the indirect methods, the constrained problem is solved as a sequence of unconstrained minimization problems.

Direct Methods:

- **Random Search**: In random search methods, a trial decision vector comprising of one random number for each decision variable is generated and verification of constraints being satisfied at the trial decision vector is carried out [78]. If any constraint is not satisfied, new trial vectors are generated until a trial vector with all constraints been satisfied has been found. Random search methods are very simple to program but are reliable in determining only a nearly optimal solution with a significantly large number of trial decision vectors.

- **Sequential Linear Programming**: In sequential linear programming, the solution of a non-linear optimization problem is determined by solving a series of linear optimization problems [81]. First order Taylor series is utilized to obtain a LP by estimating the original non-linear objective function and constraints around the decision vector X_i [82]. The simplex method is then used to solve the formulated LP problem to find the new decision vector X_{i+1}. If the convergence criteria for the optimization problem is not satisfied at X_{i+1}, then the problem is re-linearized about the point X_{i+1} and the process is repeated until the optimal solution has been found.

- **Generalized Reduced Gradient (GRG) Method**: Before applying GRG algorithm, the non-linear optimization problem is first converted to the GRG form expressed by equation(3.17) .

$$G_R = \nabla_Y f - \left([D]^{-1} [C] \right)^T \nabla_Z f \tag{3.17}$$

where f is the objective function, Y and Z are the vectors representing decision variables and state variables respectively. State variables are basically slack variables dependent on the decision variables [78, 83] and [84]. And matrices D and C are partial derivatives of system constraints with respect to Y and Z, respectively. Starting with an initial trial vector X, GRG, using equation(3.17), and the derivatives D and C

are determined and GRG is checked for convergence. Using the criterion $||GR|| \leq \varepsilon$ if all elements of the GRG are close to zero, then convergence has been achieved and the vector X provides the optimal solution. Otherwise, the search direction S and the minimum along the search direction is determined. GRG method finds application in designing control system for dynamical systems and robotics [85] and [86].

Indirect Methods:

- **Transformation**: When the constraints are expressed as explicit functions of the decision variables and have simple form, then independent variables can be transformed to solve the optimization problem [87]. Before applying transformation, the aspects that need to be considered are: 1) constraints are simple functions of decision variables, 2) it may not be possible to transform certain constraints and 3) if all constraints cannot be eliminated by changing the decision variables, it is better to avoid using transformation. Because partial transformation sometimes produces a deformed objection function which is more cumbersome to minimize than the original function.

- **Sequential Unconstrained Minimization; Penalty Functions**: An optimization problem can be transformed into an alternative formulation using the penalty function methods and then numerical solution can be obtained by solving a sequence of unconstrained minimization problems [88]. In penalty function methods, the objective function is transformed into the form given by equation(3.18) by adding a penalty term r_k, where G_j is some function of constraint g_j of the original problem $f(X)$. The unconstrained minimization problem is then solved for a series of values of penalty term.

$$\phi_k = \phi(X, r_k) = f(X) + r_k \sum_{j=1}^{m} G_j \left[g_j(X) \right] \tag{3.18}$$

3.3.3 Integer Programming Problems

The decision variable used to formulate the optimization problem and to mathematically express the system constraints may not always be continuous. They can also take integer or discrete value. Programming problems in which decision variables can only take integer value are termed as all integer programming problems. When the decision variables are constrained to take only discrete values, the problem is called a discrete programming problem. When some decision variables can only take integer values, the programming problem is called a mixed-integer (discrete) programming problem. When all the design variables are allowed to take on values of either zero or 1, the problem is called a zero–one or binary programming problem. Relay assignment program in cooperative wireless networks has been formulated as mix integer LP problem in [89] and a greedy algorithm has been proposed for relay node selection. Methods used to solve integer programming problems are described below.

Sequential Linear Discrete Programming:

Similar to the sequential linear programming, first order Taylor's series expansion is used to convert the nonlinear problem into a linear problem about a point X^o with only difference of decision variables taking discrete values. The point X^o needs to be carefully determined because mostly the discrete problem solution is located within the vicinity of the continuous optimal solution. If the continuous optimal solution is a discrete solution as well, then it is taken as X^o. Otherwise, its value is rounded off to acquire an initial discrete solution X^o. Once the first linearized discrete problem is solved, the subsequent linearizations can be made using the result of the previous optimization problem [90].

Branch and Bound Technique:

In branch and bound technique, first a continuous problem is solved by relaxing the constraint on decision variables taking only integer values [90] and [78]. If the outcome of solving the continuous problem happens to be an integer value then it is the optimal solution of the integer problem as well. Otherwise, two subproblems are formulated with additional constraints providing the upper and lower bound on optimal solution. The process of forming two subproblems is called branching. The two subproblems are again solved as continuous problems until a feasible integer outcome is obtained for one of the subproblems. This feasible integer outcome is the upper bound on the minimum value of the objective function. The nodes with larger values of objective function are removed and these eliminated nodes are said to have been fathomed. The branch and bound algorithm continues until all the nodes have been fathomed. The optimal solution of original integer NLP problem is given by the fathomed node having the integer feasible solution with the lowest value of the objective function.

Relay selection and power allocation have been jointly considered in [73] and the branch and bound technique has been used. However, as the size of the network increases, the branch and bound technique becomes expensive in terms of processing time since it takes longer to determine the optimal solution.

In subsection 3.3.4, some modern optimization techniques are discussed which find their applications in cooperative wireless networks.

3.3.4 Modern Methods of Optimization

Some new optimization methods have been developed which conceptually differ from the conventional mathematical programming approaches. These methods take the leverage of the features and behaviour of biological, molecular, swarm of insects and neurobiological systems [78]. Some of these methods are listed below:

- Genetic algorithms which utilize the concept of genetics and natural selection.
- Particle swarm optimization is based on the characteristics and behaviour of living things, e.g. swarm of insects, flock of birds or a school of fish.

- Ant colony optimization works on the principle of cooperative communication between colonies of ants. Ants collaborate with each other to locate the shortest path to food resource from their nest.

- Fuzzy optimization methods deal with the problems in which the objective function and constraints are only defined in vague and linguistic terms.

- Neural-network-based methods are based on neural networks comprising of neurons. These networks are then trained to resolve the optimization problems effectively.

A detail description of these methods is provided below.

Genetic Algorithms:

Genetic algorithms (GAs) are suitable for solving problems composed of mixed variables i.e. continuous as well as discrete and having discontinuous decision space [91] . The basic elements of natural genetics which are reproduction, crossover and mutation are employed in the genetic search procedure [92] and [93]. The decision variables are presented as strings of binary numbers which correspond to the chromosomes in natural genetics. This implies that a continuous decision variable can only be represented by a set of discrete values if binary representation is used. To achieve higher accuracy, one just need to vary the length of the binary string. Since the GAs work on the principle of the survival of the fittest, they intend to maximize a function named as the fitness function. Hence GAs are more appropriate for handling unconstrained maximization problems.

The fitness function $F(X)$ is the same as the objective function $f(X)$ of any minimization programming problem. Thus an unconstrained minimization problem can easily be transformed into a maximization problem using equation(3.19)

$$F(X) = \frac{1}{1+f(X)} \tag{3.19}$$

The fitness function is usually selected to be non-negative. However, the practical problems/ systems always have certain limitations, thus penalty parameters are needed to convert a constrained problem to an unconstrained problem before applying GA to solve the problem. A fixed size population of random strings composed of several decision variables is considered and the operation of reproduction, crossover and mutation are performed on the population to determine the fitness of each string. The reproduction operation is basically the selection operation picking the good string from the population, using a probability which is proportional to string's fitness value and generating a mating pool.The next step is then crossover operation in which new strings are created by exchanging information among the strings present in the mating pool. In mutation operation, the binary digits in a string are changed from 1 to 0 or 0 to 1 with a predefined probability of mutation p_m. These three steps are repeated till the optimal fitness value is achieved for the objective function or the maximum allowed number of generations is reached.

Fang *et al.* [74] employed GA to solve the joint relay selection, bandwidth allocation and power distribution problem in DF cooperative systems. This joint resource allocation problem is a Mix-Integer Nonlinear Programming (MINLP) problem. Each chromosome in the proposed GA is divided into three parts: the relay selection part, the bandwidth assignment part and the power allocation part. In order to accommodate this joint consideration of resource allocation, each chromosome is composed of an integer part for relay selection and two real parts for bandwidth and power assignment. To reduce the complexity of the proposed solution, two stage suboptimal implementation is proposed, in first stage the proposed GA determines the set of optimal relays using the reproduction, crossover and mutation operations. Whereas in the second stage, another GA refines the allocation of bandwidth and power among the users and the chosen relays.

Another work of Fang *et al.* [75] addressed the joint relay selection and power allocation problem for AF cooperative systems using GA. Similar to [74], it is also a two stage implementation with first stage utilizing a Hybrid GA (HGA) for relay selection and power assignment and second stage deploying convex optimization for refinement of power distribution among the relays. GA is also used by Yen *et al.* [94] to devise an energy efficient multicast routing algorithm for MANETs.

Particle Swarm Optimization:

Particle Swarm Optimization (PSO) impersonates the behavior of social organisms, e.g. swarm of insects, flock of birds or school of fish. The particle represents an individual organism in the group which works either in distributed manner relying on its own intelligence or cooperatively utilizing group intelligence [78], the rest of the swarm immediately starts following the discovered good path irrespectively of their location in the swarm. Each particle in the swarm is characterized by two parameters; a position and a velocity [95] and [96]. The particles interchange information about the discovered good positions and tune their individual velocities and positions using the received information.

The PSO performs a random search in the decision space looking for the maximum value of the objective function. The constrained optimization problem needs to be transformed into an unconstrained problem which is done by using a penalty function. The penalty function can either be stationary i.e using fixed penalty parameters throughout the optimization or non-stationary which means the value of penalty parameter changes dynamically during the optimization process [97]. However, non-stationary penalty function performs better and are preferred in practical computations. For the obtained unconstrained problem, a population of fixed size is assumed, the population or swarm shall not be composed of more than 20-30 particles, otherwise evaluation of large number of functions will be required, thus increasing the complexity of the algorithm.

Each particle has a position $X_j^{(i)}$ and a velocity $V_j^{(i)}$ where j is the particle in the swarm and i represent an iteration. Thus $X_1(0), X_2(0), ...X_N(0)$ denote the initially generated particles.

The initial velocity of the particles is set to zero for iteration $i = 1$. The velocity and position of the jth particle for the i iteration is calculated using equations(3.20) and (3.21).

$$\begin{aligned} V_j(i) = V_j(i-1) + c_1 r_1 [P_{best,j} - X_j(i-1)] \\ + c_2 r_2 [G_{best} - X_j(i-1)]; \quad j = 1, 2, ..., N \end{aligned} \tag{3.20}$$

$$X_j(i) = X_j(i-1) + V_j(i); \quad j = 1, 2, ..., N \tag{3.21}$$

where $P_{best,j}$ is the historical best value of $X_j(i)$ in the iteration while G_{best} is the best value up to the current iteration. c_1 and c_2 are individual and group learning rates respectively whereas r_1 and r_2 are random numbers uniformly distributed within the range between 0 and 1. The value of the objective function is calculated using the new position and velocities of the particles until the solution converges to the same value.

Al-Tous and Barhumi [98] studied the joint power and bandwidth allocation for multi-user AF relay networks using PSO. PSO is widely used for optimal route discovery and managing connectivity in WSNs and MANETs [99] and [100]. Ho *et al.* in [76] proposed a modified PSO scheme for selection of optimum data relay path and relay node between the sensing node and the Unmanned Aerial Vehicle (UAV) in order to minimize the energy consumption, BER and the flying time of the UAV. Kuila and Jana [101] addressed the routing and clustering problem in WSNs using PSO.

Ant Colony Optimization:

Ants cooperate with each other to find the shortest path to food from their home, this collaborative behaviour forms the basis of the Ant Colony Optimization (ACO) [78]. A multilayer graph can be used to describe the ACO process, in which the number of layers represents the number of decision variables and the nodes within a layer are the discrete values which a decision variable can take. An ant can choose only one node at each layer using the state transition probability for going from node i to j which is calculated using the pheromone trail τ_{ij}, given in equation (3.22). In equation (3.22), k represents an ant, α the degree of importance of pheromones and $N_i^{(k)}$ set of neighbouring nodes when ant k is at node i.

Pheromone is the natural excretion an ant leaves at a node it traverses on its way back to nest from the food source [102] and [103]. The increment in pheromone deposit at the arc (i, j) by ant k is given by equation (3.23). Some of the pheromone evaporates as the ant moves to the next node given by equation (3.24) where A denotes the arcs traversed by the ant, thus the information about pheromone left at the arc (i, j) is calculated using equation (3.25). ρ is the pheromone evaporation rate.

$$p_{ij}^{(k)} = \begin{cases} \frac{\tau_{ij}^{\alpha}}{\Sigma_{j \in N_i^{(k)}} \tau_{ij}^{\alpha}} & if\, j \in N_i^{(k)} \\ 0 & if\, j \notin N_i^{(k)} \end{cases} \tag{3.22}$$

$$\tau_{ij} \leftarrow \tau_{ij} + \Delta\tau^{(k)} \tag{3.23}$$

$$\tau_{ij} \leftarrow (1-p)\tau_{ij}; \qquad \forall (i,j) \in A \tag{3.24}$$

$$\tau_{ij} = (1-\rho)\tau_{ij} + \sum_{k=1}^{N} \Delta\tau_{ij}^{(k)} \tag{3.25}$$

The path composed of arcs with higher pheromone deposits is chosen as the best path from the nest to the source of food and all ants then follow the best path. ACO algorithm also finds its application in designing routing algorithms for wireless multi-hop communication networks [104–107]. G*ü*nes *et al.* in [108] developed an on-demand routing algorithm for multi-hop MANETs based on ACO. The behavior of the ants has been used to determine the shortest path in networks. Two set of messages; Forward Ant (FANT) and Backward Ant

(BANT) are used for the route discovery. FANT is sent by the source whereas BANT by the destination. Each entry in the routing table of a node contains the destination address, the next hop and pheromone value. In [109] a hybrid routing algorithm HOPNET utilizing ACO is proposed which employs a combination of both proactive and reactive routing. Within a node's neighbourhood defined as zone, route discovery is carried out proactively whereas outside the zone reactive routing is deployed.

Fuzzy Systems

In conventional design problems, the objective functions and design parameters are formulated using explicit mathematical terms. However, in real life many design problems are described in vague linguistic terms. Systems involving vague and non-specific information are modeled using Fuzzy theory. Set theory provides the fundamental tool for conversion of a linguistic term into a computational framework. Considering the imprecise nature of fuzzy systems, a transition stage needs to be defined for design/ decision variables stating whether the attained value of decision variable belongs to the permissible set or not. The set $[0,1]$ is used to describe the permissible set and a characteristic function $\mu_A(x)$ to represent the affiliation/ membership of x in A such that

$$\mu_A(x) = \begin{cases} 1 & if\, x \in A \\ \\ 0 & if\, x \notin A \end{cases} \tag{3.26}$$

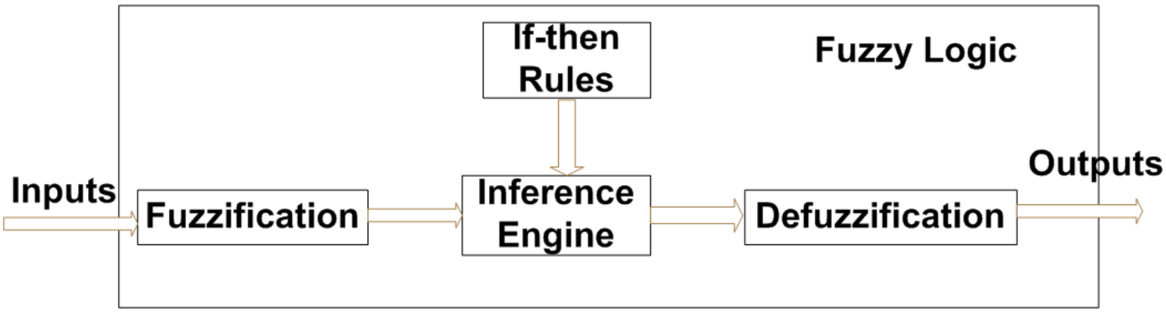
The closer the value of $\mu_A(x)$ is to 1, the more x belongs to A, i.e. the fuzzy value of design variable belongs to the permissible set. The optimization of fuzzy systems is obtained by the intersection of fuzzy objective functions and the fuzzy system constraints.

Humans and machines perceive information and perform reasoning in very different ways, humans reason in uncertain, imprecise and fuzzy ways while machines and the computers rely on binary reasoning. Fuzzy logic is a way to make machines more intelligent, enabling them to reason in a fuzzy manner like humans [110]. Fuzzy systems work on the principle of taking some inputs, performing logic operations on input parameters to make combinations of inputs and deciding the ranking of each combination using certain rules and then selecting the best combination as the output [111]. Thus the Fuzzy logic control system comprises of following components:

- Input fuzzy parameters
- Fuzzification process
- Fuzzy inference system
- Fuzzy rules
- Defuzzification process

In the process of fuzzification, crisp numerical input parameters are assigned specific static linguistic values. For example if we have two input parameters, say X and Y then we say that X can take values from the fuzzy set $X = \{weak, average, strong\}$ and Y from the fuzzy set $Y = \{low, medium, full\}$, then the output Z is determined by the fuzzy inference engine using if-then rules producing combination of membership functions of X and Y [112] and [3]. The elements of the fuzzy set are called the membership functions. The combination of membership functions of X and Y are termed as fuzzy rules, in the example stated above both X and Y can take value from fuzzy sets of size three each, thus we have 3$\times$3=9 fuzzy rules. Fuzzy rules have the form that if X takes a value a and Y takes a value b, then output Z will take value c.This mapping of fuzzy inputs to fuzzy output is determined by the fuzzy

Figure 3.3 Fuzzy logic control system [3]



inference system using the fuzzy rules. The generic form of fuzzy rules is given below:

$$\begin{cases} If\, X\, is A_1 \quad Then Y\, is B_1 \\ \dots \\ If\, X\, is A_n \quad Then Y\, is B_n \end{cases}$$

Defuzzification converts the linguistic outputs of the inference engine to numerical domain.The aim of defuzzification is to extract a crisp numeric value to best represent the linguistic output of the inference engine. Membership functions are used to describe the linguistic inputs as well as the linguistic outputs. Figure 3.3 presents the system diagram of a fuzzy controller . The operation of the fuzzy controller can be summarized using the below mentioned six steps ([110]):

- Identification of inputs, specifying the range of values they can take and labeling them.
- Identification of outputs and their range and labeling them.
- Generation of fuzzy membership function for every input and output.
- Construction of If-then rules to define the operation of the system
- Assignment of strength to rules deciding the execution of actions
- Combination of rules and defuzzification of output

Fuzzy logic has also been used to address the relay selection problem in cooperative communication. SNR, cooperative gain and channel gain have been utilized as fuzzy inputs to select the best relay for dual hop cooperative communication between the source and the destination in [111]. Kaiser *et al.* in [113] employed effective SNR and the total link delay as fuzzy input parameters for choosing the relay between the base station and the mobile station. In [114], a distributed algorithm for relay selection employing fuzzy logic has been proposed for cooperative sensor networks. The relay selection algorithm employs the relay-destination channel state information and relay's residual battery power as fuzzy input parameters which are then combined to determine the degree of relevance for each relay. The relay with highest degree of relevance is chosen to assist transmit the source's data to the sink node.

Neural-Network-Based Optimization:

The parallel processing capability and the massive computational power of neural networks make them suitable for solving problems with huge amount of sensory data. A neural network basically comprises a large number of interconnected neurons in which every neuron accepts inputs from other neurons and the computed output is then passed on to the output nodes [115] and [116]. Therefore, an artificial neural network can be defined using neurons, the network connectivity, the weights assigned to the interconnection between neurons and the activation function of each neuron. There is a weight associated with each input and the activity of a neuron is determined by the weighted sum of the inputs. The output is decided on the basis of the state of the neuron. An output is only produced when the activation level exceeds the threshold value.

Let w_i be the weight assigned to an input, then $a = \sum_{i=1}^{n+1} w_i x_i$ represents the weighted sum of the inputs.The n-dimensional input space is then mapped to a one-dimensional output using a simple function. This mapping of inputs to output is learned and the learning process comprises of finding the weights w_i which will give optimum mapping of the inputs and outputs of the neural network. A sigmoid function (equation 3.27) is usually utilized to describe the output of a neuron. The sigmoid function is capable of handling both large and small input signals. Each neuron is considered as an independent processor working in parallel with other neurons because the output of a neuron is determined only using inputs and the threshold value.

$$f(a) = \frac{1}{1+e^{-a}} \tag{3.27}$$

Kara *et al.* [117] addressed the error propagation problem in DF cooperative communication protocol for the best relay node selection. The error propagation problem occurs when the selected relay incorrectly decodes the signal received from the source and this erroneous re-encoded signal is forwarded to the destination. Artificial Neural Networks (ANNs) have been utilized to predict the optimum threshold value for selection of the best relay. The inputs to ANNs are the number of relays and the average quality of the source-relay, the relay-destination and the source-destination links. When there is no mathematical formula defining the relationship between the inputs and outputs, then ANNs are handy tools to generate the outputs for the given inputs. ANNs have usually three layers, the input layer, the hidden layer and the output layer. At the hidden layer different activation functions determine the relation between the inputs and outputs. ANNs have different types and Multi-layer Perceptron (MLP) and Radial Basis Function (RBF) networks are the two types used in [117]. The main difference between the two is that RBF is faster than MLP since it uses a Gauss function at hidden layer instead of a Sigmoid function.

In [118], Sankhe *et al.* also employed ANNs to predict the users situated in the neighbourhood of the source who are willing to participate in the cooperation process. The willingness of the neighbouring users depend on their battery power, time and day as well as the incentive being offered to them. Every user may use different criteria to determine its willingness. However, a specific pattern is followed by every user which is predictable. Neural networks along with PSO have also been used to determine optimal routes in MANETs [119]. Neural-network-based optimization is suitable for system consisting of large amount of data, with multiple system inputs and multiple outputs.

3.4 Game Theory

Game theory is a beneficial mathematical tool to be used in situations where the decision of one entity depends not only on its own environment but also on the decisions taken by other entities present in the system. For example in a game of chess, each player makes a move which is in his best interest to win the game, taking into account the move made by the other player. A game is defined as the framework which regulates the behaviour of a set of active entities and the gains they can achieve following the actions and decisions they can take [120]. An entity or agent will participate in a game if its benefit or gain is dependent not only on his actions but is also affected by the actions taken by the other agents playing the same game. The entities or agents that take part in a game and have decision making capability are called the players of the game. A player can be a company, a seller, a consumer or a node/ mobile user (in case of wireless networks). The principle of rationality governs the interaction between the players i.e. each player interacts rationally with the intention of maximizing its own gain and interest.

The set of possible decisions or actions a player can take is termed as the strategy set of that player. Each strategy provides a detailed specification of the manner a player intends to play the game from the start until the end of the game under the predefined rules of the game. Thus the strategy set of a player is basically a set of instructions dictating the actions to select in different situations [121]. There are two types of strategy: pure and mixed. When a player selects an action with certainty i.e. with a probability of 1 then the strategy of the player is termed as pure strategy. Whereas the probability distribution over the set of pure strategies constitute the mixed strategy.

Each player tends to maximize its benefit which is called the utility of that player. Depending on the nature of the game, the utility of a player can be monetary profit, achievable rate or extension of a node's lifetime. The strategy a player will follow depends on the utility of that player as well as the strategies other players will adopt. An equilibrium is achieved in a game when all players are satisfied with their individual utilities. Thus mathematically a game can be expressed as a triplet $G = (N, (S_i)_{i\in N}, (U_i)_{i\in N})$, where N is the set of players, S_i the set of available strategies for the player i and U_i is the utility (payoff) function of the ith player.

Depending on the number of players in a game, the nature of information accessible to each player and the interaction between players, a game can be classified into following categories:

- **Cooperative and Non-cooperative Games:** In a cooperative game, players agree to collaborate with one another and form a coalition to work towards maximizing the overall utility of the game [122]. However, when the players cannot enter into a coalition the game is termed as a non-cooperative game. In a non-cooperative game, each player works individually in order to maximize its own utility. Non-cooperative games are further classified into two types: zero-sum games and non-zero sum games. In zero-sum games also referred as constant sum games, the gain of one player is the loss of other player. Whereas in non-zero sum game, there is no restriction on the sum of utilities and all players can receive a gain or experience a loss together.

- **Perfect and Imperfect Information Games:** In perfect information game, the knowledge about what has already occurred in the game is available to players when they make their decision. Whereas in imperfect information game, a player is not aware of what decisions other players have taken while deciding its actions.

- **Complete and Incomplete Information Games:** In contrast to perfect and imperfect information games, the complete and incomplete information game is concerned with the information each player has on the elements of the game. If every player has full knowledge of the strategy space, possible utility of other player and so then such game is called complete information game. Potential game and Stackelberg game are example of complete information game. However, when information on elements of game is not publicly known to all players then such game is called incomplete information game and is commonly addressed using the Bayesian game. Details on Potential and Bayesian games can be found in [46] whereas Stackelberg game is discussed in chapter 4.

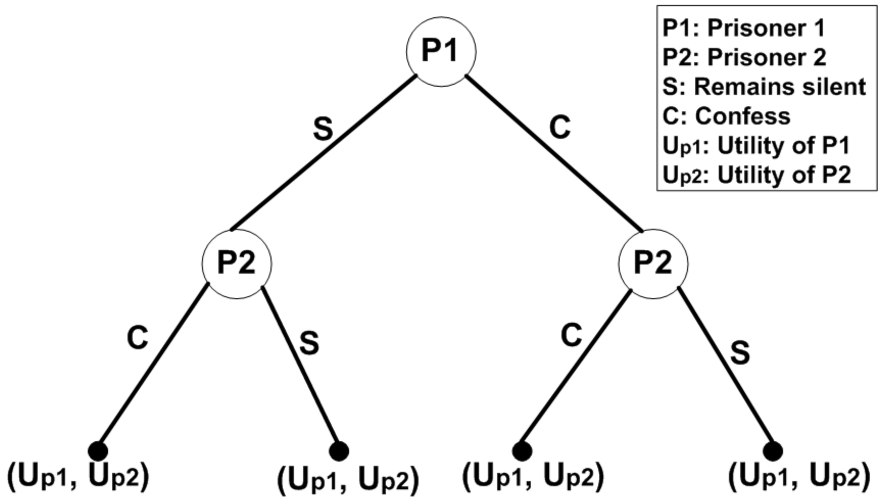
- **Normal-form and Extensive-form Games:** When a game is represented in a single turn and all players are simultaneously involved then such an illustration of a game is called a strategic or normal form. All possible combinations of strategies of all players and the utility associated with each strategy are shown in a tabular form. Table 3.1 presents the normal/ strategic form of the famous prisoner's dilemma game with strategy and utility of each prisoner. An extensive form of a game comprises of multiple turns and a decision tree is used to define the specifications of the game. A node in the tree depicts the player whose turn is to choose a strategy with branches indicating the set of available actions. The utility of each player is determined by following one of the possible routes in the tree from the root/ initial node to the terminal node [121]. Figure 3.4 depicts the extensive form of the prisoner's dilemma game with nodes representing the prisoners and branches showing the strategy sets of the prisoners.

  The prisoner's dilemma game presents a scenario of independent decision making in which two prisoners are individually interrogated. Each prisoner has two strategies, either confess the crime or remain silent. The strategy a prisoner chooses affects the utility of other prisoner. For example if both prisoners remain silent, there is no solid evidence against them and they will be set free. However, if one of them confesses and betrays the other, then the one who confesses is jailed for one year while the other is

Table 3.1 Normal/ strategic form of Prisoner's dilemma: prisoner 1 (p_1) , prisoner 2 (p_2)

	Confess	Silent
Confess	$(Utility_{p_1}, Utility_{p_2})$	$(Utility_{p_1}, Utility_{p_2})$
Silent	$(Utility_{p_1}, Utility_{p_2})$	$(Utility_{p_1}, Utility_{p_2})$

Figure 3.4 Extensive form game: Prisoner's dilemma



jailed for 3 years. If both of them confess, then their sentence is reduced to one year each.

- **Repeated Games:** When a game is played multiple times in a row with same set of rules, by same players having the same strategies set and utility functions then such a game is called a repeated game.The history of the game is used to determine the optimum strategy of a player.

The strategy that gives the highest payoff for a player irrespective of strategies chosen by the other players is called the dominant strategy and shall be taken as the solution to the game. But not in all games do all players have dominant strategies and the iterative strictly dominance procedure, i.e eliminating the dominated strategies of a player, can be used to find the solution of the game. However, the iterative dominance techniques are not sufficient in many cases in determining the solution of the game [46]. Thus the prediction of the equilibrium state between players is an important aspect of analysis of a game and determines the solution of the game. Equilibrium in game theory is basically the state in which no player wants to alter his strategy unilaterally given the strategies chosen by other players [122]. Existence of equilibrium is analyzed for non-cooperative games where each player selects the course of action individually. Nash equilibrium is the most widely used equilibrium concept in game theory. In Nash equilibrium, the strategy chosen by a player is the best response to the actions taken by other players.

3.4.1 Application of Game Theory in Communication Networks

Game theory finds its application in situations where there exists a conflict between decision making entities competing with one another to gain maximum utility [123]. Thus game theory has also been used to solve network design problems in telecommunication networks with its first utilization in developing pricing schemes for Internet services [124–127]. In addition to determining economic solutions, game theory has been deployed to address design issues like resource management, formulating network protocols, power, admission, flow and congestion control and performance optimization in computer networks. In wireless networks, especially in ad-hoc wireless networks composed of self-interested users/ nodes capable of independent individual decision making and adapting their mode of operation according to their environment, game theory is a more useful tool compared to other optimization techniques.

Due to the complexity of wireless networks resulting from dynamic network topology, unpredictable link quality and different mobility and traffic arriving patterns, each layer of Open Systems Interconnection (OSI) model presents completely different problems. Power control being the physical layer problem has been addressed by developing a non-cooperative power control game for Code Division Multiple Access (CDMA) and Orthogonal Frequency Division Multiple Access (OFDMA) systems [128, 129] and [130]. If a user keeps on increasing its transmit power to achieve better SINR, it is in reality worsening its SINR by forcing other users to increase their transmit power and adding harmful interference to the network. Thus game theory is a handy tool to encourage every user of the system to decide its transmit power considering the interference as well as the transmit power of other users present in the system [46]. Fair allocation of limited available spectrum among users of the network is another problem where game theory has been employed [131]. The concept of pricing which is essential for determining the utility function of the network users in any game has been used to study the spectrum assignment problem in cognitive radio networks [132].

Chen and Kishore proposed a repeated game to model the cooperative interaction between the selfish users, willing to forward other users' data towards the destination considering their future utility and payoff [133]. Game theory also finds its application at the data link layer handling the unfair access to the channel by selfish users [122]. The network layer in the OSI model is responsible for establishing paths between the source and the destination and forwarding packets on these paths. Since each source individually determines the optimal path to the destination and also the intermediate nodes forming the optimal route decides whether to assist the source-destination transmission or not, the role of game theory to address routing and forwarding problems in wireless networks is inevitable.

In order to control the load on the network, the admission of new service requests from users needs to be restricted and overloaded situations need to be resolved, which is carried out at the transport layer by triggering congestion control. Game theory has been used to determine the efficiency of the congestion avoidance mechanisms. The admission control game is played either among service providers or between the provider and the customer. When the game is between service providers, it is played in rounds. In each round, the request offering maximum utility is selected by the network provider [134]. However, in case of the game between the customer and the provider, utilities of both i.e utility of customer and utility of service provider need to be considered where the service provider tends to maximize its revenue and the customer wants to maximize the received QoS while minimizing the expenditure. A two tier game has been proposed in [135] for the cell selection and the resource assignment in the heterogeneous wireless networks. In first tier of the game, named the inter cell game, the cell is chosen by the mobile user considering its payoff. Whereas in the second tier i.e intra cell game, the mobile user selects the resource (time-frequency block) in the chosen cell to maximize its utility/ payoff.

In cooperative games, it is mostly assumed that the users are always willing to cooperate, however in reality they may behave selfishly or even cheat to increase their own individual payoff. Thus to encourage users to participate in the cooperative game, the users which assist the collaborative communication shall be rewarded whereas the selfish and the malicious users shall be punished. To discourage the selfish behaviour exhibited by the network users, two commonly used cooperative incentive mechanisms are: reputation based and credit based mechanisms [122]. The reputation of a node/ user in a wireless network basically represents its willingness to utilize its resources for other users of the network, which can be determined either centrally at a specialized central station or individually at each node. The main advantage of this approach is in detection of misbehaving selfish and/ or malicious nodes and isolating them, since the reputation of a node is computed based on observations from multiple entities [136]. However, there are several issues with reputation based mechanisms which have not been considered [137]. Firstly, the incentives given to the selfish nodes have not been properly analyzed, in order to earn good reputation, network users may be over generously using their resources, thus putting themselves at a loss. Secondly, the selfish nodes may conspire to increase their benefit which has not been considered in reputation based schemes. Also these schemes rely on broadcast nature of wireless channel to compute reputation which with the introduction of directional antennas will become difficult and challenging.

In credit based mechanisms, a user earns tokens or monetary benefits by assisting fellow users of the network. These token and monetary benefits compensate for the cost incurred by the cooperating users, which may be in terms of battery power or sharing of bandwidth or transmission time. The earned credits can then be utilized to purchase cooperation from other users when needed and thus putting the users with no credits at disadvantage. The relay selection algorithm proposed in this work employs a credit based mechanism to encourage the in-range primary users to take part in the data forwarding service, different credit based mechanisms are discussed in detail in section 3.5.

3.5 Credit Based Mechanisms and Pricing Schemes

Different credit based mechanisms and pricing schemes have been proposed for cooperative communication to motivate users to collaborate with one another and this subsection provides a brief analysis of some of these proposed methods. In [137], a simple credit based system is proposed by Zhang *et al.* to promote cooperation among selfish users of mobile ad-hoc networks. A centralized entity, the Credit Clearance Service (CCS), is responsible for receiving credits from the source node and distributing among the intermediate nodes assisting the source- destination communication. The source node pays for the data transmission to the destination node, the relaying nodes upon receiving and forwarding the source's data submit a receipt to CSS and the CSS upon receiving the message delivery receipt from the destination node makes payments to the helping intermediate nodes in the form of credits. Zhang *et al.* have analyzed their scheme from the prospective of security to avoid cheating from the selfish nodes colluding with each other.

The incentive based scheme suggested by Altman *et al.* [138] enforces cooperation among self-interested rational users by punishing the misbehaving users. Instead of an aggressive punishment in which on detection of a misbehaving node all other users of the network completely stop forwarding its messages, a less harsh policy is proposed. If the amount of messages forwarded by a user is less than that relayed by the other users of the network then a misbehaving user is identified and as a punishment other users will decrease the fraction of messages they were relaying for the misbehaving user. The proposed method leads to partial cooperation, thus giving some freedom to the network users to sometimes deliberately choose to save their resources for themselves and bear less aggressive punishment. Han *et al.* [139] also proposed a punishment based policy to enforce cooperation and to control transmission rate in wireless networks.

[140] by Han *et al.* is another work which has employed threat of punishment in future to promote cooperation among the self-interested users. They have formulated a framework in which a repeated game is used to enforce collaboration and a distributed self-learning process to determine optimal forwarding probability of each user of the network. Each user detects the greedy behaviour of other users by comparing its utility to a threshold value, if the utility is less than the threshold then it implies that some users are deviating for cooperation and as a punishment for a fixed period of time the user who detects the misbehaviour plays non-cooperatively. The punishment based incentive mechanisms will not work for the network scenario studied in this thesis because the in-range primary users do not need the out-of-range secondary users to access their data unless and until they move out of the transmission range of the access point or base station.

Crowcroft *et al.* in [141] devised an incentive model that stimulates mobile ad-hoc users to act as transit nodes and earn credits which can then be used to send their own traffic. When a user joins an ad-hoc network, it has some initial balance, which it can top up by relaying data for other users. The transit nodes determine the price of their service in a distributed manner considering the usage of their bandwidth and power. The traffic generating user considering its credit balance evaluates its willingness to pay to the intermediate transit nodes. The price the intermediate nodes ask for data delivery is deducted from the balance of the data generating node and the credit balance of helping nodes is incremented. The volume of data generated by a node is directly proportional to its credit balance and Crowcroft *et al.* demonstrated that it is beneficial for a node to move to those locations in the network where it can relay more data and earn more credits for its own traffic.

In wireless ad-hoc networks, the nodes are constrained in terms of their time and battery power usage which require them to act rationally and not to accept every relaying request. In [142], Srinivasan *et al.* have utilized the Generous TIT-FOR-TAT (GTFT) algorithm for a wireless ad-hoc node to determine whether to accept a relay request or refuse it. The GTFT algorithm is based on non-cooperative game theory and employs behavioural strategy in which each player takes its decision based on the past conduct of other nodes in the network. In GTFT algorithm, nodes are a bit generous since they accept to forward traffic for other nodes even if a reciprocal amount of help is not offered by other nodes. The decision of acceptance or rejection is made by nodes on per session basis in order to reduce the processing overhead.

Pricing mechanisms have also been used to incentivize selfish users to help the other users with low battery power to achieve energy saving [143]. Stackelberg games and genetic algorithms have been employed to develop the optimal pricing model for sharing of bandwidth in an integrated WiMAX and WiFi network in [144]. Shastry and Adve also formulated a pricing mechanism that induces cooperation among the source node and the relays which takes into account both the real energy cost incurred by the relay and the cost of delays relay's own data suffers [145]. In addition to stimulating cooperation among selfish users, pricing mechanisms have also been adapted to discourage users from exploiting the system's resource selfishly and degrading the performance of the system [146, 147] and [148].

Auction theory is another method to promote competition among selfish users with source nodes being the buyers offering bids and the relay nodes the sellers [149]. Two auction mechanisms were proposed by Huang *et al.* [150] which are indeed repeated games in which each user knowing the previous bids of other users iteratively updates its bid in order to maximize its own utility. Auction based schemes require a central controlling entity called the auctioneer to govern the interaction between the seller and the buyer.

In short, the credit and pricing based mechanisms can be divided into three main categories. The first category of credit and pricing mechanisms utilize the threat of future punishment to enforce the network users to cooperate with each other. The second category provides the network users with opportunities to earn credits and tokens which they can use later when needed, giving them incentives to help each other. Whereas the third category of credit and pricing mechanisms employs auction theory to promote collaboration among network users.

3.6 Proposed Methodology

Optimization theory as well as game theory have been extensively used to address the relay selection problem in wireless networks. The mathematical model for the rural wireless network extension problem using the in-range ordinary users stated in section 2.6 has been developed in section 3.2. The formulated mathematical model is a multi-objectives programing problem with the objectives of maximizing the utility of the primary users, the utility of the secondary users and minimizing the relaying cost experienced by the primary users in terms of battery power consumption. These three objective functions are conflicting in nature and the decision variables x_{ij}, P_{ij} and p_{ij} used to model this multi-objectives problem take values from binary, integer and real domain respectively. The usage of optimization theory to determine optimal solution to this multi contradicting objectives problem with mixed decision variables taking values from binary to integer to real domain is mathematically expensive. Sub-optimal solutions can be determined but with compromise on either the utility of the primary users or the utility of the secondary users or ignoring the fair utilization of battery power of the primary users.

Game theory, on the other hand, is a useful tool for addressing problems arising due to conflict of interests between different entities who only care about their own benefit. Game theory tends to determine an equilibrium point without compromising the interests of any entity from which no entity wants to deviate unilaterally. It provides incentives to the selfish entities and users to cooperate with one other. In the research problem studied in this thesis, the willingness of the primary users to assist the secondary users depends on the price it receives from the secondary user for its service. Whereas the decision of the secondary user whether to accept the services of a particular primary user or not is dependent on the utility the primary user can offer. Thus the decision made by the primary user affects the strategy chosen by the secondary user. In such scenarios comprising of interdependent decision making, game theory provides the right tool set. Hence, a heuristic solution based on game theory utilizing a Stackelberg game in particular owing to its seller-buyer configuration has been proposed to solve the relay selection problem in rural wireless networks in this thesis. The literature employing game theory to address the relay selection problem in wireless networks has been analyzed in detail in section 2.4. The proposed solution provides incentives to the self-interested primary users to participate in relaying data to the secondary users and earn credits for themselves, at the same time ensuring the battery power of all primary users present in the network is utilized fairly. Details on the Stackelberg game and its usage in developing a heuristic relay selection solution in a rural wireless environment is given in chapter 4.

Chapter 4

Relay Selection Algorithm

As discussed in chapter 2, when it comes to the selection of relays, very little attention has been paid to the physical layer fairness i.e. the fair utilization of battery power of relays. In the research problem studied in this thesis, the relays are the primary users. In this chapter, two relay selection solutions emphasising on the fair consumption of battery power of the selfish relays are proposed. The first solution, Fair Battery Power Consumption (*FBPC*) relay selection algorithm, employs the concept of proportional fairness when assigning the primary users as relays. The *FBPC* algorithm uses the ratio of cumulative to instantaneous battery power consumption as the relay selection criterion to ensure that the battery power of all primary users in the network is fairly utilized. Since the *FBPC* algorithm does not incentivize the primary users to participate in the relay selection process, a second relay selection solution, the Credit based Fair Relay Selection (*CF-RS*) protocol, utilizing a Stackelberg game is also proposed in this chapter. In addition to achieving the fair dissipation of battery power of the primary users, the *CF-RS* protocol exploits a credit-based mechanism to motivate the primary users to actively and generously help the secondary users providing better utility to both the primary and the secondary users.

Unlike the literature discussed in sections 2.3, 2.4 and 2.5, the *CF-RS* protocol takes into account of the selfish nature of the primary users and their concern regarding the fair consumption of their battery power simultaneously when determining the willingness of the primary users to relay data for the secondary users. This chapter also provides a detailed mathematical analysis of the *CF-RS* protocol. A pricing function has also been derived to compensate the primary users for utilizing their battery power relaying data and information to the secondary users.

4.1 Fair Battery Power Consumption (*FBPC*) Relay Selection Algorithm

The concept of proportional fairness has been used in formulation of the *FBPC* relay selection algorithm. The algorithm takes into account the instantaneous battery power consumed by a relay i.e. by the primary user for a particular transmission to the secondary user as well as the cumulative battery power the relay has spent using equation(4.1)

$$U = \frac{\overline{CBP_i}}{CBP_{ij}} \tag{4.1}$$

where i represents the primary user, j is the secondary user, $\overline{CBP_i}$ the cumulative battery power expenditure of i, CBP_{ij} the current battery power required for successful data transfer between i and j and U the cost the primary user experiences while providing assistance to the secondary users. The objective of the *FBPC* algorithm is to achieve fair utilization of battery power of relays which is obtained by minimizing the cost incurred by a relay i.e minimizing its cumulative to current battery power dissipation.

Unlike the relay selection techniques described in sections 2.4 and 2.5, in the *FBPC* algorithm the primary users behave obediently only until their battery power is greater than a predefined threshold value. After reaching the threshold battery power level, the primary users do not accept any data relaying request from the secondary users.

In *FBPC* algorithm, the secondary user first sends a request to all primary users asking for their assistance. On receiving the request, each primary user determines whether it is in the transmission range of the access point and the secondary user or not. The primary user then checks its battery power which should be greater than the predefined threshold value. If the conditions on transmission range and battery power are not met, the primary user declines the secondary user's request. Otherwise the primary user calculates its cost i.e. the ratio of its cumulative battery power consumption to its current battery power expenditure for a particular secondary user and replies to the secondary user with its cost. The secondary user selects the primary user with the minimum $\frac{\overline{CBP_i}}{CBP_{ij}}$ as the relay and sends acknowledgement to that primary user. The selected primary user updates its cumulative battery power consumption and informs the AP to send the data requested by the secondary user. Initially the cumulative battery power spent by each relay is set to zero and is updated as it serves the secondary users. The power primary user will be using for providing the relay service is distance dependent i.e. $P_{ij} \propto d_{ij}$ and its battery power will be consumed accordingly i.e. $CBP_{ij} \propto P_{ij}$.

Different steps of the *FBPC* algorithm are shown in Figure 4.1 in the form of a flowchart and table 4.1 summarizes the parameters used in the *FBPC* algorithm.

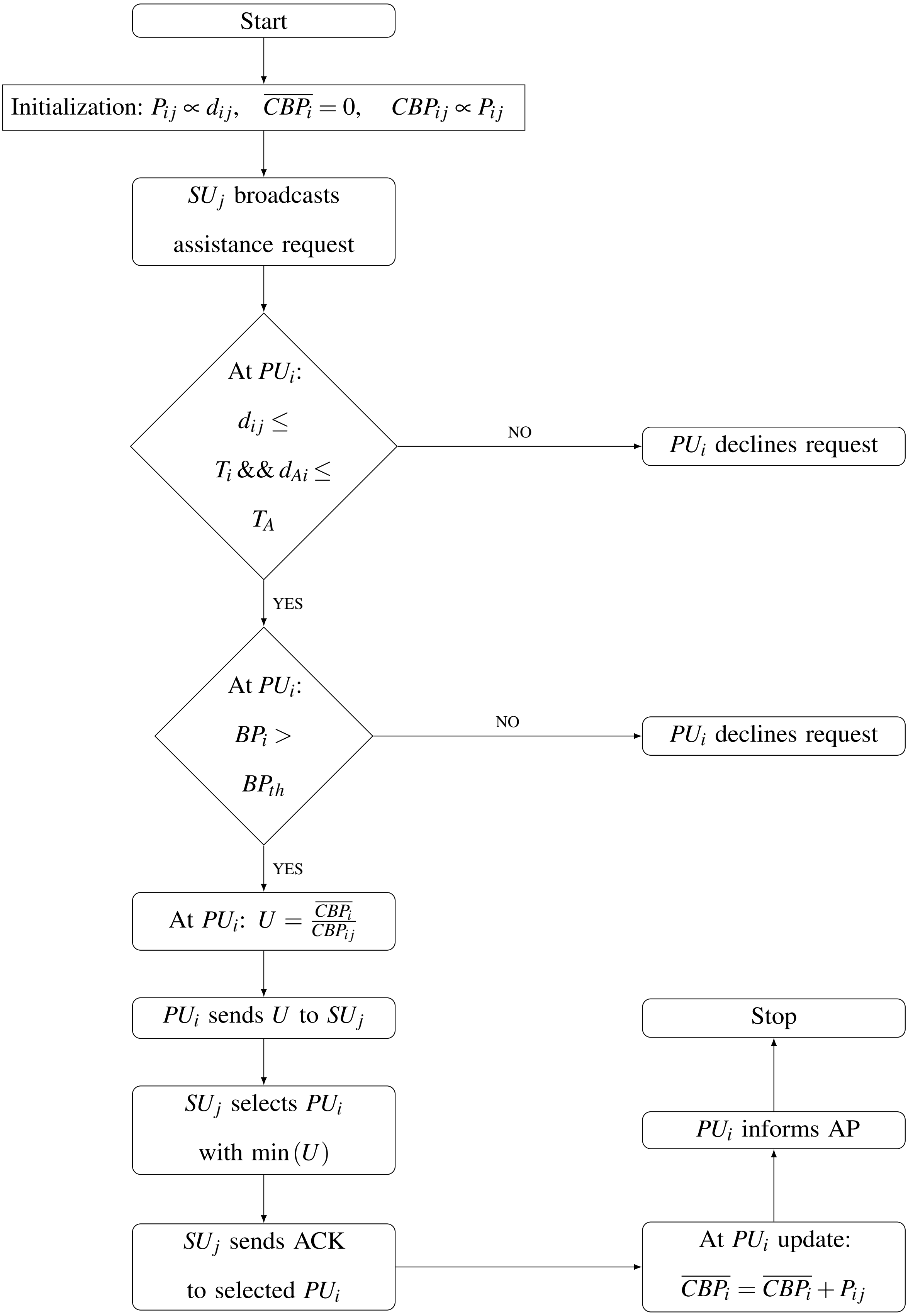


Figure 4.1 Flowchart for Fair Battery Power Consumption (FBPC) Algorithm

Table 4.1 Parameters used in *FBPC* algorithm

Symbol	**Parameter**
$i \in N$	Set of primary users (PU)
$j \in N$	Set of secondary users (SU)
d_{ij}	Distance between PU i and SU j
d_{Ai}	Distance between PU i and access point
T_i	Transmission range of PU i
T_A	Transmission range of access point
P_{ij}	Transmission power of PU i for SU j
BP_i	Battery power of PU i
BP_{th}	Threshold battery power
CBP_{ij}	Battery power consumption for current transmission
$\overline{CBP_{ij}}$	Cumulative consumed battery power of PU i
U	Cost incurred by PU i

Since the *FBPC* algorithm focuses on fair utilization of battery power of the primary users, the Jain's fairness Index [151], a commonly used metric for measuring fairness given by equation(4.2), has been employed to determine how fairly the battery power of relays is being consumed when the *FBPC* algorithm is used for the relay selection. Equation(4.2) has been modified to calculate the fairness index for consumption of battery power of relays according to equation(4.3).

$$f(X) = \frac{[\sum_{i=1}^{N} x_i]^2}{N \sum_{i=1}^{N} x_i^2} \tag{4.2}$$

$$f(X) = \frac{[\sum_{i=1}^{N} CBP_i]^2}{N \sum_{i=1}^{N} CBP_i^2} \tag{4.3}$$

where N is the number of available primary users.

4.1.1 Shortcomings of *FBPC* Algorithm

The *FBPC* algorithm tends to minimize the cumulative battery power consumption to ensure that the battery power of all the relays in the network is fairly used. This may result in choosing the relays with poor channel quality and thus compromising the maximum achievable data rate at the secondary users. In the *FBPC* algorithm, it has also been assumed that the primary users are obediently willing to provide the data forwarding service to the out-of-range secondary users as long as their battery power is greater than a predefine threshold level. However, when a primary user relays data for a secondary user, it experiences a cost in terms of depletion of its battery power. Apart from its battery power being fairly consumed, it also needs to be compensated for the cost it suffered. The compensation can be in the form of an immediate gain or in the form of a long term benefit. Thus a relay selection scheme for a rural wireless network comprising of self-interested users is required to take into account both the fair utilization of the battery power of relays and the achievable data rate along with providing incentives to the in-range primary users to happily and eagerly participate in the relaying process to gain some benefit.

4.2 Credit Based Fair Relay Selection (*CF-RS*) Game

To compensate for the deficiencies of the *FBPC* algorithm, a Credit based Fair Relay Selection (*CF-RS*) game has been developed as a new protocol for fair distribution of relaying operation. The aim of this game is to ensure fair consumption of battery power along with providing better achievable data rate at all secondary users. This game employs a credit-based mechanism to encourage the primary users to relay data for the secondary users.

Game theory and Stackelberg game, in particular, have been extensively used in literature to address the relay selection problem in wireless networks ([22, 11, 64–66]), considering the benefits of both the relays and the end users which in the considered network model are the out-of-range users. Stackelberg game is a seller buyer/ leader follower game in which both the seller/ leader and the buyer/ follower try to maximize their own benefit [46]. Just like any game, Stackelberg game comprises of three parameters:

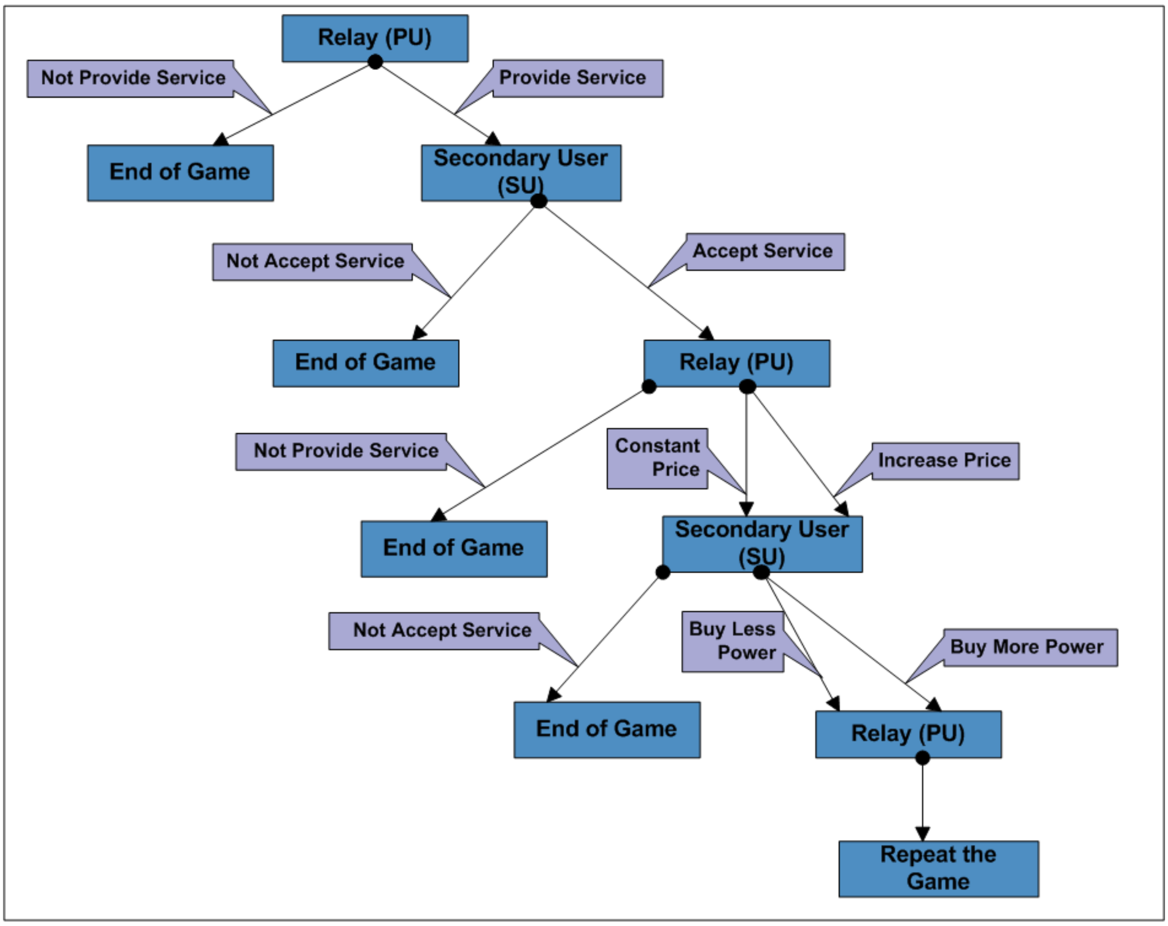
- The set of players
- The strategy set of each player
- The utility function of each player

Strategy set of a player consists of all possible actions the player can take in order to maximize its utility. Utility function of a player takes into account the benefit the player gains by following a particular strategy as well as the cost incurred by adopting that strategy.

The proposed *CF-RS* game consists of two sets of players: the set of primary users and the set of secondary users. The primary user is the seller in the *CF-RS* game since it is selling its data forwarding service, whereas the secondary user is the buyer of this data forwarding service. In the beginning of the *CF-RS* game, the primary user determines whether to provide data forwarding service to a particular secondary user or not by analyzing its own utility. Depending on which strategy the primary user decides to follow, the secondary user determines whether to accept the data forwarding service from the primary user or to refuse the service. If the secondary user denies the offer of a service, the game ends. After providing the service to the secondary user, the primary user makes a decision on whether to:

1. Increase the price of its service
2. Keep the price constant
3. Or not to provide service any further

Figure 4.2 Extensive form of Credit based Fair Relay Selection (*CF-RS*) game



On the basis of the price advertised by the primary user, the secondary user can choose from three possible strategies; which are:

1. Buy more power from the primary user
2. Buy less power
3. Or not to accept the service

The game ends when the primary user decides not to participate in the relaying process or when secondary user rejects the service of the primary user. Figure 4.2 presents the extensive form of *CF-RS* game along with the strategy set of each player at each step of the game.

The strategy a player follows at each step of the game is determined using the utility function of the player. The utility function of the primary user has been defined as the difference between the price per unit power paid by the secondary user and the cost of the relay, experienced while providing data forwarding service given in equation(4.4).

$$U_i = p_{ij}P_{ij} - c_{ij} \tag{4.4}$$

p_{ij} is the price per unit power advertised by the primary user i for secondary user j and P_{ij} is the amount of transmission power the secondary user j buys from the primary user i. The smaller the price per unit power, the larger the transmission power bought by the secondary user. The amount of transmission power should not exceed the maximum allowable power i.e. $P_{ij} \leq P_{max}$. In the case of WiFi, for example, the maximum allowable transmission power is limited to 20dBm or 100mW [152]. The price advertised by the relay should be greater than its cost in order to be incentivized to participate in the data relaying service. This is why the primary user is termed as the leader of the game, i.e. the primary user sets the price of its service and the secondary user has to pay that price if it wants to avail service from that primary user. The decision on availing assistance from a particular primary user is made by the secondary user considering its budget. The secondary user asks itself the question do I have enough budget to pay for the primary user's help? The payment made to the primary user becomes its credit, which the primary user can utilize to buy the data forwarding service for itself when it cannot directly communicate with the access point.

The secondary user also takes a decision on which strategy to adopt at each step of the game using its own utility function, given in equation(4.5), which is defined as difference between the normalized achieved data rate via a primary user and the price paid to that primary user. The primary user as well as the secondary user tends to maximize their utility functions. The *CF-RS* game makes the primary and the secondary users opt for a strategy that results in providing benefit for both types of users.

$$U_j = R_{ij} - p_{ij}P_{ij} \tag{4.5}$$

The primary user also needs to decide on the price it shall advertise for its service in order to attract more secondary users. Along with attracting the secondary users, the primary user acting as a relay is always concerned about its own cost in terms of its battery power consumption. Similar to the *FBPC* relay selection algorithm, the cost function used in the *CF-RS* game takes into account the instantaneous power dissipation of the primary user for a particular secondary user as well as its cumulative battery power consumption as given in equation(4.6).

$$c_{ij} = \frac{\overline{CPB_i}}{CBP_{ij}} \tag{4.6}$$

Since each primary user wants to minimize its relaying cost and to maximize its own utility, this formulation of the cost function of the primary users utilizing the concept of proportional fairness provides fair opportunity to each primary user to participate in the relay selection process. This fair participation results in diminishing the monopoly of the primary users located close to the secondary users from being repeatedly selected as relays as well as results in fair utilization of battery power of all the primary users present in the network. Equation(4.3) is again used to determine how fairly the battery power of primary users is used. Since the achievable data rate is also considered when choosing the relay, the results discussed in Chapter 5 depict that there is no compromise in terms of attainable data rate.

4.3 Mathematical Analysis of *CF-RS* Game

This section provides the mathematical analysis of the *CF-RS* seller buyer game. The aim of this analysis is to obtain the closed-form solution to the proposed *CF-RS* game, i.e. the optimal power the secondary user shall purchase from the primary user and the optimum price the primary user shall advertise for providing the relaying service. In this section, first the game is analyzed from the perspective of the secondary user, determining the mathematical expression for the optimal power it shall buy from the primary user in order to maximize its utility. Then the calculation of the optimal price per unit power that a primary user shall advertise for its service has been carried out.

4.3.1 Analysis of the Secondary User's Game: Buying Power

In order to maximize its utility, the secondary user chooses the suitable relay considering the price advertised by the relay and decides on how much power it shall buy from the relay. Secondary user's best response can be calculated by taking the derivative of equation(4.5).

$$\begin{aligned}\frac{\partial U_j}{\partial P_{ij}} &= \frac{\partial R_{ij}}{\partial P_{ij}} - p_{ij}\frac{\partial P_{ij}}{\partial P_{ij}} \\ &= \frac{\partial R_{ij}}{\partial P_{ij}} - p_{ij}\end{aligned} \tag{4.7}$$

where from section 3.1, $R_{ij} = W\log_2(1+SINR)$ and $SINR = \frac{P_{Ai}P_{ij}G_{Ai}G_{ij}}{\sigma^2\left(P_{Ai}G_{Ai}+P_{ij}G_{ij}+\sigma^2\right)}$. Let $A = \frac{P_{Ai}G_{Ai}}{\sigma^2}$, $B = \frac{P_{Ai}G_{Ai}+\sigma^2}{G_{ij}}$ and $\overline{W} = \frac{W}{\ln 2}$

$$R_{ij} = \overline{W}\ln\left(1+\frac{AP_{ij}}{P_{ij}+B}\right) \tag{4.8}$$

Substituting equation 4.8 in equation 4.7, we get

$$\begin{aligned}\frac{\partial U_j}{\partial P_{ij}} &= \frac{\partial}{\partial P_{ij}}\left\{\overline{W}\ln\left(1+\frac{AP_{ij}}{P_{ij}+B}\right)\right\} - p_{ij} \\ &= \frac{\partial}{\partial P_{ij}}\left\{\overline{W}\ln\left(\frac{P_{ij}+B+AP_{ij}}{P_{ij}+B}\right)\right\} - p_{ij} \\ &= \overline{W}\left\{\frac{1+A}{(1+A)P_{ij}+B} - \frac{1}{P_{ij}+B}\right\} - p_{ij}\end{aligned}$$

After performing simplification, we have

$$\frac{\partial U_j}{\partial P_{ij}} = AB\overline{W} \left\{ \frac{1}{(1+A)\,P_{ij}^2 + (2B+AB)\,P_{ij} + B^2} \right\} - p_{ij} \tag{4.9}$$

The second order partial derivative of U_j is calculated by equation(4.10)

$$\begin{aligned} \frac{\partial^2 U_j}{\partial P_{ij}^2} &= AB\overline{W} \left[\frac{-1\left\{2\,(1+A)\,\frac{\partial P_{ij}}{\partial P_{ij}} + 2B + AB\right\}}{\left\{(1+A)\,P_{ij}^2 + (2B+AB)\,P_{ij} + B^2\right\}^2} \right] \\ &= -AB\overline{W} \left[\frac{2\,(1+A) + 2B + AB}{\left\{(1+A)\,P_{ij}^2 + (2B+AB)\,P_{ij} + B^2\right\}^2} \right] \end{aligned} \tag{4.10}$$

Since $\frac{\partial^2 U_j}{\partial P_{ij}^2} < 0$, this implies that the function U_j given in equation(4.5) is strictly concave and the local maximum at P_{ij} is also the global maxima. Thus P_{ij} maximizes the utility function of the secondary user. By equating $\frac{\partial U_j}{\partial P_{ij}} = 0$, the optimal power the secondary user shall buy from the primary user can be obtained as given in equation(4.11)

$$\begin{aligned} AB\overline{W} &= p_{ij}\left\{(1+A)\,P_{ij}^2 + (2B+AB)\,P_{ij} + B^2\right\} \\ p_{ij}\,(1+A)\,P_{ij}^2 + (2B+AB)\,p_{ij}P_{ij} + p_{ij}B^2 - AB\overline{W} &= 0 \end{aligned} \tag{4.11}$$

Solving the quadratic equation, we acquire

$$P_{ij} = \frac{-p_{ij}\,(2B+AB) \pm \sqrt{ABp_{ij}\left\{ABp_{ij} + 4\overline{W}\,(1+A)\right\}}}{2p_{ij}\,(1+A)} \tag{4.12}$$

Since transmission power cannot be less than zero, equation 4.12 becomes

$$P_{ij} = \frac{-p_{ij}\,(2B+AB) + \sqrt{ABp_{ij}\left\{ABp_{ij} + 4\overline{W}\,(1+A)\right\}}}{2p_{ij}\,(1+A)} \tag{4.13}$$

Equation(4.13) gives the optimal power the secondary user shall procure from the primary user in order to maximize its own utility. From equation(4.13), it can be seen that the optimal power depends on the channel gains of the AP-primary user and the secondary-primary users links, the available bandwidth as well as the price advertised by the primary user for its data forwarding service.

4.3.2 Analysis of the Primary User's Game: Advertising Price

The primary user maximizes its utility by selecting an appropriate price for its unit power. Primary user's best response can be calculated by taking the partial derivative of equation(4.4).

$$\frac{\partial U_i}{\partial p_{ij}} = P_{ij} = \frac{-p_{ij}\left(2B+AB\right)}{2p_{ij}\left(1+A\right)} + \frac{\sqrt{ABp_{ij}\left\{ABp_{ij}+4\overline{W}\left(1+A\right)\right\}}}{2p_{ij}\left(1+A\right)} \tag{4.14}$$

The second order partial derivative of U_i can be calculated by equation(4.15)

$$\frac{\partial^2 U_i}{\partial p_{ij}^2} = \frac{\partial}{\partial p_{ij}}\left\{\frac{-p_{ij}\left(2B+AB\right)+\sqrt{ABp_{ij}\left\{ABp_{ij}+4\overline{W}\left(1+A\right)\right\}}}{2p_{ij}\left(1+A\right)}\right\} \tag{4.15}$$

By solving equation 4.15, we obtain

$$\begin{aligned}\frac{\partial^2 U_i}{\partial p_{ij}^2} &= \frac{-4\overline{W}\left(1+A\right)^2 ABp_{ij}}{4p_{ij}^2\left(1+A\right)^2\sqrt{A^2B^2p_{ij}^2+4\overline{W}ABp_{ij}}} \\ &= \frac{-\overline{W}AB}{p_{ij}\sqrt{A^2B^2p_{ij}^2+4\overline{W}ABp_{ij}}}\end{aligned} \tag{4.16}$$

Since $\frac{\partial^2 U_i}{\partial p_{ij}^2} < 0$, therefore the function U_i given in equation(4.4) is strictly concave and there exists an optimal price p_{ij} which will maximize the utility function of the primary user. By equating $\frac{\partial U_i}{\partial p_{ij}} = 0$, the value of p_{ij} is determined as given below

$$
\begin{aligned}
-p_{ij}(2B+AB)+\sqrt{A^2B^2p_{ij}^2+4\overline{W}(1+A)ABp_{ij}} = 0 \\
p_{ij} = \frac{\overline{W}(1+A)AB}{B^2(1+A)} = \frac{\overline{W}A}{B}
\end{aligned}
\qquad (4.17)
$$

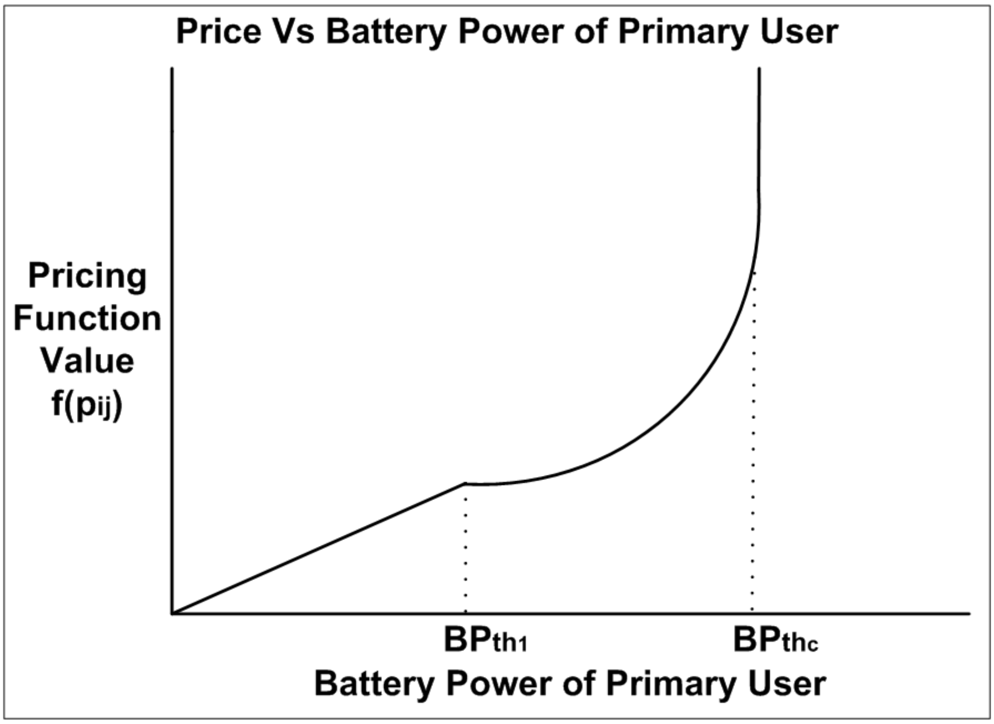
Equation(4.17) presents the optimal price the primary user shall advertise for providing assistance to the secondary user in order to maximize its own utility. Equation(4.17) shows that the value of optimal price is dependent on the available bandwidth and the channel gains of the AP-primary user link and the primary user-secondary user link.

4.4 Derivation of Pricing Function

The mathematical expression for the optimal price derived in subsection 4.3.2 shows that the optimal price a primary user shall advertise for its service depends on the available bandwidth W and the channel gains of the access point-primary user link and the primary user-secondary user link. However, in order to achieve fair utilization of battery power of the primary users participating in the data forwarding service, the primary users should also take into account their cost i.e. their battery power consumption in the calculation of the optimal price. This implies that the cost incurred while relaying data shall be considered in determining the optimal price. The cost of relaying in the model proposed in this thesis is given by $c_{ij} = \frac{\overline{CBP_i}}{CBP_{ij}}$.

In order to promote competition among the primary users, two threshold values for primary user's battery power consumption have been defined in *CF-RS* game. When the battery power of the primary user is greater than or equal to the first threshold BP_{th_1}, the primary user increases its price linearly with depletion of its battery power. Beyond BP_{th_1} until the battery power is greater than the second threshold BP_{th_c}, the critical threshold, the price will be increased exponentially to force the secondary users to avail services of other

Figure 4.3 Graphical representation of pricing function given in equation(4.18)



primary users located a bit far from them or with not best channel conditions and when the battery power is depleted to BP_{th_c}, the primary user will no longer participate in the relaying process till its battery is fully charged again. The idea of introducing two threshold values is to provide a fairer chance to each primary user to earn some benefit by relaying data for the secondary users and at the same time not to overly consume their battery power. Thus the optimal pricing function for the primary users derived in subsection 4.3.2 has been modified to incorporate the cost experienced by the primary users and the threshold values for their battery power expenditure. The modified pricing function is given in equation(4.18) and is depicted in Figure 4.3.

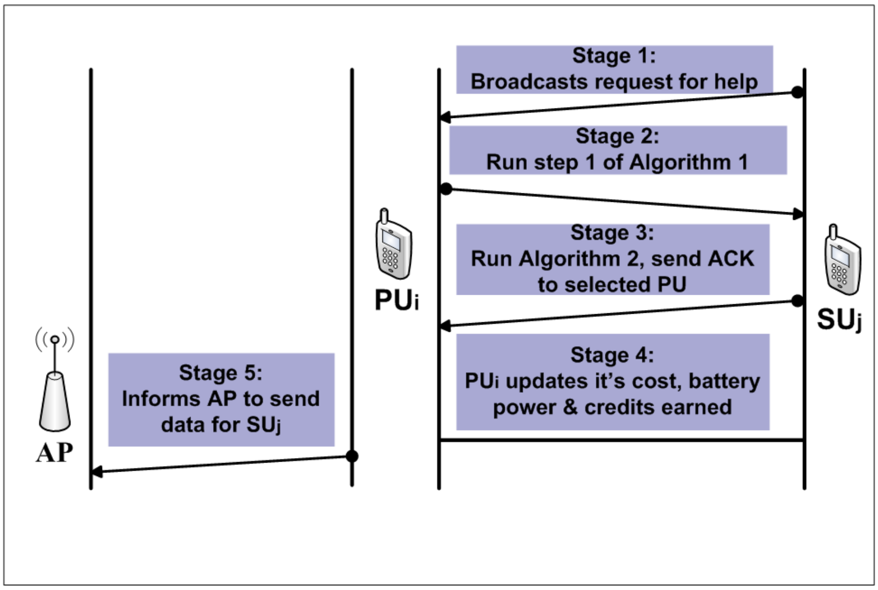
$$f\left(p_{ij}\right) = \begin{cases} p_{ij} + c_{ij}t & BP_i \geq BP_{th_1} \\ p_{ij}e^{c_{ij}t} & BP_{th_1} > BP_i > BP_{th_c} \\ \infty & \text{otherwise} \end{cases} \tag{4.18}$$

Since the price advertised by the primary users is the factor controlling the fair utilization of battery power of the primary users, therefore the pricing function defined by equation(4.18) takes into account the initial price p_{ij} calculated using channel gains and bandwidth as well as the cost c_{ij} suffered as a result of providing data forwarding assistance. In equation(4.18), t is the number of iterations i.e. the number of times the same primary user has been approached by a secondary user for data relaying service. The purpose of initially increasing the price linearly is that the secondary users can receive assistance from the primary users with best channel conditions providing maximum data rate. However, as the battery power of the best primary users is dissipated beyond BP_{th_1}, they need to push the secondary users towards other primary users to conserve their battery power. Thus beyond BP_{th_1}, until the battery power is greater than BP_{th_c}, the price is incremented exponentially with respect to the cost.

4.5 Credit Based Fair Relay Selection (*CF-RS*) Protocol

Credit based Fair Relay Selection (*CF-RS*) protocol is based on the *CF-RS* game described in section 4.2. The *CF-RS* protocol provides the framework for the implementation of the *CF-RS* game. It outlines the set of steps the primary and the secondary users will follow when they interact with one other and the messages that will be exchanged regarding the willingness of the primary users to help the secondary users and the price of their relaying service. The aim of the *CF-RS* protocol is the same as that of the *CF-RS* game i.e. to achieve fair utilization of battery power of the primary users without compromising the attainable data rate at the secondary users. The same credit-based mechanism described for the *CF-RS* game in section 4.2 is employed to incentivize the primary users to assist the secondary users. In the *CF-RS* protocol for simplification, it has been considered that a secondary user can obtain service from only one primary user at a time, thus buying all available transmission power from that primary user. Also whenever a primary user assists a secondary user, it

Figure 4.4 Various stages of *CF-RS* protocol



will always increase its price in order to compensate for its cost and will only keep its price constant when it is not helping any secondary user.

The *CF-RS* protocol consists of five stages process as illustrated in Figure 4.4. Stage 1 comprises of each secondary user sending a broadcast message with a request of assistance for its data transmission and reception. In stage 2, each primary user in the range of the secondary users as well as the access point runs step 1 of algorithm 1 to determine its willingness to help the secondary users. Willingness of the primary user depends upon its available battery power BP_i being greater than critical threshold value BP_{th_c} and its utility being greater than zero i.e. $U_i > 0$. The primary user calculates its cost for each secondary user present in the network using the cumulative to instantaneous power dissipation ratio $(\frac{\overline{CPB_i}}{CBP_{ij}})$. The power primary user will be using for providing the relay service is distance dependent i.e. $P_{ij} \propto d_{ij}$ and its battery power will be consumed accordingly i.e. $CBP_{ij} \propto P_{ij}$. The primary user i then uses equation (4.18) to determine the price of its data forwarding service for secondary user j depending on its battery power BP_i . The primary user then sends an acknowledgment (ACK) message to the secondary users along with the price for its services.

Algorithm 1 :Stage 2 of Credit based Fair Relay Selection (*CF-RS*) Algorithm

Initialization
$P_{ij} \propto d_{ij}, \quad \overline{CBP_i} = 0, \quad CR_i = 0\ , \quad U_i = 0$
Request received from SU_j
$CBP_{ij} \propto P_{ij}$
if $d_{ij} \leq T_i$ && $d_{Ai} \leq T_A$ **then**
  Step 1: Willingness Determination
  if $BP_i > BP_{th_c}$ **then**
    Calculate cost $c_{ij} \leftarrow \frac{\overline{CBP_i}}{CBP_{ij}}$
    Calculate p_{ij} using equation (4.18)
    if $U_i > 0$ **then**
      Send ACK to SU_j along with p_{ij}
    end if
  end if
end if
Step 2: Accepted as Relay
Update cumulative battery power consumption PU_i: $\overline{CBP_i} \leftarrow \overline{CBP_i} + P_{ij}$
Update credits earned by PU_i: $CR_i \leftarrow CR_i + p_{ij}$

The secondary user then runs algorithm 2 in stage 3 of the *CF-RS* protocol. Algorithm 2 checks whether the secondary user's budget to pay for its whole data transmission using the service of the primary user is greater than the price advertised by the primary user or not. A finite budget has been considered for each secondary user to pay for the price advertised by the primary user for its relaying service in the *CF-RS* protocol, which is the case in real wireless networks comprising of self-interested users. The secondary user then calculates its utility for all the primary users which fulfill the criteria of available budget. The primary user

Algorithm 2 Stage 3 of Credit based Fair Relay Selection (*CF-RS*) Algorithm

Received ACK from primary users
for $i = [1, 2, ..., N]$ **do**
  if $\beta_j > p_{ij}$ **then**
    Calculate utility of SU_j: $U_j \leftarrow R_{ij} - p_{ij}$
  end if
end for
$I \leftarrow \max\left(U_j\right), \quad I$ is selected as relay
Update budget of SU_j: $\beta_j \leftarrow \beta_j - p_{ij}$
Inform the selected PU_i

providing the maximum utility is selected as the relay by the secondary user. The secondary user updates its budget subtracting the price it pays for the services and informs the selected primary user. In stage 4, the primary user updates its cumulative battery power consumption $\overline{CPB_i}$, its cost and the price it receives from the secondary user is added to its credits CR_i. The selected primary user informs the access point to send the data of secondary user i to it in stage 5.

The purpose of accumulation of credits is to utilize them to buy data forwarding service when the in-range primary user moves out of the coverage of the access point and becomes the out-of-range secondary user. The same *CF-RS* protocol is used by both the primary and secondary users when they switch their positions, with only difference of credits of a node (which was primary user before) become its budget. Section 4.6 describes this scenario of switching of roles and how the *CF-RS* protocol will be deployed in that situation. Parameters used in *CF-RS* protocol are listed in table 4.1 and 4.2.

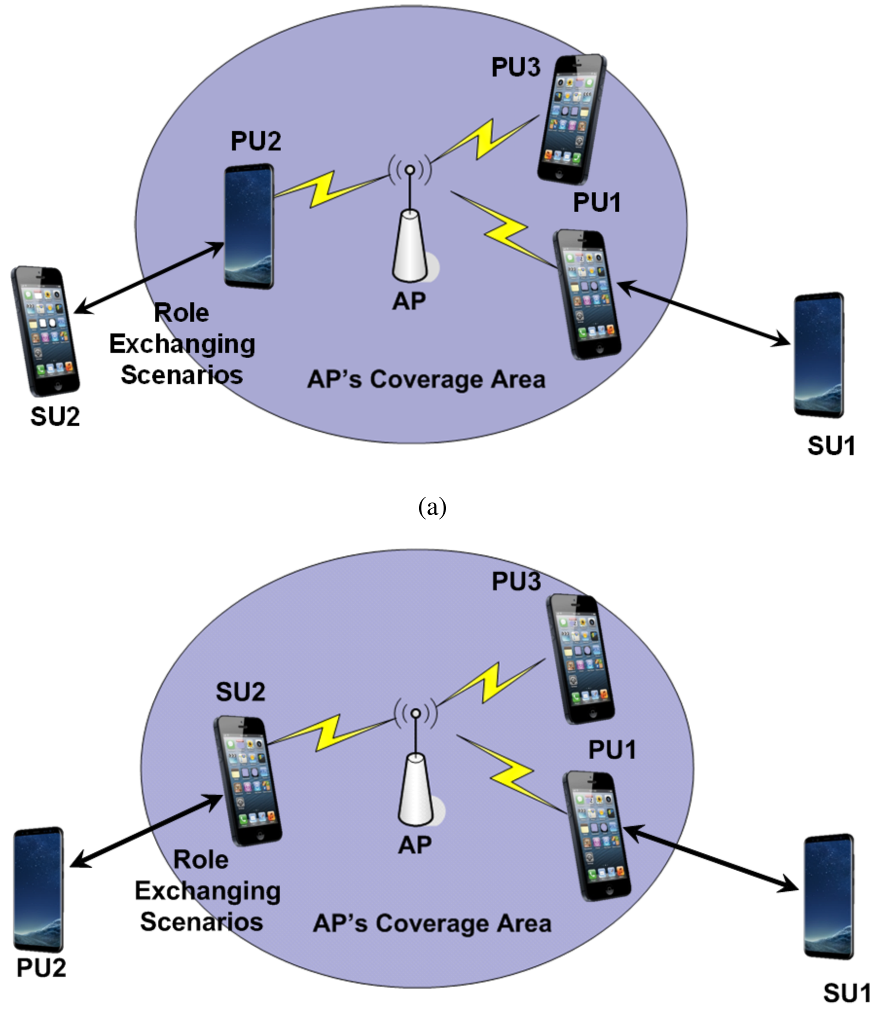
Table 4.2 Parameters used in *CF-RS* protocol

Symbol	**Parameter**
CR_i	Credit earned by PU i by being relay
U_j	Utility of SU j
U_i	Utility of PU i
c_{ij}	Cost incurred by PU i for providing relay service to SU j
p_{ij}	Price advertised by PU i for SU j
R_{ij}	Data rate at SU j via PU i

4.6 Exchange of Roles: Swapping of Positions

In order to motivate the primary users to use their battery powers more generously, earning some benefit by relaying data for other users may not be enough. There should be a long

Figure 4.5 Network scenario with primary and secondary users exchanging their role



(a)

(b)

term benefit for the primary users acting as relays utilizing their battery power for other users' data transmission [21]. By long term benefit we mean how and where the primary users can utilize the benefit they have earned as relays. There will be situations when a primary user will move out of the coverage range of an AP and will become a secondary user as demonstrated in Figure 4.5. When it becomes the secondary user, it will then require the relaying service from the in-range primary users in order to access its data and can then utilize the benefit it had earned by being the relay for the other users. The more benefit it had gained as being the relay, the more data forwarding assistance it can receive from other primary users once it becomes the secondary user.

In case of the *CF-RS* protocol, the benefit a primary user earns by helping the secondary users access their data is the price which it receives from the secondary users for its services. This price then becomes the credits earned by the primary user. The more credits a primary user has accumulated as a relay, the higher the opportunity it has to buy service from other primary users when it moves out of the transmission range of the AP and can no longer directly communicate with the AP. When the primary user becomes the out-of-range secondary user, its credits are converted to its budget, which it utilizes to purchase the relaying service from the in-range users. This change in the manner a user or node functions and behaves in the network i.e. the in-range user becoming the out-of-range user and asking for assistance rather than providing help has been termed as exchange of roles and swapping of positions in this thesis. The same *CF-RS* protocol is applicable when the primary and the secondary users exchange their roles with just one adjustment of credits earned by the node as relay becoming its budget.

Apart from the price or earned credits which constitute the immediate benefit for the primary users, similar to Mastronarde *et al.* [21] work, the long term benefit for the primary users has also been defined. The long term benefit for a node is the difference between the data rate a user/node receives through a relay when it is the secondary user and the cost it experiences when it becomes the primary user/ relay given by equation(4.19).

$$B_k = R_k - C_k \tag{4.19}$$

where k is the node in the network changing its role, R_k is the data rate node k received as secondary user , C_k the overall cost it bore as relay and B_k is its overall benefit. It is beneficial for node to provide data forwarding assistance only if its overall benefit is greater than zero. This implies that along with being paid for its service as a relay, a node or user also enjoys receiving data via other in-range users for the cost it experienced in terms of its battery power while being a relay.

4.7 Research Contribution

Two relay selection solutions, namely *FBPC* and *CF-RS*, for coverage extension of rural wireless networks have been proposed. The aim of the *FBPC* algorithm is to achieve fair utilization of battery power of the primary users. The fair consumption of battery power is attained by minimizing the cost experienced by the primary users for assisting the secondary users. Instead of keeping the relaying cost constant like [21, 22], in the *FBPC* algorithm the cost is updated according to the cumulative to instantaneous battery power dissipation of the primary users. Unlike the relay selection techniques discussed in section 2.5 which have considered fully obedient relays, in the *FBPC* algorithm the primary users behave obediently only until their battery power is greater than a predefined threshold value. On reaching the threshold level, the primary user declines any further request received from the secondary users.

Since the real public networks may comprise of self-interested users, who along with demanding fair utilization of their battery power, also ask for compensation for the cost they bear for helping the secondary user. Also if only the fair usage of battery power of the primary users is used as the relay selection criterion, it may compromise the data rate achieved at the secondary user. Thus the *CF-RS* protocol focuses on both the fair utilization of battery power of the primary users and the attainable data rate at the secondary users. The salient features of *CF-RS* protocol are listed below:

1. Compared to the schemes described in sections 2.3, 2.4 and 2.5, the *CF-RS* protocol is the only technique that has addressed the fair consumption of battery power of the primary users as well as their self-interested nature.

2. The *CF-RS* protocol employs a credit-base mechanism which provides instantaneous as well as long-term benefit to the primary users to reimburse the relaying cost they incurred.

3. Just like the *FBPC* algorithm, in the *CF-RS* protocol the cost suffered by the primary user is regularly updated with its battery power expenditure.

4. A unique pricing function given by equation(4.18) has been developed. The proposed pricing function provides a fair opportunity to all primary users to help the secondary users. This results in earning some benefit in terms of credit which the primary users can utilize later when they move out of the transmission range of the access point.

5. Since the proposed pricing function gives every primary user the chance to act as relay (verified by the results given in Chapter 5), this results in fair utilization of battery power of primary users.

6. Unlike the relay selection techniques analysed in section 2.4 for self-interested users, the *CF-RS* protocol has considered a finite budget for the secondary users to buy the relaying service from the primary users. This encourages the secondary users that when choosing the relay they shall take into account both the data rate provided by a primary user as well as the price it is advertising for its services.

7. Like [21], in the *CF-RS* protocol the primary users have finite battery power. However, to ensure fair utilization of battery power of the primary users two battery power threshold values have been defined in the *CF-RS* protocol. Till the first threshold value, a primary user generously help the secondary users. After the first threshold value and above the second threshold value, the critical threshold, the primary user becomes more caution of its battery power and asks for higher price to assist the secondary users. On reaching the critical threshold value, the primary user refuses to participate in the relay selection process.

The key parameters to validate the performance of the *FBPC* algorithm are:

- The data rate achievable at the secondary users.
- The Jain's fairness index value for consumption of battery power of the primary users.

Along with the parameters listed above for the *FBPC* algorithm, there are three more parameters essential for evaluating the performance of the *CF-RS* protocol, which are:

- Utility of the secondary users.
- Utility of the primary users i.e. their instantaneous benefit.
- The overall benefit of a node i.e. the long-term benefit for the primary users.

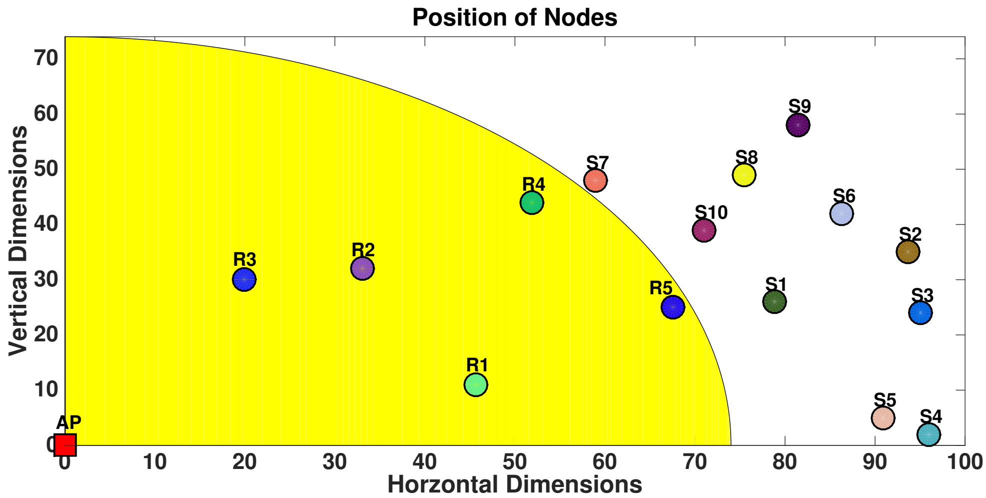
To evaluate the performance of the proposed *FBPC* algorithm and *CF-RS* protocol, a network consisting of the primary and the secondary users has been simulated. The details of simulated network and the results obtained are given in Chapter 5.

Chapter 5

Performance Evaluation

This chapter provides a detailed performance evaluation of the proposed *FBPC* algorithm and the *CF-RS* protocol . To assess the performance of the *FBPC* algorithm and the *CF-RS* protocol, a default algorithm employing only SINR as relay selection criterion is used. In the default algorithm, the primary users are assumed to be obedient and the primary users with the best channel conditions are repeatedly chosen to serve as relays for the secondary users. The achievable data rate, Jain's fairness index and the battery power consumption of the primary users are the parameters used to evaluate the performance gains achieved by deploying the *FBPC* algorithm and the *CF-RS* protocol for relay selection in a wireless network. The results obtained demonstrate that the *CF-RS* algorithm outperforms the default and the *FBPC* relay selection algorithms in terms of achievable data rate whereas the *FBPC* algorithm achieves higher level of fairness for consumption of battery power compared to the *CF-RS* protocol. The simulated network scenario and the results obtained are discussed in the following sections.

Figure 5.1 Simulated network scenario comprising of 5 relays and 10 secondary users



5.1 Simulated Network Model

The network model described in section 3.1 and depicted in Figure 3.1 has been simulated with 15 nodes, 5 of them being the primary users (relays) and 10 secondary users. The reason for choosing 10 secondary users and 5 primary users is to examine the performance of the *FBPC* relay selection algorithm and the *CF-RS* protocol when there are more out-of-range users in the network than the available relays. Figure 5.1 presents the simulated network model and the semi-circle represents the coverage area of an access point (AP). WiFi has been used as the baseline technology for the simulated wireless network operating in 802.11b mode at 2.4GHz frequency band and bandwidth of 22Mbps. Since the outdoor coverage range of 802.11b is 140m [153], therefore for the simulated network model approximately half of the outdoor range has been taken as the AP's coverage range. Thus any node located at distance of or more than 75 *m* from the AP is categorized as the secondary user. A primary user can serve more than one secondary user and the capacity it can offer is dependent on the number of secondary users it is currently serving. The cost a primary user experiences while providing relaying service is determined using cumulative to instantaneous battery power consumption of the primary user and the price is calculated using the pricing function given in equation(4.18).

A default relay selection algorithm is also simulated to compare the performance of the *FBPC* relay selection algorithm and the *CF-RS* protocol in terms of fair utilization of battery power of primary users, data rate and utility of secondary users and utility of primary users. The default algorithm utilizes SINR as the criterion for choosing the best relay for data forwarding to the secondary users. Terminating simulations are used to determine how long it takes for the battery power of the primary users to reach the critical threshold value in case of the default and the *FBPC* relay selection algorithms and the *CF-RS* protocol and how the battery power affects the data rate and utility of secondary users and utility of primary users.

The data demand of the secondary users has been modelled using Bernoulli distribution [62] with a request probability of 50%. Data demand actually represents the percentage of assistance requests generated by the secondary users. For example the data demand of 100% means that in the simulation duration of x number of slots, the secondary user is asking for data in every slot and data demand of 50% implies that during each slot the probability that the secondary user requires assistance is 0.5. Simulation duration is represented as time slots and at the beginning each slot, all three relay selection solutions check if the secondary user requires data forwarding service from the primary user. A specialized simulator has been developed using MATLAB to implement and compare the default and the *FPBC* algorithms and the *CF-RS* protocol. The main simulation parameters are listed in table 5.1. Simulation duration of 50 slots is considered because after 50 slots the battery power of all participating primary users in the case of the default algorithm decreases rapidly and quickly reaches the second threshold value.

The *FBPC* algorithm considers primary users to be obedient; therefore the utility of the secondary users only depends on the achievable data rate i.e. $U_j = R_{ij}$. For the *CF-RS* protocol, a primary user increments the price of its services linearly until 20% its battery

Table 5.1 Simulation Parameters

Parameter	**Value**
Number of Nodes	15
PHY Mode	WiFi PHY Mode
MAC Model	IEEE 802.11 b
Band of Operation	2.4 GHz
Bandwidth	22 Mbps
Request Probability of Secondary Users	50%
BP_{th_1}	20% of Initial *BP*
BP_{th_c}	50% of Initial *BP*

power is consumed, after which the price is increased exponentially until half of the battery power has been dissipated. When battery power of a primary user reaches 50% of its initial value, it will no longer participate in the relay selection process. A small same initial price (p_{ij}) has been assumed for all five primary users. Whereas the default algorithm has been analysed with both obedient and selfish primary users. In the case of obedient primary users, they act as relays as long as their battery power is greater than 50% of their initial power and do not ask for any price for their services. However, the selfish primary users in the case of the default algorithm also advertise a price for providing relaying service.

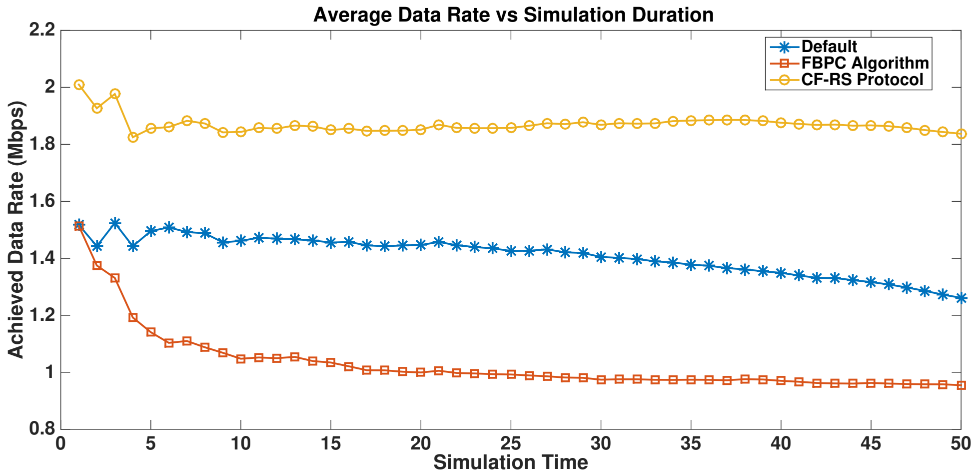
Ten sets of positions of the primary and the secondary users were examined and in each position set, the location of the primary and the secondary users was randomly generated with the maximum allowable distance between the primary and secondary users not more than 75 m and the distance of the secondary user from the AP not exceeding 100 m. A similar trend was obtained for the achievable data rate and utility at the secondary users, utilization of battery power and utility of the primary users in all ten sets of positions and for the ease of presentation and understanding the results discussed in section 5.2 are for the set of positions of the primary and the secondary users shown in Figure 5.1. However, in subsections 5.2.4 and 5.2.5 the different positions of the primary and the secondary users are considered to analyse the impact of relay's position on performance of the *CF-RS* protocol and the scenario of exchange of role of primary and secondary users. The details of these network configurations and the reason of choosing different positions of primary and secondary users than that depicted in Figure 5.1 is explained in the respective subsections.

In section 5.2, first all three relay selection solutions are examined considering infinite budget for the secondary users and then the *CF-RS* protocol with finite budget has been compared with the default algorithm having finite as well as infinite budget. The impact of variation in data demand from the secondary users on achievable data rate and fair dissipation of battery power have also been analysed when the default algorithm and the *CF-RS* protocol are used for relay selection and results are presented in subsection 5.2.1. To verify that the *CF-RS* protocol provides better utility to the selfish primary users compared to the default algorithm, the average and individual utility of the primary users has been examined in subsection 5.2.3. Four extreme configurations of positions of primary and secondary users have been considered in subsection 5.2.4 to study the impact of position of relays on the performance of the *CF-RS* protocol. The exchange of role scenario has been inspected in detail in subsection 5.2.5. To validate that the *CF-RS* protocol gives enough incentives and long-term benefits to the self-interested primary users to provide relaying service to the secondary users, two test case scenarios of swapping of roles have been analysed. In test case scenario one, the primary and secondary users exchange their roles once and the *CF-RS* protocol has been compared with four different variations of the default algorithm. Whereas in scenario two, the primary and secondary users exchange their positions four times. The detailed explanation of these test case scenarios and the simulated network model is provided in subsection 5.2.5.

5.2 Simulation Results

The three relay selection techniques; the default algorithm, the *FBPC* algorithm and the *CF-RS* protocol have been compared in terms of the average date rate achievable by the secondary users. Figure 5.2 shows that the *CF-RS* protocol attains highest data rate which is

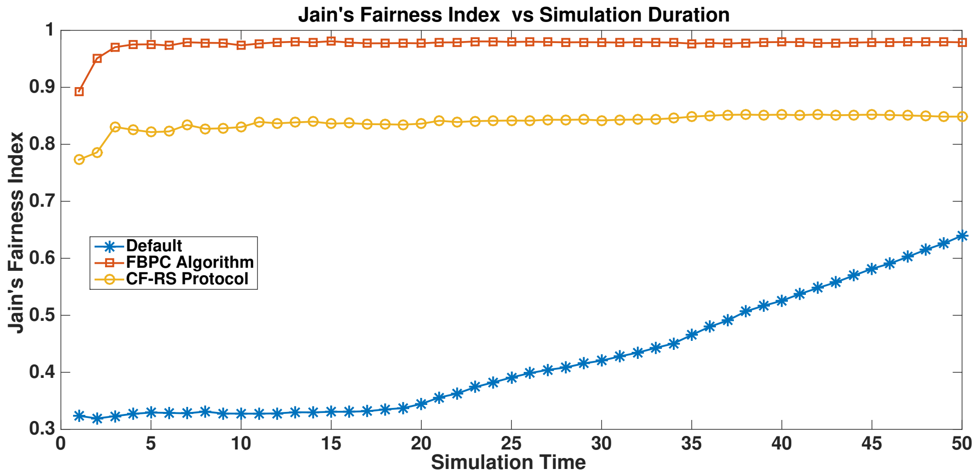
Figure 5.2 Comparison of data rate achieved using the default and the *FBPC* algorithms and the *CF-RS* protocol



due to the fact that the *CF-RS* protocol uses the utility function given in equation(4.5) for relay selection which takes into account the capacity a primary user can offer while serving other secondary users. However, in the default case the primary user with best SINR is chosen as the relay irrespective of the number of secondary users it is currently serving. In the default case, the data rate further drops when the battery powers of the nearest primary users reach their second threshold value i.e. 50% of their battery power and some other primary user needs to be selected to serve the secondary user. Whereas the *FBPC* algorithm focuses on fair utilization of battery power of relays only and does not take into consideration the acquirable data rate when picking the best primary user, thus the lowest data rate values are reached with *FBPC* algorithm.

Jain's fairness index has been used to determine how fairly the battery power of the relays is being utilized which is the main objective of both the *CF-RS* protocol and the *FBPC* algorithm. The higher the value of Jain's fairness index, the fairer the system. From Figure 5.3, it can be clearly seen that in the case of the *FBPC* algorithm Jain's fairness index is nearly one throughout the simulation duration since the *FBPC* algorithm employs the cumulative to instantaneous battery power consumption ratio $\frac{\overline{CBP_i}}{CBP_{ij}}$ as the relay selection

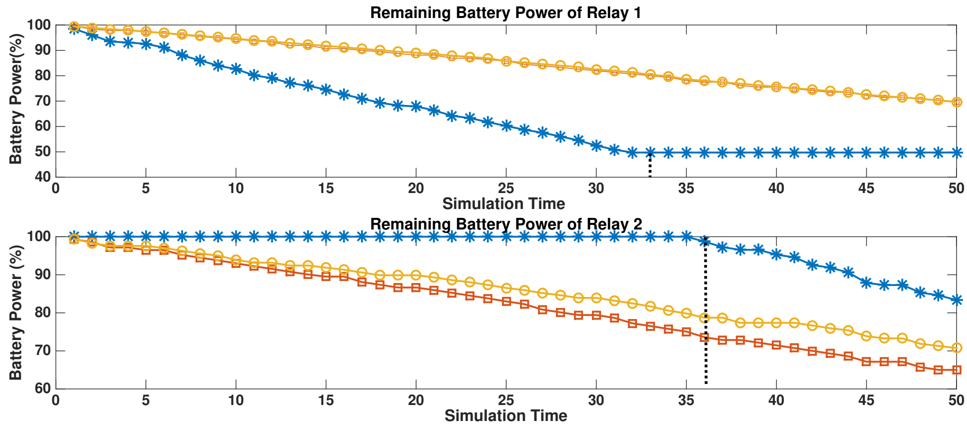
Figure 5.3 Jain's fairness index obtained for the default algorithm, the *FBPC* algorithms and *CF-RS* protocol



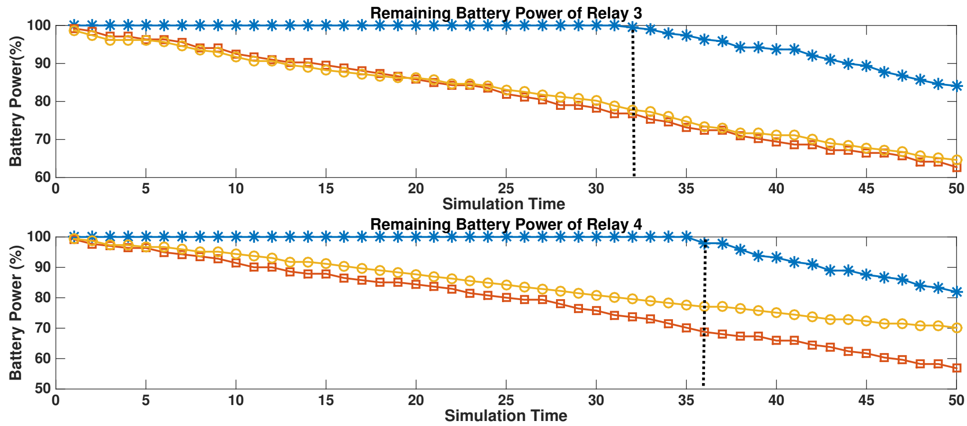
criterion. Thus *FBPC* algorithm provides fairer opportunity to the primary users to be chosen as relays. Fair dissipation of battery power of the participating relays is also the core design parameter for the *CF-RS* protocol, though its performance is not of the same level as that of the *FBPC* algorithm for Jain's Fairness Index but it still achieves 80% fairness. However, in the default case the value of Jain's fairness index is comparatively very low until the battery power of some of the relays reach their critical threshold value and relays which were not participating before are forced to provide assistance after which there is an increase in Jain's fairness index as can be seen after simulation duration of 20 slots in Figure 5.3.

The depletion of battery power of the primary users for all three relay selection techniques is depicted in Figure 5.4. In the default case, a secondary user always selects the nearest primary user therefore the battery power of relays with better SINR reach their second threshold value, i.e. the critical threshold value, quickly. In Figure 5.4, for the default case the secondary users start acquiring the services of relay 3 only when relay 1 can no longer provide data forwarding assistance. Same is the case with relay 2 and 4, they are forced to participate when the battery power of relay 5 reaches its critical threshold value. The black dotted lines in Figure 5.4 presents the switching of relays by the secondary users as

Figure 5.4 Comparison of utilization of battery power of individual relays for the default and *FBPC* algorithms and *CF-RS* protocol : (a) Battery power of relays 1 and 2 ; (b) Battery power of relays 3 and 4 and (c) Battery power of relays 5.



(a)



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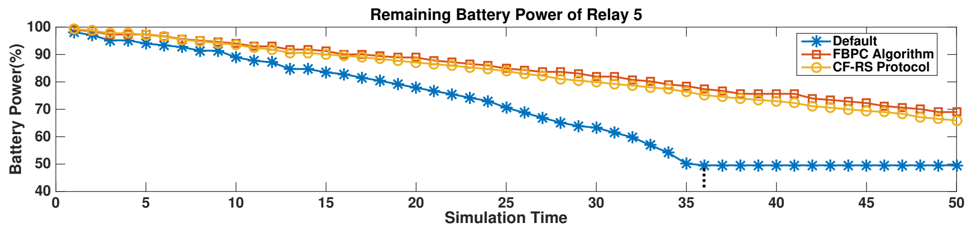
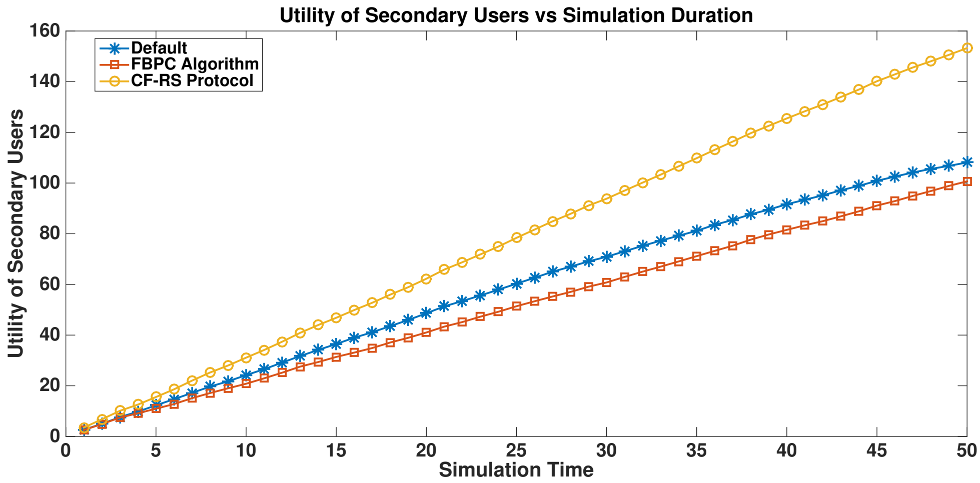


(c)

Figure 5.5 Comparison of average utility of secondary users for the default and the *FBPC* algorithms and *CF-RS* protocol



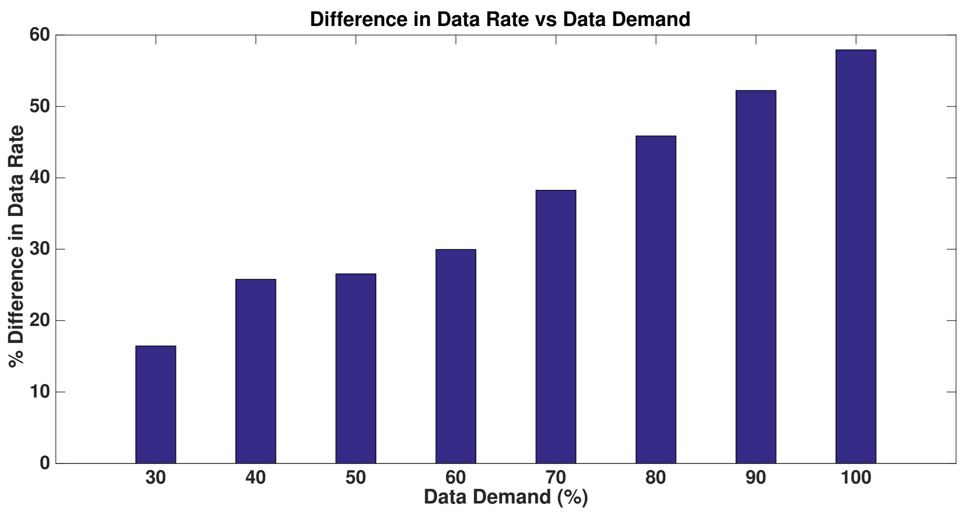
relays' battery power get depleted. In the case of the *FBPC* algorithm, the primary users get fair opportunity to act as relays, thus their battery power is consumed equally. However, in Figure 5.4 the dissipation of battery power of relays 2 and 4 when the *FBPC* algorithm is used is steeper compared to that achieved with the *CF-RS* protocol, hence the *CF-RS* protocol accomplishes a longer service time for the primary users before their battery power reach the critical threshold value. This is due to the more flexible pricing function defined in equation(4.18).

Figure 5.5 provides the comparison between the cumulative utility the secondary users gain when relays are selected using the default algorithm, the *FBPC* algorithm and when the *CF-RS* protocol is used. In the default case, the primary user with best SINR is selected as relay by most of the secondary users. This implies that the capacity offered by the selected primary user will be shared among the secondary users associated with that primary user, thus affecting the data rate achievable at the secondary users. In the default case, the utility of the secondary users depends on the achievable data rate only, therefore the utility with the default algorithm is lower than that achieved when the *CF-RS* protocol is used. Similarly the utility of the secondary users for the *FBPC* algorithm is not much different than that obtained with the default algorithm since the *FBPC* algorithm uses the cumulative to instantaneous battery power ratio as the relay selection criterion and ignores the data rate attainable by the secondary users when choosing the relays. The *CF-RS* protocol takes into consideration the achievable data rate when making decision on the relay selection and thus obtains better utility.

From the results compared in Figures 5.2, 5.3, 5.4 and 5.5, it can concluded that overall the *CF-RS* protocol's performance is better than the performance of the *FBPC* algorithm since the *CF-RS* protocol achieves fair utilization of battery power of relays without compromising data rate and utility of secondary users and also provides comparatively longer service time. Thus the results presented in the rest of this chapter only provide comparative analysis of the default algorithm and the *CF-RS* protocol.

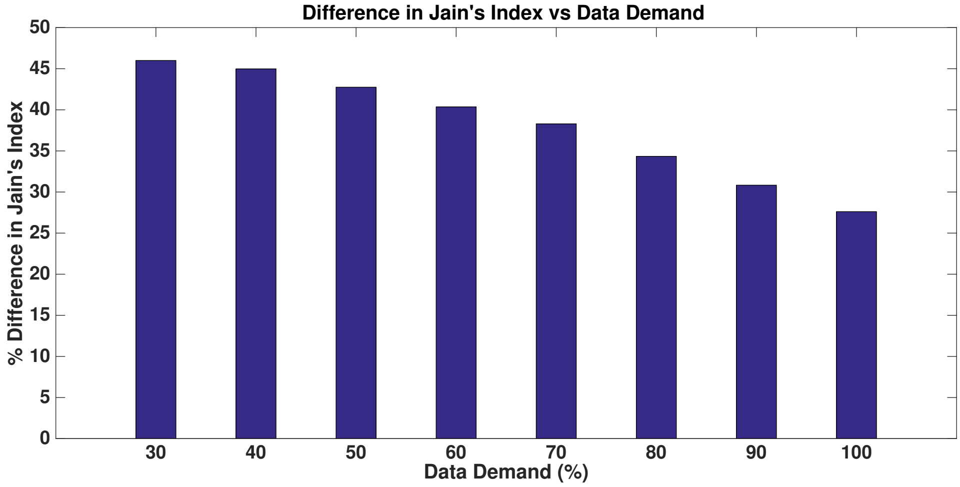
5.2.1 Variation in Data Demand

Figure 5.6 Comparison of difference in data rate against varying data demand



The variation in the data rate and Jain's fairness index in the case of the default algorithm and for the *CF-RS* protocol with variation in data demand from the secondary users has also been analyzed. Figure 5.6 depicts the difference in the data rate between the *CF-RS* protocol

Figure 5.7 Comparison of difference in Jain's fairness index against varying data demand



and the default algorithm against the data demand from secondary users. It can be clearly seen from Figure 5.6 that as the data demand increases the percentage difference in the data rate also rises. This is due to the fact that as secondary users request more and more data, the battery powers of relays drain out more quickly in the default case and there are no relays left with enough battery power to fulfill the demand of the secondary users. However, the percentage difference in Jain's fairness index decreases with the increase in the data demand as shown in Figure 5.7. When secondary users' request rate increases, all the primary users are forced to act as relays in the default case as well, consuming some of their battery power, improving the fair utilization of battery power of all relays and thus resulting in decrease in difference of Jain's fairness index between the *CF-RS* protocol and the default algorithm.

5.2.2 Finite and Infinite Budget Comparison

In the results discussed so far it has been assumed that the secondary users have infinite budget and are always willing to pay the price the primary user is advertising/ asking for providing assistance. However, practically it is not possible to have infinite budget. Therefore, the performance of the *CF-RS* protocol has been evaluated for limited/ finite budget against the default case having both finite and infinite budget for the secondary users. Having finite budget for the secondary users also implies that the primary users considered in the default case are no longer obedient but are asking for a price for their services. The cost and the price of providing data forwarding assistance is calculated in the same way for the default case as for the *CF-RS* protocol to provide a fair comparison.

Figure 5.8 Comparison of data rate with infinite and finite budget for secondary users

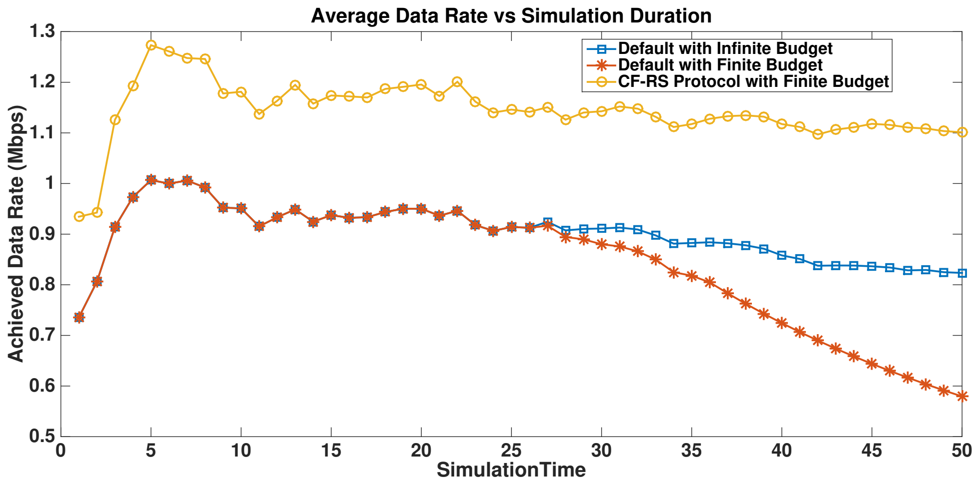
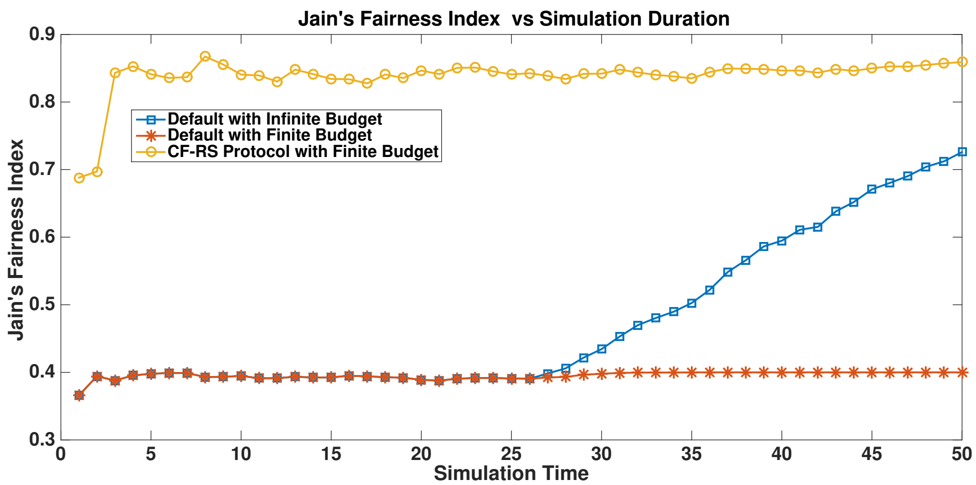
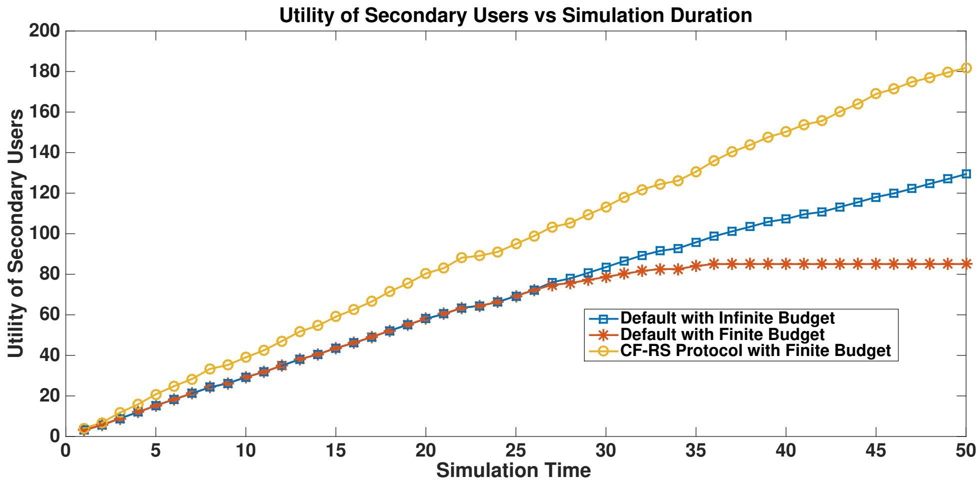


Figure 5.9 Comparison of Jain's fairness index with infinite and finite budget for secondary users



The *CF-RS* protocol outperforms the default case with both finite and infinite budget in terms of both attainable data rate and Jain's fairness index, as depicted in Figures 5.8 and 5.9. In the default case with infinite budget, the secondary users always get the data forwarding

Figure 5.10 Comparison of utility of secondary users with infinite and finite budget for secondary users



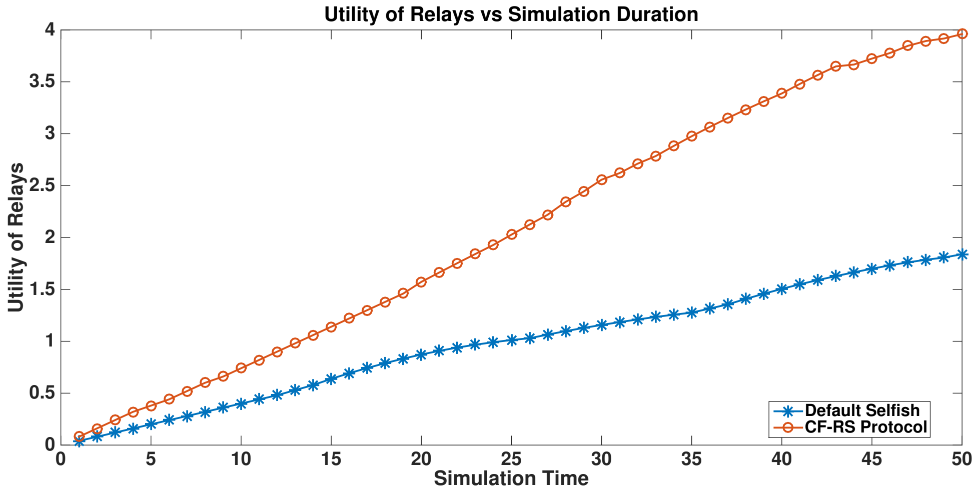
service as long as the battery power of primary users is above the critical threshold value. Thus the drop in data rate provided to the secondary users is less steep for the default case with infinite budget than that with finite budget, as shown in Figure 5.8, and also Jain's fairness index improves for infinite budget (see Figure 5.9).

Figure 5.10 presents the utility of secondary user and it can be clearly seen that the budget of the secondary users for buying assistance from the primary users is exhausted more rapidly for the default case with finite budget. When the secondary user's budget is completely consumed, it no longer can receive any data and its cumulative utility becomes constant.

5.2.3 Utility of Selfish Relays

The public networks often consist of self-interested users who are primarily concerned with their own benefit. These self-interested users want some gain in return of their services and therefore are termed selfish users. The next step is to analyze the utility attained by the selfish primary users when the default algorithm and the *CF-RS* protocol are used for relay selection. For providing assistance to the secondary users, the selfish primary user asks for a price for its service. The average cumulative utility attained by the selfish primary

Figure 5.11 Utility gained by the selfish primary users in case of default algorithm and when CF-RS protocol is used



users for providing assistance to the secondary users is plotted in Figure 5.11. From Figure 5.11, it can be clearly seen that selfish relays achieve around 50% better utility when the *CF-RS* protocol is used. This is due to the fact that a primary user in the *CF-RS* protocol case determines its willingness to serve as the relay using both its cost and the credits in terms of the price it will receive for its service. Since each primary user gets an opportunity to assist the secondary user, the price for its assistance considering its cost is not too high, which means the secondary user with its limited budget can use the primary users' service for a longer time, thus giving the primary users the chance to earn more utility.

To examine the utility gain of an individual primary user, a random positioning of primary and secondary users as depicted in Figure 5.12 has been considered. From the network scenario of Figure 5.12, it is evident that since the primary user/ relay 4 is situated far from the secondary users compared to the other primary users, and since it is a selfish user, it has no incentive to provide the data forwarding service to the secondary users in the case of the default algorithm. Therefore the utility of relay 4 as presented in Figure 5.13 in the case of the default algorithm is zero. However, in the case of the *CF-RS* protocol the credit base system encourages all primary users to participate in the relaying process as well as

Figure 5.12 Another network scenario example of random positions primary and secondary users

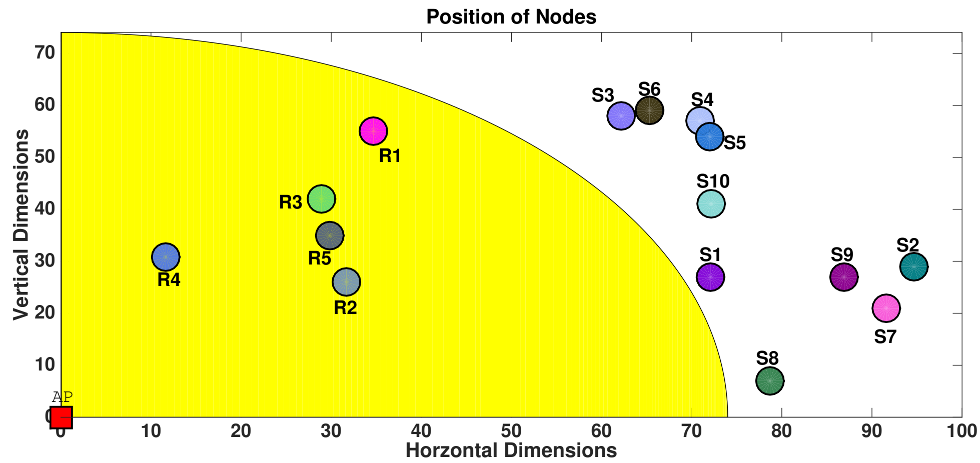
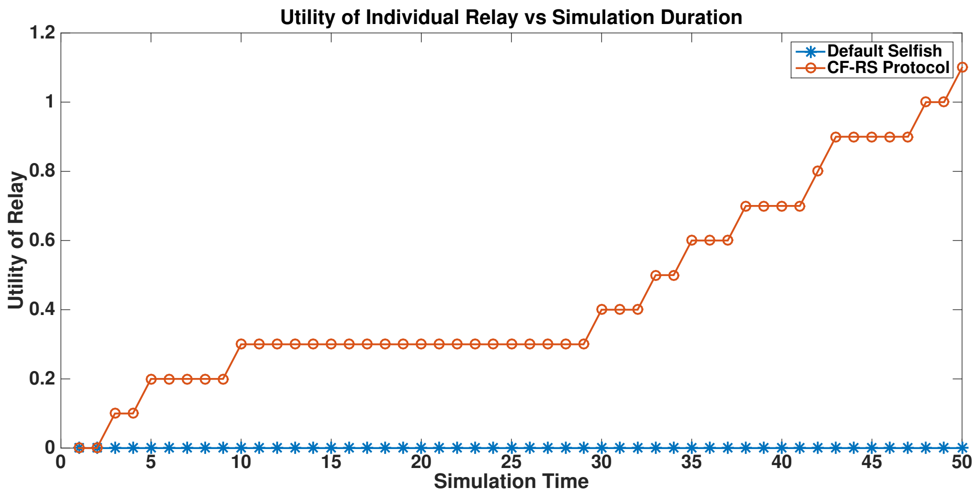


Figure 5.13 Individual utility gain of PU 4, which is a selfish user



motivates the secondary users to buy service from the less likely used primary users since their service price is comparatively lower. Thus *CF-RS* protocol achieves 50% better average utility for the primary users as well as higher utility for individual primary users. In Figure 5.13, the interval during which the utility of relay becomes flat indicates the relay is not serving any secondary user during that interval.

5.2.4 Performance Evaluation in Extreme Positions

To analyse the impact of relays' positions on the performance of the *CF-RS* protocol, four extreme position configurations have been examined. These four configurations are given below:

1. **Configuration** a**:** All primary users located closer to the AP and farther from the secondary users and the secondary users are situated just outside the coverage range of the AP, shown in Figure 5.14(a).

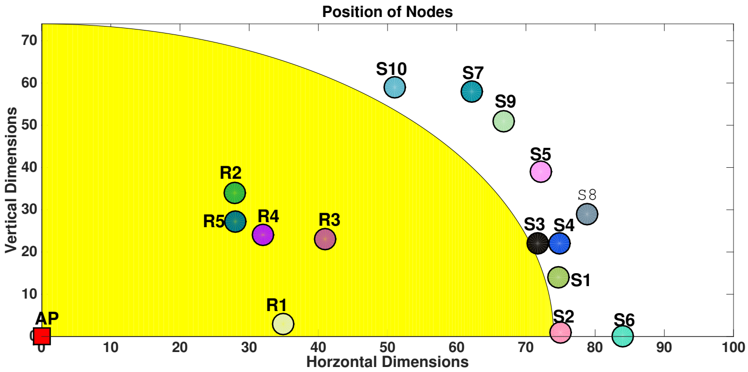
2. **Configuration** b**:** There is only one nearby primary users close to the coverage boundary, others are located far from the secondary users. The secondary users are situated just outside the coverage range of the AP, shown in Figure 5.14(b).

3. **Configuration** c**:** All primary users are situated closer to the coverage boundary of the AP, shown in Figure 5.14(c).

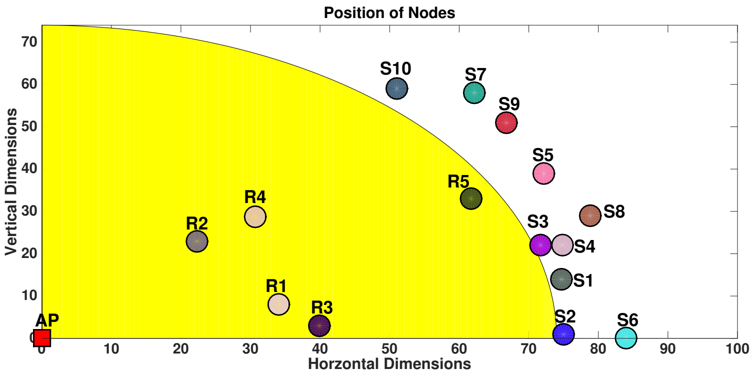
4. **Configuration** d**:** The primary users are randomly located within the transmission range of the AP whereas the secondary users are on the edge of maximum distance allowable range from the AP considered for the network model, shown in Figure 5.14(d).

These four configurations represent some of the extreme positions the primary and the secondary users may take in a network. The considered four extreme positions present the most challenging configurations to test the performance of the *CF-RS* protocol that how successfully the *CF-RS* protocol incentivizes the self-interested primary users to relay data for the secondary users. These four configurations have been chosen to evaluate the performance gains provided by the *CF-RS* protocol in situations when all primary users are located far from the secondary users, they are in near vicinity of the secondary users and when there is only one neighbouring primary user.

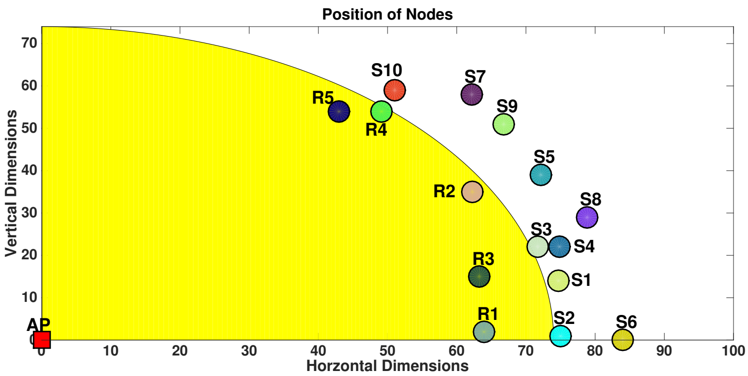
Figure 5.14 Network configurations with extreme positions of primary and secondary users: (a) All relays located far; (b) Only one nearby relay; (c) All relays located on coverage boundary; and (d) Secondary users on edge on maximum allowable distance.



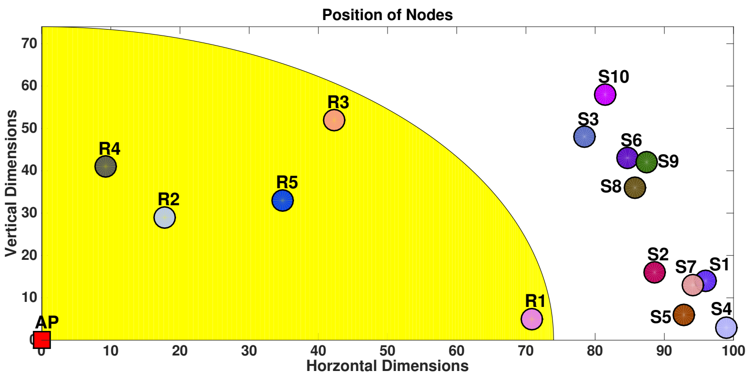
(a)



(b)

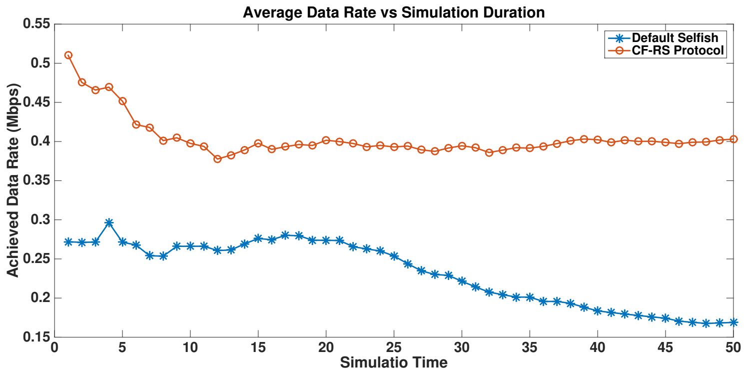


(c)

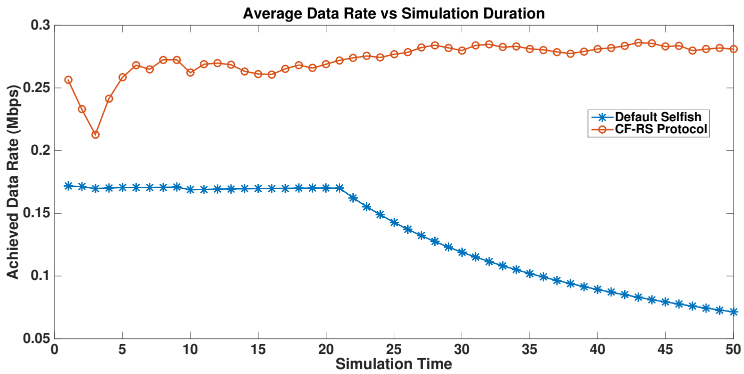


(d)

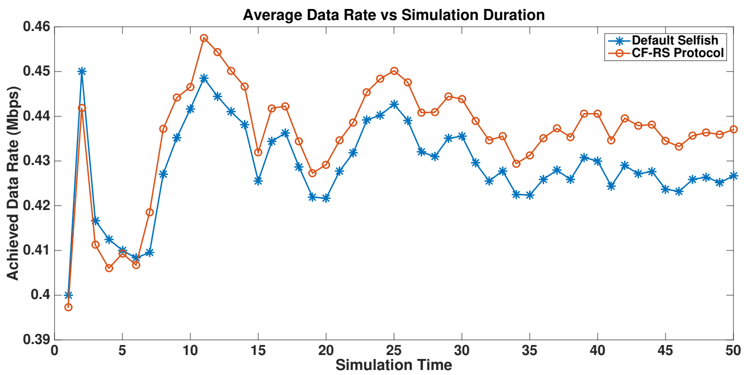
Figure 5.15 Data rate achieved in case of default and CF-RS Game for all four configurations: (a) All relays located far; (b) Only one nearby relay; (c) All relays located on coverage boundary; and (d) Secondary users on edge on maximum allowable distance.



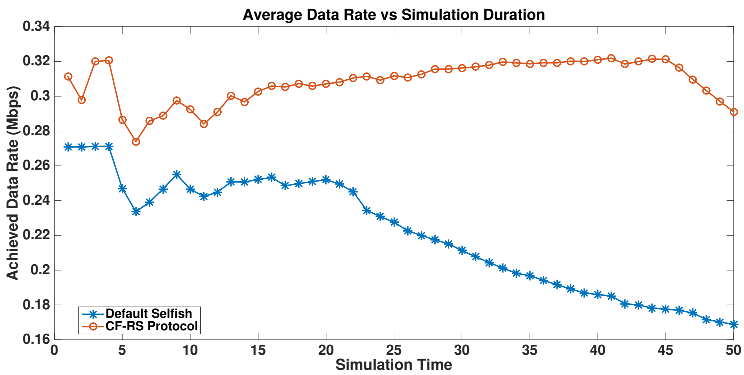
(a)



(b)



(c)



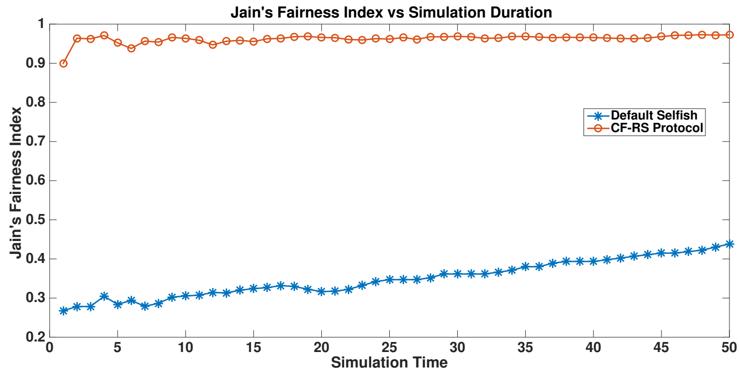
(d)

The cumulative average data rate attained by the secondary users in all four extreme configurations is presented in Figure 5.15. In all four configurations, the *CF-RS* protocol achieves better data rate for the secondary users compared with the default case owing to the credit based incentive mechanism it uses. For configurations *a* and *d* depicted in Figures 5.14(a) and 5.14(d), the data rate in the case of the default algorithm decreases because the battery power of the primary users with best SINR have reached their critical threshold value and some of the primary users are not even participating in the service delivery. For configuration *b* depicted in Figure 5.14(b), when default algorithm is used, there is only primary user ($R5$) willing to assist the secondary users, thus the achieved data rate decreases very sharply when $R5$'s battery power reaches its critical threshold. Whereas when the *CF-RS* protocol is used, all primary users have incentive to help the secondary users. However, when the primary users are located close to the secondary users (configuration *c* presented in Figure 5.14(c)), there is marginal difference between the achieved data rates.

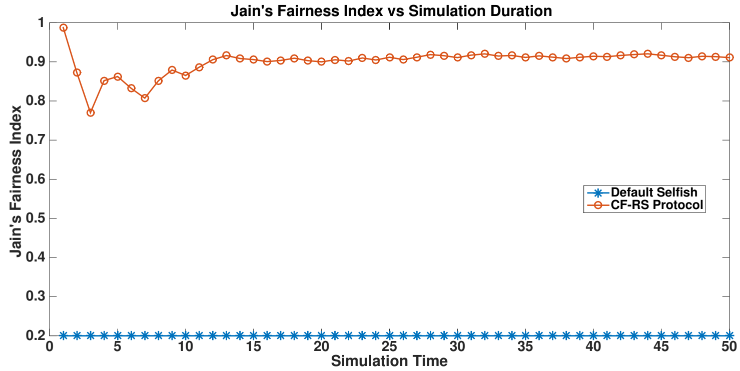
In terms of fair utilization of battery power of relays, again *CF-RS* protocol performs well for all four extreme configurations, achieving approximately 90% fairness for configurations *a*, *b* and *c* displayed in Figure 5.16. Whereas for configuration *d*, *CF-RS* game attains 70-75% fairness, see Figure 5.16(d). In all four configurations, the performance of the default algorithm is comparatively better for configuration *c* reaching nearly 70% fairness, as exhibited in Figure 5.17(b) which is due to the fact that all primary users are located near the secondary users, all of them can provide good SINR and are willing to serve the secondary users.

Configurations *b* and *c* reveal interesting results for the utility of the secondary users. In configuration *b* since only one relay is serving all the secondary users when the default algorithm is used, when this relay's battery power is drained out the secondary users stop receiving any utility and their cumulative utility flattens out as shown in Figure 5.17(a). Whereas in configuration *c*, just like the achieved data rate, there is marginal difference

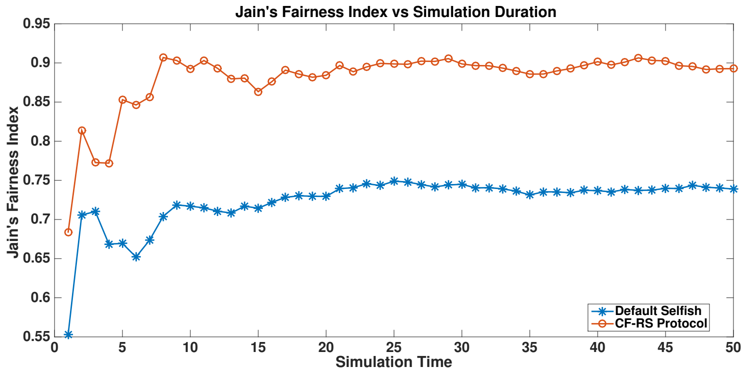
Figure 5.16 Jain's fairness index for all four configurations: (a) All relays located far; (b) Only one nearby relay; (b) All relays located on coverage boundary; and (d) Secondary users on edge on maximum allowable distance.



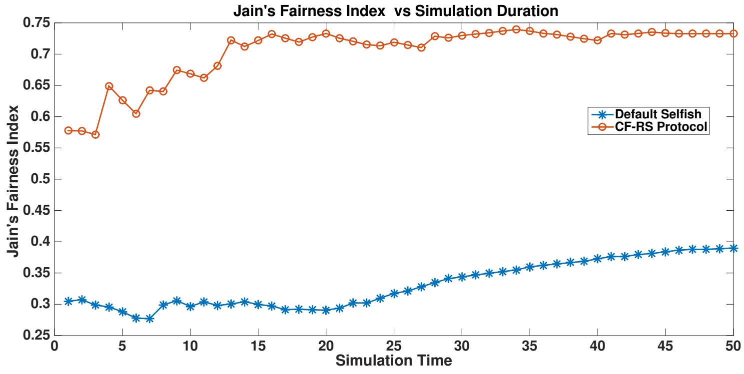
(a)



(b)



(c)

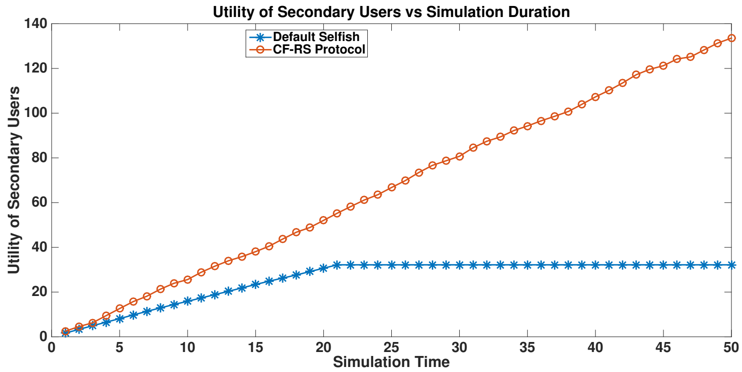


(d)

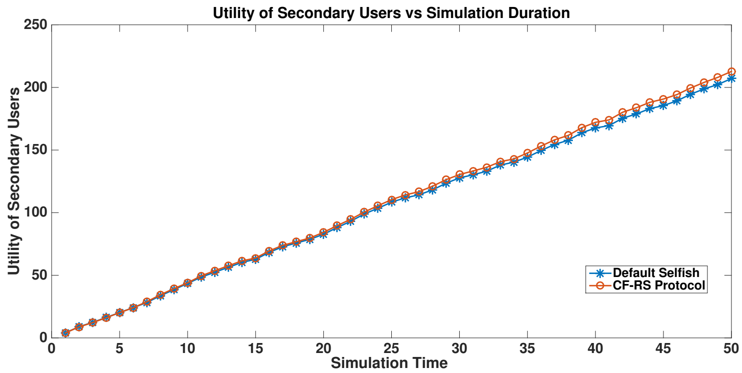
between the attained utility for the *CF-RS* protocol and the default algorithm since the primary users are located very close to the secondary users providing good SINR. The utility of secondary users for configuration *c* is depicted in Figure 5.17(b).

The utility gained by the primary users and their battery power utilization is of particular interest for configuration *b* when there is only one relay serving all the secondary users in the case of the default algorithm. From Figure 5.18, it can be seen that utility of the relay serving the secondary user is near to zero in the default case whereas for the *CF-RS* protocol the relays receive good utility which is because the underlaying credit based mechanism encourages the primary users to assist the secondary users and earn credits for themselves.

Figure 5.17 Utility of secondary user for configurations *b* and *c*: (a) Only one nearby relay; and (b) All relays located on coverage boundary.



(a)



(b)

Figure 5.18 Utility gained by primary users in configuration *b*

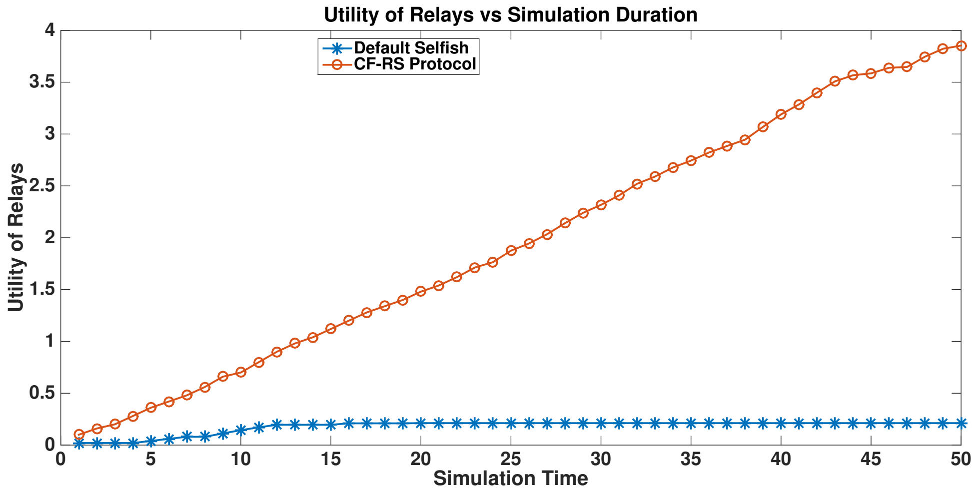
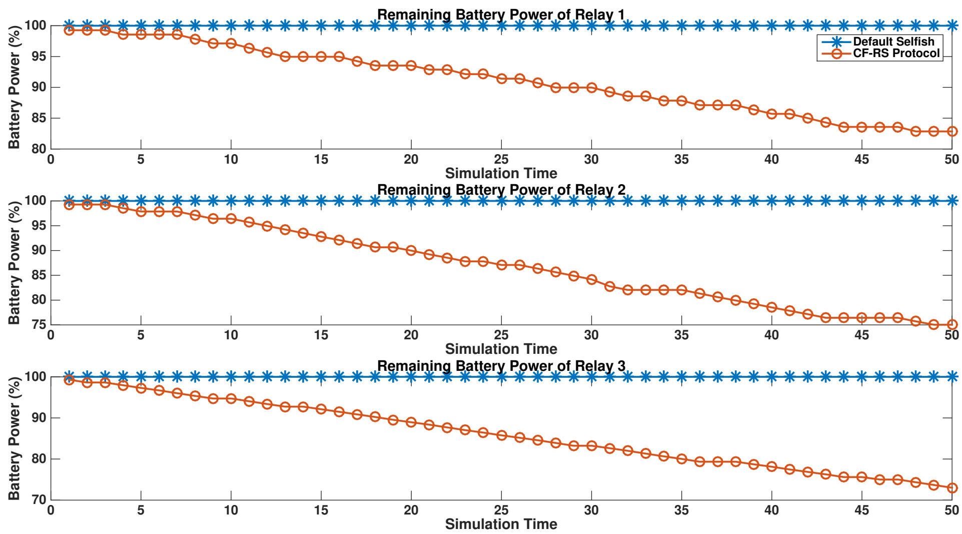


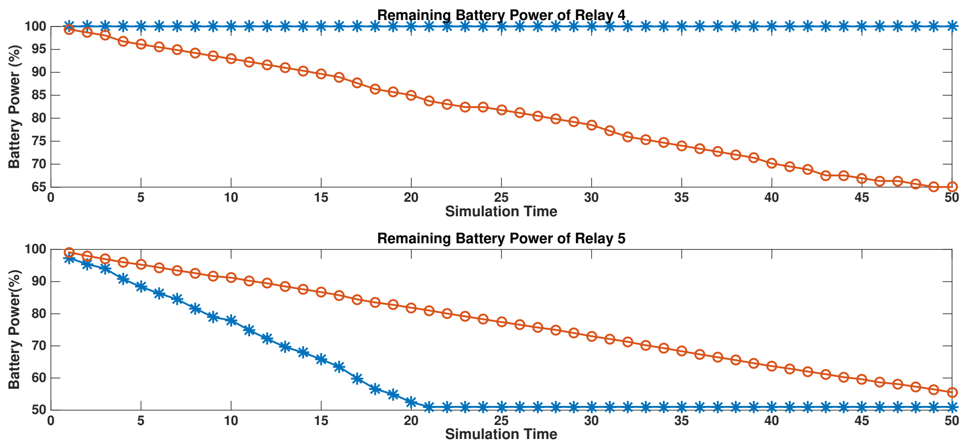
Figure 5.19 presents the battery power consumption of the primary users for configuration *b*. Battery power of relay 5 quickly reaches the critical threshold value and the rest of the relays do not participate in the relay selection process.

After analysing the performance of the *CF-RS* protocol and the default algorithm in all four considered extreme configurations, it can be concluded that the *CF-RS* protocol outperforms the default algorithm. However, the performance gains, in terms of the achievable data rate, Jain's fairness index, utilities of primary and secondary users and service time, are greater in configurations *a*, *b* and *d* when the distance between the primary and the secondary users is large. Especially in configuration *b* when there is only one nearby primary user, the *CF-RS* protocol brings the greatest benefit compared to the default algorithm. Whereas in configuration *c* when the distance between the primary users and the secondary users is small, the default algorithm performs comparatively better. This is because all primary users can provide good SINR to the secondary users and these selfish primary users have enough incentive in terms of price of their service to help the secondary users.

Figure 5.19 Battery power dissipation in configuration b : (a) Battery power of relays 1,2 and 3; and (b) Battery power of relays 4 and 5.



(a)



(b)

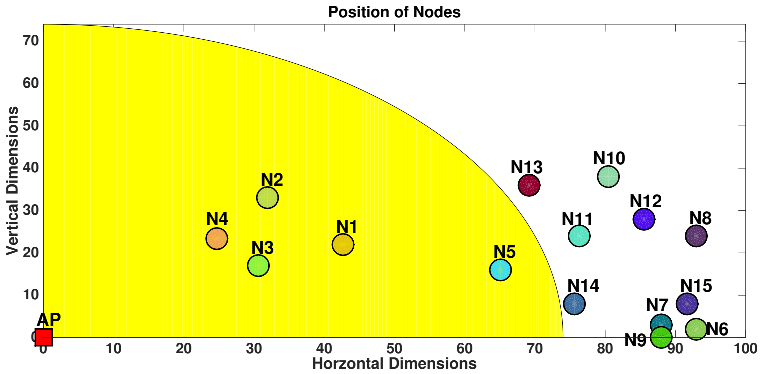
5.2.5 Exchange of Roles: Swapping of Positions

To demonstrate the long term benefit of the *CF-RS* protocol given by equation(4.19) and accumulation and usage of credits earned by a node via the *CF-RS* protocol, a network model with nodes exchanging their roles as primary and secondary users, depicted in Figure 4.5, has been analyzed. The network model still consists of 15 nodes as presented in Figure 5.1; 5 primary users and 10 secondary users with just one addition that, half way through the simulation duration, five of the secondary users swap their roles with the primary users. To assess the performance of the *CF-RS* protocol when such exchange of roles occur, two test case scenarios have been considered. In scenario 1, the primary and secondary users change their positions only once as shown in Figure 5.20. Whereas for scenario 2, four such exchange of positions have been examined, see Figure 5.21.

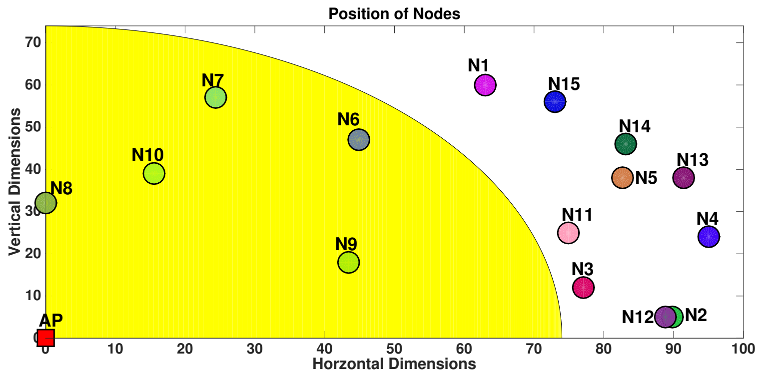
For the test case scenario 1, the *CF-RS* protocol has been compared with four different variations of the default algorithm:

- In variation 1, for the default algorithm it has been assumed that the primary users are obedient users and do not ask for any price for their services.
- Variation 2 of the default algorithm considers selfish primary users but there is no pricing or credit based mechanism to motivate them to assist the secondary users.
- Variation 3 also deals with the selfish primary users who ask for a price for their services but are still willing to help the secondary users even if the price paid by the secondary users is less than their cost of providing service. Also there is no mechanism to ensure fair utilization of battery power of the primary users.
- In variation 4 of the default algorithm, the primary users only aid the secondary users when the price paid by the secondary users is greater than the cost experienced by the primary users. Still there is no mechanism to guarantee fair usage of relay's battery power.

Figure 5.20 Simulated network scenario with primary and secondary users exchanging their role once: (a) Position 1 before exchange; and (b) Position 2 after exchange.



(a)



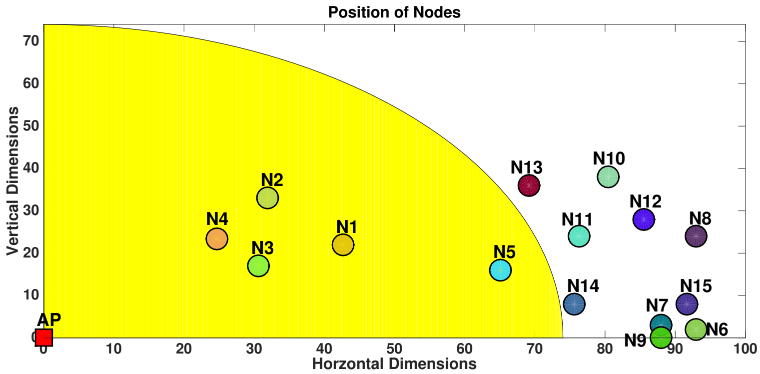
(b)

The results obtained when the primary and secondary users exchange their roles for all these four variations of the default algorithm in comparison with the *CF-RS* protocol are discussed below.

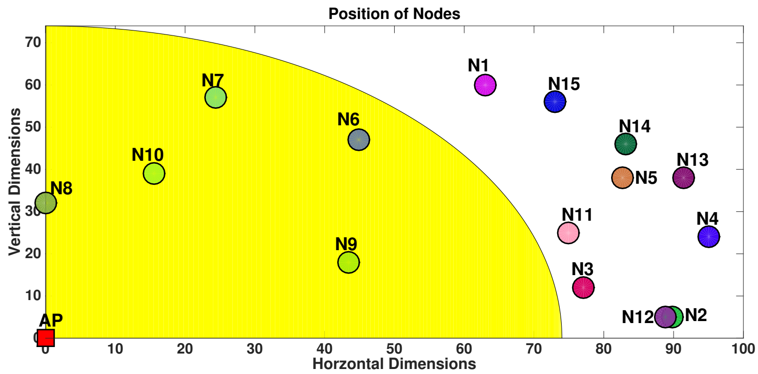
Variation1:

Figure 5.22 presents that overall benefit gained by the nodes who were the primary users in position 1 depicted in Figure 5.20(a) and became the secondary users in position 2 shown in Figure 5.20(b). The overall benefit of a node depends on the cost it experienced being a relay and the data rate it received being the secondary user. Simulation duration of 120 slots with a request probability of 50% from the secondary users and the exchange of positions occurring

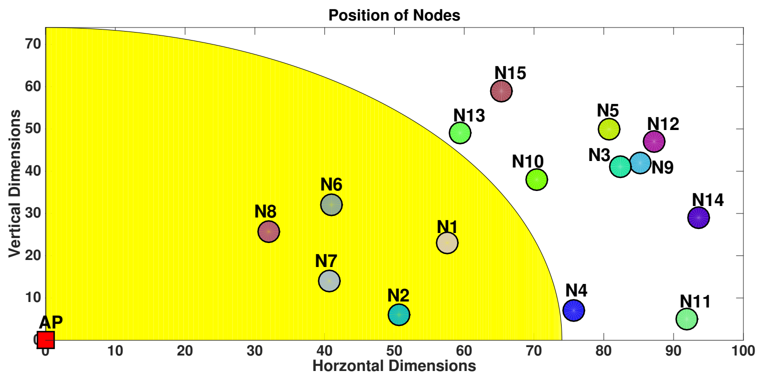
Figure 5.21 Simulated network scenario comprising of four exchange of positions of primary and secondary users: (a) Position 1; (b) Position 2; (c) Position 3 and (d) Position 4.



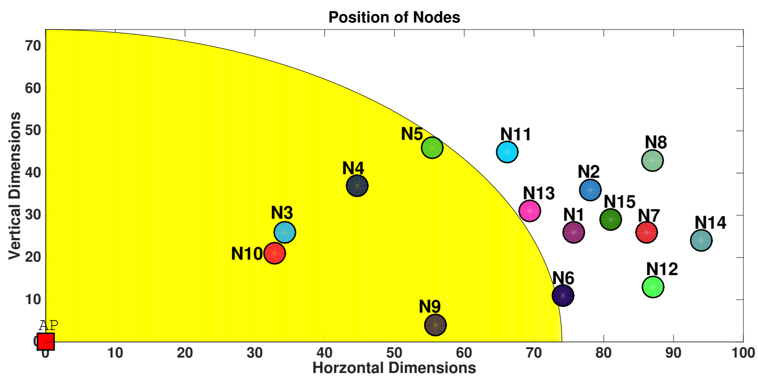
(a)



(b)

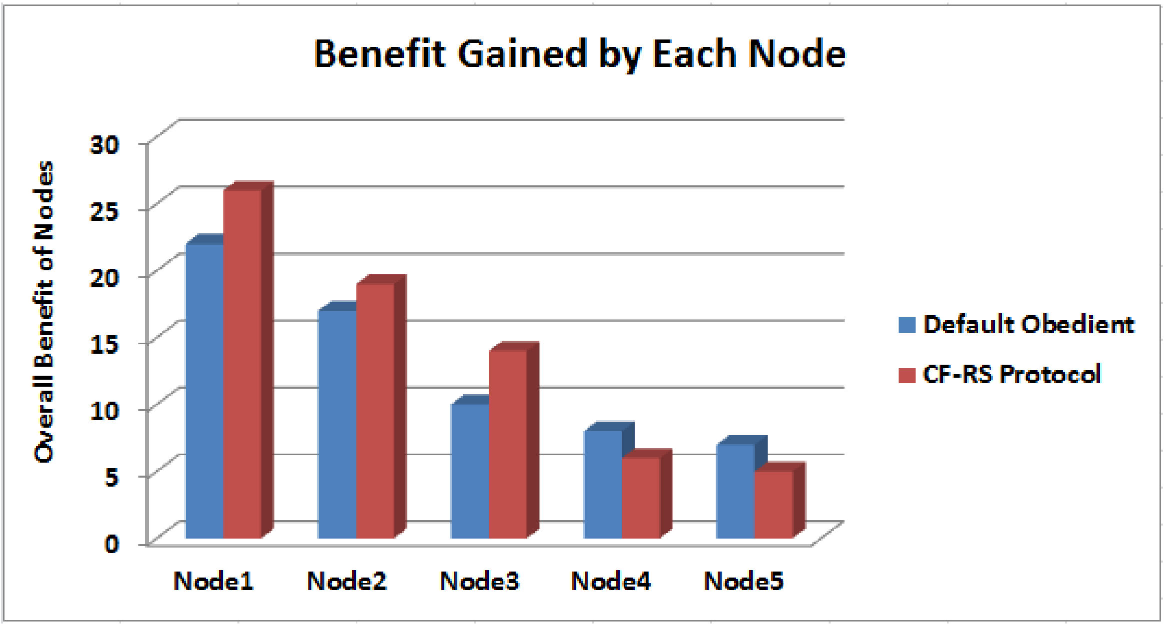


(c)



(d)

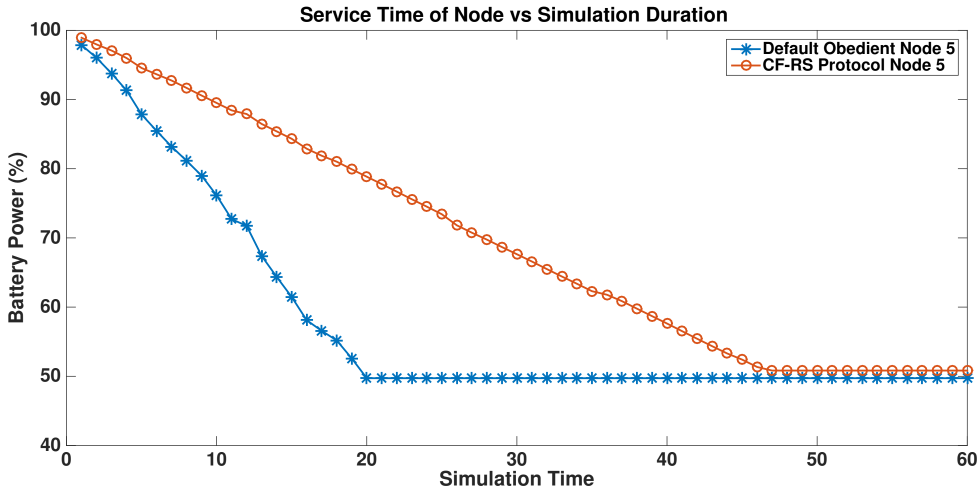
Figure 5.22 Overall benefit attained by nodes when default obedient algorithm and CF-RS protocol are used



after first 60 slots has been simulated. Since the primary users for the default algorithm are considered to be obedient, irrespective of whether the nodes $N1$, $N2$, $N3$, $N4$ and $N5$ provide data forwarding service in position 1 or not, they will always receive assistance when they become the secondary users. This is because the nodes $N6$, $N7$, $N8$, $N9$ and $N10$ in position 2 are also obedient users. Therefore, all the five nodes $N1$, $N2$, $N3$, $N4$ and $N5$ achieve good positive overall benefit for the default algorithm as well.

There are five relays in position 1 (Figure 5.20(a)), however despite the relays being obedient users, the secondary users only avail the services of $N5$ in case of the default algorithm. Therefore, in Figure 5.23 the service time of only $N5$ has been plotted. Service time is the duration in which the relay is assisting the secondary user before its battery power reaches the critical threshold value. From Figure 5.23, it can be concluded that the *CF-RS* protocol provides approximately 50% longer service time compared to the default algorithm with obedient relays in this scenario. Acquisition of credits by nodes $N1$, $N2$, $N3$, $N4$ and $N5$ when they are the primary users and then the expenditure of these earned credits

Figure 5.23 Service time of $N5$ when default obedient algorithm and CF-RS protocol are used



when these five nodes become the secondary users is exhibited in Figure 5.24. The black vertical line represents the transition when these five nodes change their role from providing assistance to requiring assistance. The flat period in Figure 5.24 in position 1 represents that either the node has ran out of its battery power or is asking for too much price and the secondary user cannot afford to pay. In position 2 the flattening means that node has exhausted its credits bank or in other words its budget has been fully used and has no more budget to buy relaying service for itself.

Figures 5.25, 5.26 and 5.27 present the comparison of the price received by a node as the relay for its services vs the cost it experienced, the cost incurred by it as the relay for its services vs the utility it gained as the secondary user and the cost incurred by it as the relay vs the data rate it received as the secondary user in case of the CF-RS protocol, respectively. From Figures 5.25, 5.26 and 5.27, it is clear that even though the in-range users experience a cost when helping the out-of-range users it is still advantageous for them to participate in the relaying process considering the benefits provided by the CF-RS protocol in terms of credits, utility and data rate.

Figure 5.24 Accumulation of credits when acting as the relay and usage of credits when become the secondary user for the *CF-RS* protocol

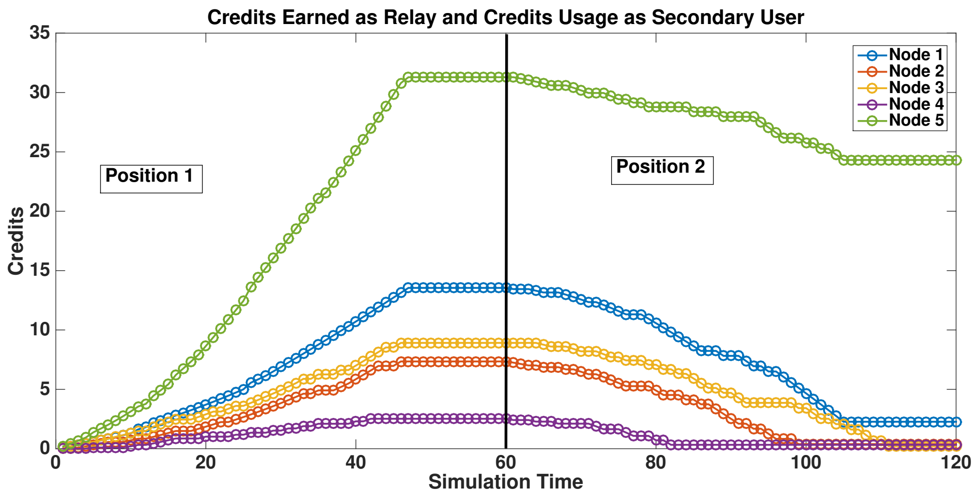


Figure 5.25 Comparison of price received by a node as relay for its services vs the cost it experienced for the *CF-RS* protocol

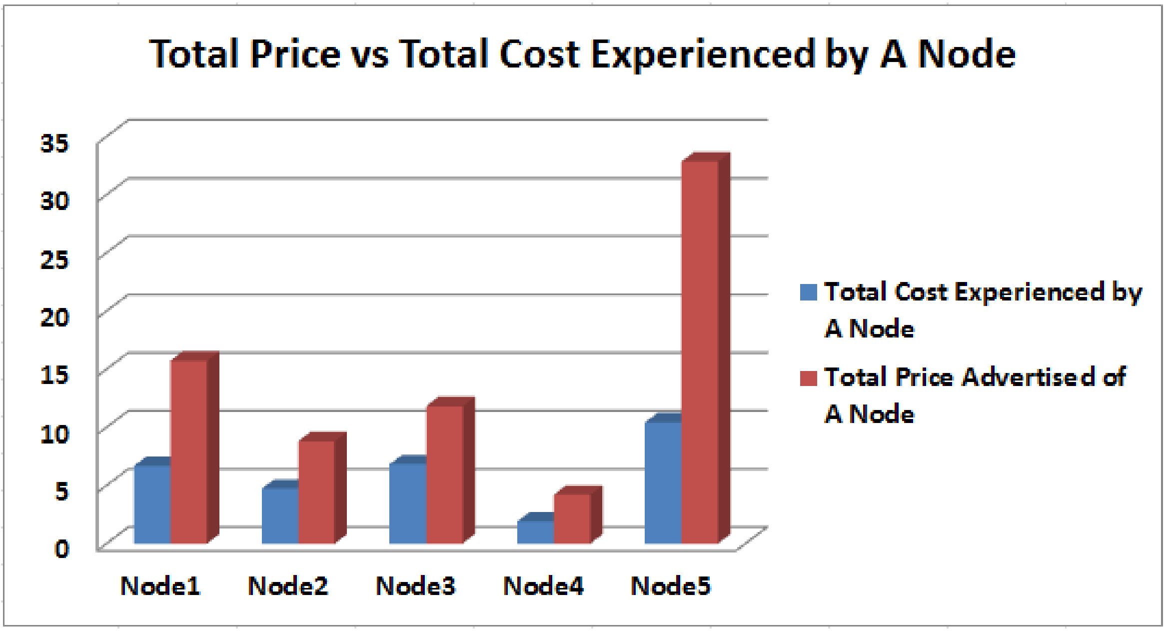


Figure 5.26 Comparison of cost incurred by a node as relay for its services vs the utility it gained as the secondary user for the *CF-RS* protocol

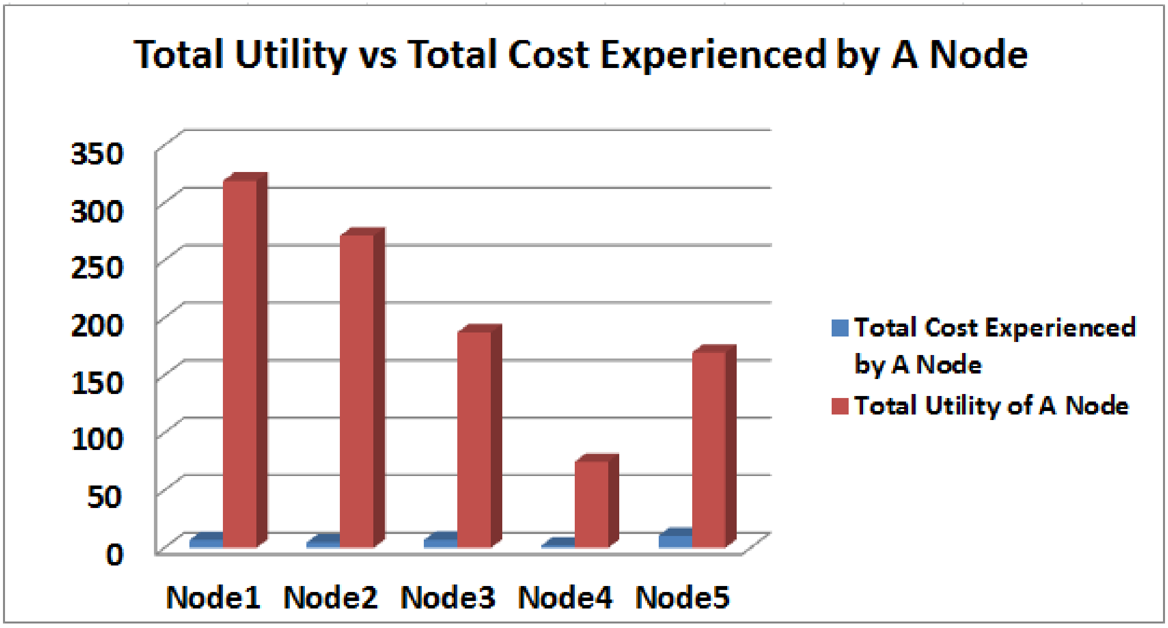


Figure 5.27 Comparison of cost incurred by a node as relay for its services vs the data rate it received as the secondary user for the *CF-RS* protocol

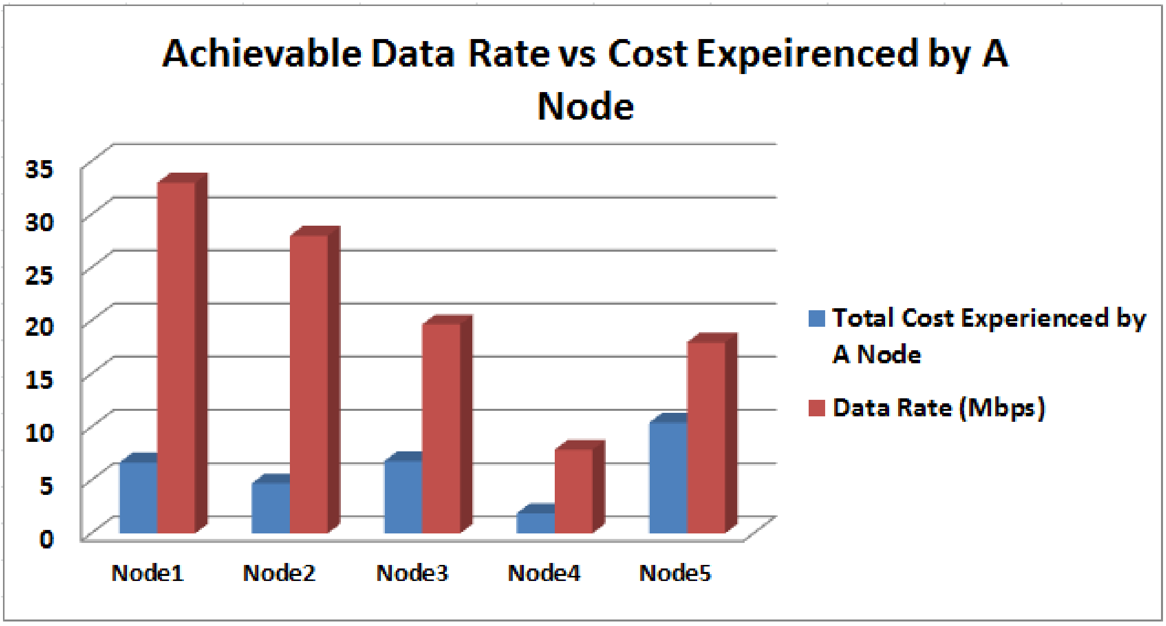
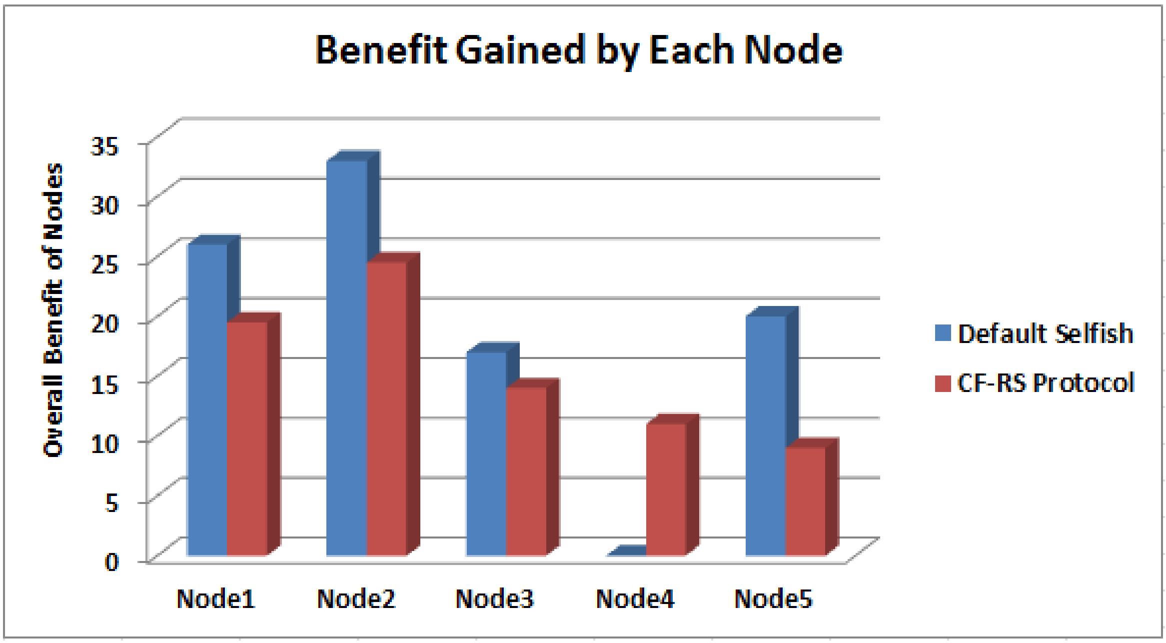


Figure 5.28 Overall benefit attained by nodes when default algorithm considering selfish primary users asking for price, irrespective of their cost and *CF-RS* protocol are used



Variation2:

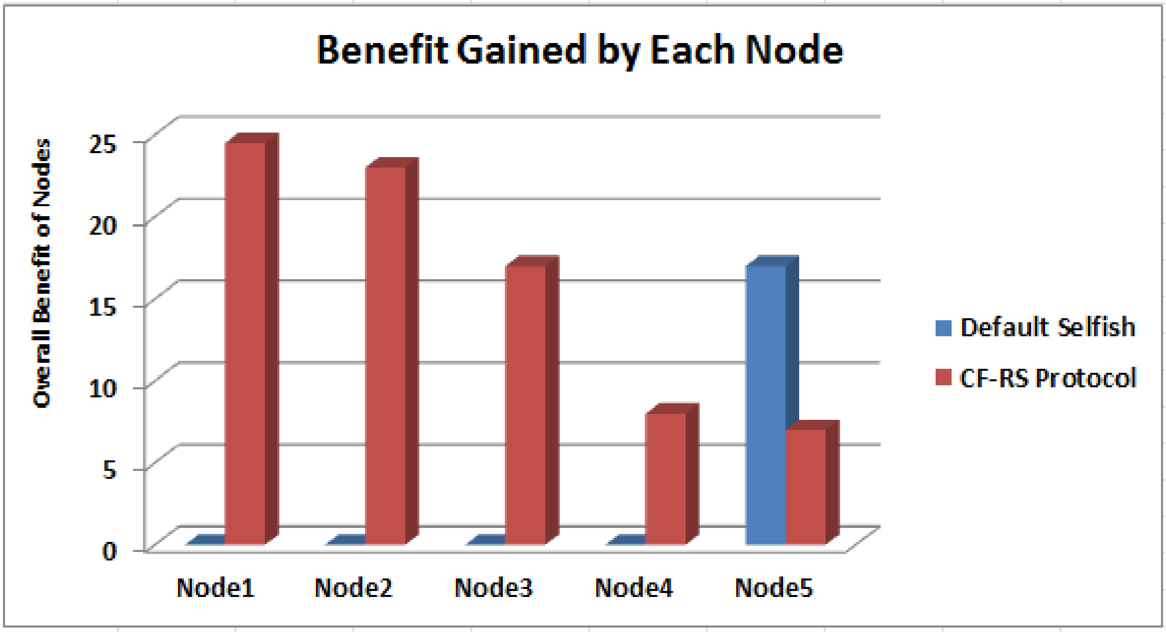
In variation2, since the primary users are selfish for the default algorithm as well, but there is no mechanism to incentivize them to act as relays, they are not going to take part in providing relaying service to the secondary users. When these selfish users move out of direct transmission range of the AP, they can only access their data through obedient relays if there are any. Whereas in case of the CF-RS protocol the credit based mechanism encourages these selfish users to help the secondary users considering their own benefit.

Variation3:

In variation3, the default algorithm also offers price to the primary users assisting the secondary users irrespective of the cost in terms of battery power consumption they undergo. Figure 5.28 shows the overall benefit gained by the nodes $N1$, $N2$, $N3$, $N4$ and $N5$ when the default algorithm and the *CF-RS* protocol are used for relay selection. In case of the *CF-RS* protocol, the benefit is more evenly distributed among the five nodes as compared to the default algorithm. Also node $N4$ receives almost negligible benefit. This is because in position 1 of Figure 5.20, in case of the default algorithm $N4$ has no incentive to help the secondary users, thus earns zero credits and cannot avail for itself relaying services when it becomes a secondary user in position 2 of Figure 5.20. Also the cost of providing assistance as well as fair dissipation of battery power of relays have not been taken into account while determining the willingness of the primary users to act as the relays for the default algorithm.

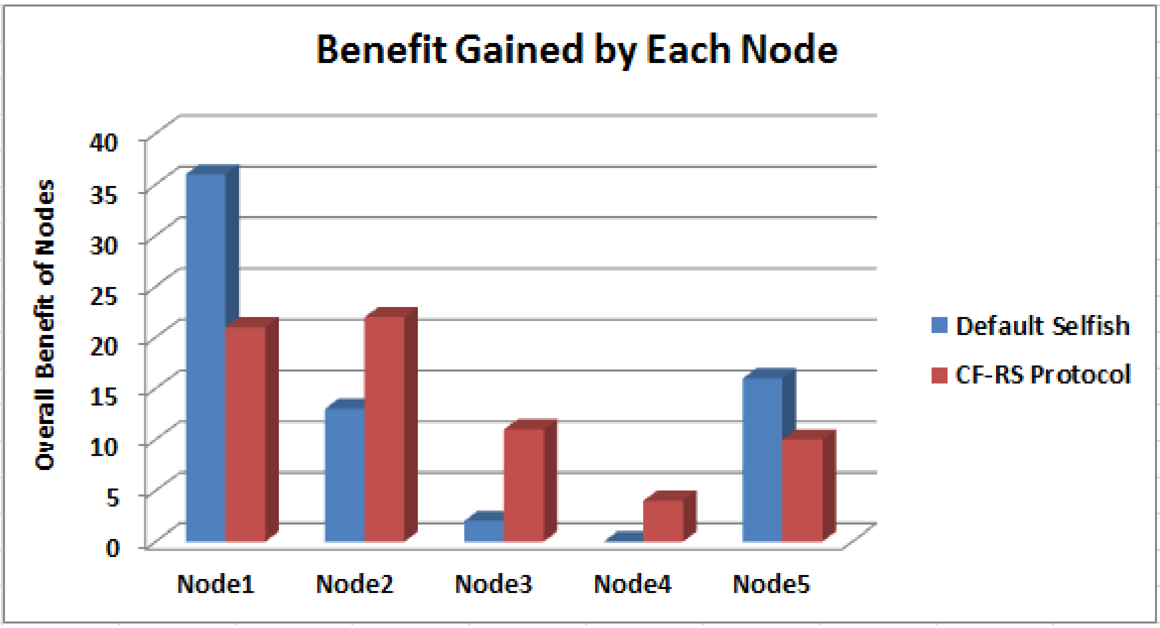
Variation4:

Figure 5.29 Overall benefit attained by nodes default algorithm considering selfish primary users with price as well as consideration for relay's cost and *CF-RS* protocol are used



Since there is no mechanism in the case of the default algorithm to implement fair utilization of battery power relays, when the cost is used to determine the price of providing assistance, the price advertised by the nodes $N1$, $N2$, $N3$ and $N4$ is high and no secondary user can afford to pay for their services. Therefore when $N1$, $N2$, $N3$ and $N4$ become secondary users in position 2 of Figure 5.20, they have no budget/ credits to purchase the relaying service for themselves. Whereas the CF-RS protocol uses the credit based mechanism which

Figure 5.30 Overall benefit attained by nodes for test case scenario 2 where the primary and secondary users swap their positions multiple times.

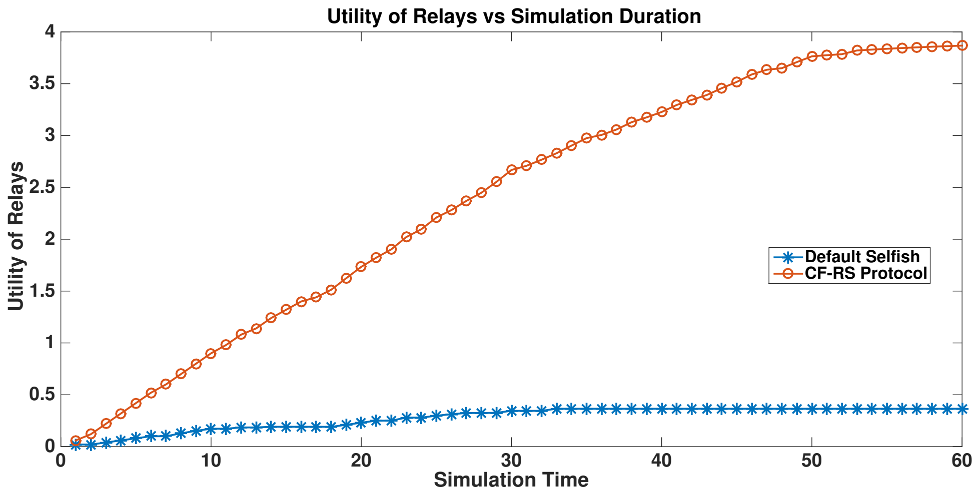


ensures fair utilization of battery power keeping the cost experienced by the relays under control, thus all five nodes $N1$, $N2$, $N3$, $N4$ and $N5$ get the opportunity to earn credits and utilize them when they move outside the coverage range of the AP as shown in Figure 5.29.

For the test case scenario 2, the primary and the secondary users exchange their roles four times as depicted in Figure 5.21. In positions 1 and 3 (in positions 1 and 4) of Figure 5.21 nodes $N1$ and $N2$ ($N3$, $N4$ and $N5$) are the primary users whereas in positions 2 and 4 (positions 2 and 3) they become the secondary users. In the test case scenario 2 of swapping of roles, the default algorithm with pricing irrespective of the relaying cost for the selfish primary users is considered.

Figure 5.30 displays the overall benefit gained by nodes $N1$, $N2$, $N3$, $N4$ and $N5$ swapping their role as the primary and secondary users multiple times during the simulation period of 120 slots, twice acting as the relay and twice as the secondary user. Even when the nodes change their roles multiple times, all nodes receive benefit when the *CF-RS* protocol is used. Whereas the default algorithm provides benefit to only $N1$, $N2$ and $N5$ and almost negligible

Figure 5.31 Cumulative utility of nodes $N1$, $N2$, $N3$, $N4$ and $N5$ for test case scenario 2 when acting as relays



to $N3$ and $N4$, thus giving no long term benefit to $N3$ and $N4$ to assist the secondary users. Therefore, the cumulative utility achieved by $N1$, $N2$, $N3$, $N4$ and $N5$ when helping the secondary users is approximately 80% less than that achieved with the CF-RS protocol as depicted in Figure 5.31

5.3 Summary

In this chapter, the performance of the *FBPC* algorithm and the *CF-RS* protocol have been compared with the default algorithm which employs SINR as the relay selection parameter. In terms of fair utilization of battery power of the primary users, the *FBPC* algorithm accomplishes approximately 100% fairness but at the expense of the data rate achievable at the secondary users. Whereas the *CF-RS* protocol achieves nearly 80% fair utilization of battery power and provides 25-45% and 65-85% better data rate compared to that achieved with the default and the *FBPC* algorithms, respectively. In terms of utility of the secondary user, again the *CF-RS* protocol outperforms the default algorithm by 45% and the *FBPC* algorithm by 55%. The difference in the data rate between the *CF-RS* game and the default algorithm increases with increase in data demand from the secondary user whereas the difference in terms of Jain's fairness index decreases with increase in data demand.

The performance of the *CF-RS* protocol has also been evaluated when the secondary users have limited/finite budget to pay to access the relaying service. In terms of data rate with finite budget for the secondary users, the *CF-RS* protocol attains 85% better results compared to the default algorithm with finite budget. The *CF-RS* protocol achieves 90% fair consumption of batter power in contrast to only 40% achieved by the default algorithm. Since the public network may comprise of self-interested users, the *CF-RS* protocol provides 50% better utility to the primary users, thus giving them good incentives to help the secondary users.

Four different sets of positions of primary and secondary users have been chosen to analyse the impact of position of relays on performance of the *CF-RS* protocol. In all four configurations, the *CF-RS* protocol outperforms the default algorithm, however the maximum benefit with *CF-RS* protocol is achieved in scenarios where the distance between the primary and the secondary users is large. To evaluate the long term benefit provided by the *CF-RS* protocol, two test case scenarios with primary and secondary users exchanging their roles have been considered. From the results obtained in subsection 5.2.5, it can be clearly seen that the *CF-RS* protocol provides longer service time compared to the default algorithm. The *CF-RS* protocol provides enough incentives to encourage the self-interested in-range users to take part in the relaying process and provides long term benefit to all participating users. Despite the cost experienced when relaying data for the out-of-range users, it is beneficial for a node to act as a relay considering its overall benefit in terms of earned credits, utility and data rate when the *CF-RS* protocol is used for relay selection.

Chapter 6

Conclusion

Provision of the Internet access is essential for the social and economic development of rural communities. Compared with urban and sub-urban areas, the broadband providers face completely different challenges in rural areas owing to the topography of the rural areas and sparsely populated rural communities. Various solutions using satellite communication, WiFi technology [24, 29, 28, 6, 30] and [31] and IEEE 802.22 standard [34] have been proposed to provide Internet access to rural populations. However, even with the wireless broadband access technologies, it is still very hard to reach every user in rural settings. Cooperative communication utilizing the ordinary in-range users to relay data for the out-of-range users is an effective technique to extend the coverage range of an existing wireless network without deploying any extra infrastructure to reach larger number of users in rural environments.

The relay selection problem employing the in-range ordinary users as relays to expand wireless networks in rural settings has been analysed in this thesis. Optimization theory and game theory are two commonly used mathematical tools to model the relay selection problem in wireless networks. However, game theory is a handier tool in the scenarios in which participating entities or agents have conflict of interest. Since the problem studied in this thesis comprises of self-interested in-range users who are predominately interested in their own benefit and need to be given incentives to help the out-of-range users, therefore game theory has been utilized to address the relay selection problem in rural wireless networks.

Two heuristic relay selection solutions have been formulated. In addition to extending the transmission range, the objective of both solutions is to provide fair opportunity to all in-range users termed as the primary users to participate in the relay selection process so that their battery power is consumed fairly. The first solution called the Fair Battery Power Consumption (*FBPC*) relay selection algorithm focuses only on fair utilization of battery power of the primary users and primary users behave obediently until their battery power is above a pre-defined threshold value. The ratio of cumulative to instantaneous battery power consumption is used as the relay selection criterion and the primary user with the minimum ratio is chosen as the relay for the out-of-range secondary user. Since the *FBPC* relay selection algorithm uses fair utilization of battery power of primary users as the selection criterion, this results in data rate achievable at the secondary users being compromised. The public networks are also composed of selfish users which need to be given incentives in order to persuade them to act as relays for the other users of the network.

To overcome the shortcomings of the *FBPC* relay selection algorithm, a Credit based Fair Relay Selection (*CF-RS*) game has been developed, outlining the strategy sets for the primary and secondary users at every step of the game. The *CF-RS* game has been mathematically analysed to determine the expression for the optimal value of power and price that maximizes the utilities of the primary and the secondary users. Utility of a primary user depends on the cost it experiences while providing relaying service and the price it receives from the secondary users for its relaying service. Whereas the utility of the secondary users depends on the data rate achieved with the help of the primary users and the price paid to the primary users for their services. The designed *CF-RS* game forms the foundation of the *CF-RS* protocol to model the interaction between the primary and the secondary users and uses credits as incentives to encourage the self-interested primary users to provide relaying service to the secondary users. The secondary users pay the primary users for their forwarding service and the payment made to the primary user becomes its credit. In addition to using the ratio of battery power consumption, the *CF-RS* protocol takes into account the data rate achievable at the secondary users when choosing the suitable relay for the secondary user, this accomplishes better data rate and utility for the secondary users compared to the *FBPC* algorithm.

A flexible pricing function has also been formulated, given in equation(4.18), for the *CF-RS* protocol which gives a primary user more freedom to choose the price for its forwarding service using its available battery power and channel conditions which enables the primary user to provide longer service to the secondary users. The *CF-RS* protocol, along with giving instantaneous benefit, also provides long term benefit to the primary users i.e. the credits earned as a relay can be utilized to buy data forwarding service when the primary user moves out of the transmission range of the AP and becomes the secondary user.

A specialized simulator has been formulated using MATLAB to evaluate the performance of the *FBPC* relay selection algorithm and the *CF-RS* protocol. The *FBPC* relay selection algorithm and the *CF-RS* protocol are compared with a default algorithm which uses SINR as relay selection parameter and the primary users with best channel conditions are repeatedly selected as relays until their battery power is greater than 50% of their initial battery power. A basic network model, presented in Figure 3.1, operating in 802.11b mode at 2.4 GHz frequency and 22 Mbps bandwidth consisting of 5 primary users and 10 secondary users is simulated. Secondary users are located at a distance of 75m or more from the AP and primary users are within the transmission range of the AP. In the simulated network model, a secondary user can avail relaying service of only one primary user at a time and primary user's relaying cost is calculated using its cumulative to instantaneous battery power consumption. Bernoulli distribution has been used to model the data demand of the secondary users in each simulation time slot.

All three relay selection solutions are first examined considering infinite budget for the secondary users. The *FBPC* algorithm accomplishes approximately 100% fairness for utilization of battery power of primary users but at the expense of the achievable data rate at the secondary users. Whereas the *CF-RS* protocol achieves nearly 80% fair utilization of battery power and provides 65-85% and 25-45% better data rate and 55% and 45% better utility for the secondary users compared to the *FBPC* and the default algorithms respectively. The impact of variation in data demand from the secondary users on attainable data rate and Jain's fairness index for battery power utilization have also been analysed when the default algorithm and the *CF-RS* protocol are used. The simulation results show that the difference in the data rate between the *CF-RS* game and the default algorithm increases with increase in data demand from the secondary user whereas the difference in terms of Jain's fairness index decreases with increase in data demand.

In practical systems, secondary users have limited budget to buy services from the relays and simulation results confirm that even with limited budget, the *CF-RS* protocol attains 85% better data rate compared to the default algorithm with finite budget. The *CF-RS* protocol with finite budget for secondary users achieves 90% fair consumption of batter power in contrast to only 40% achieved by the default algorithm. Since the public network may comprise of self-interested users, to verify the *CF-RS* protocol provides better utility to the selfish primary users compared to the default algorithm, the average and individual utility of the primary users have been examined. The results show that the *CF-RS* protocol provides 50% better average utility to the primary users, thus giving them good incentives to help the secondary users.

To analyse the impact of position of relays on performance of the *CF-RS* protocol, four different sets of positions of primary and secondary users have been chosen. In all four configurations, the *CF-RS* protocol outperforms the default algorithm; however the maximum benefit with *CF-RS* protocol is achieved in network scenarios in which the primary users are located far from the secondary users. Two test case scenarios with primary and secondary users exchanging their roles have been considered to evaluate the long term benefit provided by the *CF-RS* protocol. From the results obtained in subsection 5.2.5, it can be clearly seen that the *CF-RS* protocol provides longer service time compared to the default algorithm. The *CF-RS* protocol provides enough incentives to encourage the self-interested in-range users to take part in the relaying process and provides long term benefit to all participating users. Despite the cost experienced when relaying data for the out-of-range users, it is beneficial for a node to react as a relay considering its overall benefit in terms of earned credits, utility and data rate when the *CF-RS* protocol is used for relay selection.

6.1 Future Work

- The proposed *CF-RS* protocol has been tested under the scenario where the in-range and the out-of-range users swap their positions i.e. some of the primary users move out of the transmission range of the AP and become secondary users. Future work can comprise of performance evaluation of the *CF-RS* protocol under different mobility models and network scenarios with high mobility users. Different mobility models that can be considered for testing the performance of the *CF-RS* protocol are: random work, random way-point, random direction, weighted way-point and Gauss-Markov model etc.

- Interference avoidance is an important aspect of 802.11 based networks, though network model simulated to evaluate the *CF-RS* protocol did take into account the interference generated by the neighbouring nodes, still detailed mathematical analysis of interference and interference mitigation scheme is needed for *CF-RS* protocol. An approach similar to that proposed in [154] and [155] can be used as interference avoidance mechanism.

- It has been assumed for the *CF-RS* protocol that the primary users are reliable and trustworthy i.e. the integrity and confidentiality of the secondary user's data is maintained while being relied by the primary users. However, this assumption might not always be valid, since the primary users may behave maliciously. Thus the *CF-RS* protocol needs to include measures to ensure that the data for the secondary user is secure and protected. The concept of block-chain and different data encryption algorithms can be used to protect the integrity and confidentiality of secondary users' data.

- Future work can also include hardware implementation the *CF-RS* protocol using Android mobile phone to perform experimental evaluation of the proposed *CF-RS* protocol. Development of a mobile application will also be required for realistic implementation of the *CF-RS* protocol. The concept of *CF-RS* protocol can also be applied to vehicular communication to analysis the overall benefit achievable with *CF-RS* protocol.

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