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Socially Aware Resource Allocation Scheme for Downlink Orthogonal Frequency Division Multiple Access (OFDMA) Networks

by

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Abstract

A two-hop based socially aware scheme is proposed for resource allocation in the downlink of Orthogonal Frequency Division Multiple Access networks. An optimization problem has been formulated with the objective to maximize the overall network utility and the data rate achieved by the users of a network plagued by limited bandwidth, limited power and user selfishness. Degree and eigenvalue centrality metrics capture the social awareness of the users. The mixed integer non-linear programming optimization problem formulated is solved using the advanced integrated multidimensional modeling system optimization solvers. The proposed scheme is compared to conventional allocation schemes using system spectral efficiency, system fairness index and overall network utility performance metrics. Numerical results show that employing the proposed scheme for dense networks achieves performance improvement of approximately 75% in terms of spectral efficiency, up to 50% in terms of fairness and up to 7% in terms of utility over the conventional schemes.

Preface

This thesis includes some materials (e.g. figures, texts, and tables) submitted in one conference paper as follows:

V. Shah, and A.O. Fapojuwo, "Socially Aware Resource Allocation in Downlink Orthogonal Frequency Downlink Multiple Access (OFDMA) Networks," submitted to *IEEE Wireless Communications and Networking Conference (WCNC),* pp. 1-6, Apr. 2014.

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To Mom, Dad, Vinesh and Sarla Faiba.

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List of Abbreviations

Acronym	**Meaning**
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
BS	Base Station
MA	Most Active user
FIFO	First In First Out
TDMA	Time Division Multiple Access
SFI	System Fairness Index
SSE	System Spectral Efficiency
RRM	Radio Resource Management
QoS	Quality of Service
RT	Real Time applications
NRT	Non Real Time applications
VoIP	Voice over Internet Protocol
FTP	File Transfer Protocol
WWW	World Wide Web
CSI	Channel State Information
NGN	Next Generation Network
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Networks
MSN	Mobile Social Network
SNA	Social Network Analysis
NP-hard	Non-deterministic Polynomial-time-hard
NLP	Non-Linear Programming problem
MINLP	Mixed Integer Non-Linear Programming problem
LP	Linear Programming problem
MILP	Mixed Integer Linear Programming problem
MATLAB	Matrix Laboratory
AIMMS	Advanced Integrated Multidimensional Modeling Software
OA	Outer Approximation
B&B	Branch-and-Bound
AOA	AIMMS Outer Approximation
BARON	Branch-And-Reduce Optimization Navigator

List of Symbols

Symbol	**Definition**
$C_{degree,g}$	Degree Centrality of node g
$C_{betweenness,g}$	Betweenness Centrality of node g
$C_{closeness,g}$	Closeness Centrality of node g
$C_{eigen,g}$	Eigenvalue Centrality of node g
B	Total bandwidth available in the network
N	Total number of subcarriers in the network
J	Total number of communities in the network
K	Total number of users in the network
n	Subcarrier index, $n \in [1,2,.., N]$
j	Community index, $j \in [1,2,.., J]$
k	User index, $k \in [1,2,.., K]$
k^*	Most Active user in community j.
B_{sub}	Bandwidth of a subcarrier n
P_{max}	Total transmission power of the Base Station
$h_{PL_{n,k}}$	Path-loss (in dB) experienced by a user k receiving on subcarrier n
$h_{S_{n,k}}$	Lognormal Shadowing random variable
$h_{F_{n,k}}$	Rayleigh Fading
$h_{n,k}^{Total}$	Total attenuation experienced by the signal carried by subcarrier n which has been allocated to user k
N_j	Subset of subcarriers allocated to community j
K_j	Total number of users in community j
$H_{n,k,j}$	Gain calculated for user k belonging to community j receiving over subcarrier n
$SNR_{n,k}$	Signal-to-noise ratio for user k on subcarrier n
ζ	System Fairness Index
$SE_{n,k}$	Spectral Efficiency of user k
$U_{k,j}$	Utility of user k belonging to community j
U_{min}	Minimum utility value
U_{max}	Maximum utility value
$s_{n,k,j}$	Subcarrier allocation variable. Indicates subcarrier n is allocated to user k belonging to community j.
$p_{n,k,j}$	Power allocation variable. Indicates power allocated to subcarrier n assigned to user k belonging to community j.
$x_{k,j}$	Social metric value of user k belonging to community j
$P_{k^*,j}$	Transmit Power of the most active user k^* belonging to community j
$R_{k,j}^{min}$	Minimum data rate requirement of user k belonging to community j

$R_{k,j}$	Data rate achieved by user k of community j
$R_{k^*,j}$	Data rate achieved by the most active user k^* of community j
$R_{k^*\rightarrow k,j}$	Data rate achieved by user k belonging to community j when content transfer takes place from the most active user k^* of community j to user k
$\mathrm{R}_{\mathrm{end-to-end}}$	Achievable data rate of a two-hop path
q_k	Variable used to transform the max-min optimization formulation objective to maximization based objective.
x_{max}	Maximum social metric value possible for a user
R_{max}	Maximum data rate a user can achieve

Chapter 1: Introduction

1.1 Problem Definition and Motivation

A social network is a structure made up of users (individuals and/or organisations) and the ties connecting them. It can be represented as a graph i.e., a social graph where the nodes represent the network users and the edges represent the relationship (e.g. friendships, common interests, subscription to common services, etc.) between the users they connect [1], [2], [3]. Recently, social networks and their applications have attracted a great amount of attention of several researchers working in various fields [1]. Every entity (an individual, an organisation, etc.) is connected to the other entities in some way. Entities sharing common interests form groups using social network applications and share data amongst themselves.

Today, the mobile devices available for usage are technologically advanced. These devices not only perform the task of placing a call or text messaging, but also provide a connection to the internet, along with possessing high storage and computational capacity [1], [2]. Due to this ability of the devices, users are enabled to access various social network applications via their devices. Mobile devices have become part and parcel of daily lives of billions of people worldwide [2]. This helps create a sense of "every time connectedness" among the users and realize the notion of share "whatever-whenever-wherever", which is the main idea behind social networking applications such as Facebook[1], Twitter[2], YouTube[3], etc. [4], [5]. As mobile devices are already used by almost everyone everywhere, they possess the ability to become the main sources for collecting data of the environment they belong to. This data can help in improving the services provided by a network;

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[1] www.facebook.com
[2] www.twitter.com
[3] www.youtube.com

thereby, creating a new research area in regards to content exchange, sharing and delivery [1]. This gives rise to the concept of mobile social networks (MSNs), which are a combination of social network and mobile wireless network disciplines. They possess the ability to access, share and distribute data to a particular group (or a community) of mobile users sharing the same interest [1].

In a wireless network, communication between two users does not occur in a random manner, it depends on the relationship existing between any pair of users [6]. Social network analysis helps determine the relationship existing between the pair of users. Literature suggests that social network awareness can help resolve various network related issues such as resource management, network planning, meeting users' quality of service (QoS) requirements, mobility management, etc. [1], [2].

Community detection, content-aware data transfer, privacy and security in relation to social networks are well researched fields. However, resource management and QoS support in socially aware wireless networks i.e., the effect of social relations existing among users on resource management in such networks is still an open research issue [1], [2]. Resource management in a wireless network utilizes available resources efficiently to guarantee a certain level of QoS for the network users depending on their QoS requirements [7]. However, very limited amount of resources are available in a wireless network to support the needs of the ever growing network users. Thus, resource management techniques have to be implemented to achieve efficient resource utilization in the wireless network [7]. A Next Generation Network (NGN) is a packet based network that supports various types of data services such as voice, data, World Wide Web browsing, email and multimedia [8]. In references [6], [8]-[10], bandwidth allocation in NGN has been studied by introducing the social awareness of the existing users in the network in form of social distance parameter. However, to the best of author's knowledge, a resource allocation scheme for Orthogonal

Frequency Division Multiple Access (OFDMA) networks using the awareness of the social relations existing among the users in the underlying network has not been proposed in literature.

In an OFDMA network, for resource management, the total bandwidth available in the network is divided into subcarriers and the transmission power is allocated to these subcarriers. These subcarriers are distributed among the network users [8]. This thesis proposes a two-hop based socially aware resource allocation scheme (joint subcarrier and power as well as fixed power allocation) to efficiently allocate resources to users in an OFDMA-based wireless network. The impact of the awareness about the social relations existing among the network users on the resource allocation performed using the provisioned network resources has been studied here.

1.2 Thesis Objectives and Contributions

1.2.1 Thesis Objectives

The main objective of this thesis is to propose a resource allocation scheme, with the ability to exploit the awareness of the existing social relationship among the users in the underlying wireless network. This social awareness will be used for the purpose of efficiently using the network resources for downlink transmission and to evaluate its performance. Specifically, this thesis provides answers to the following research questions:

- How is the awareness regarding the relationship existing between users introduced in the network? [Chapter 4].
- How well does the proposed socially aware resource allocation scheme perform in comparison to the existing conventional resource allocation schemes? [Chapter 6].
- Is the proposed scheme scalable? Scalability helps determine whether practical implementation of the proposed scheme for very large networks is possible. [Chapters 6 and 7].

- Is joint subcarrier and power allocation necessary or is performing fixed power based resource allocation sufficient to achieve an acceptable level of performance? [Chapter 6].

1.2.2 Thesis Contributions

The main contributions of this thesis are twofold. The first contribution is the proposal of a two-hop based socially aware resource allocation scheme for a downlink OFDMA-based wireless network. The second contribution is the performance evaluation of the proposed scheme to assess its effectiveness relative to the conventional resource allocation schemes, under different network operation scenarios. The details of these contributions are summarized as follows.

- Selection of Social Metrics: The social metrics existing in the literature to measure the relative importance of a user in the network are reviewed. Centrality metrics determine the influence of users in their network. Based on the need to determine the most active (MA) users in the network in terms of their communication activities (i.e. popularity and degree of influence in the network), degree centrality and eigenvalue centrality metrics are chosen to determine the social standing (or social metric value) of the user in the network and their community [Chapters 2 and 3].
- Proposed Socially Aware Utility Function: A utility function helps determine the network users' satisfaction levels, when a certain amount of resources are allocated to them. In order to introduce the social metric value of a user in the network, the existing utility function which generally depends on the data rate achieved by the network user has been modified. A socially aware utility function has been proposed in this thesis. This utility function is formed by integrating the social metric value of a network user into already existing utility function in the literature [Chapter 4].

- Proposed Optimization Formulation: A two-hop based socially aware resource allocation based optimization problem has been formulated to assign resources to the users of a network which has been partitioned into non-overlapping communities. [Chapter 4].
- Implementation Framework: The formulated optimization problem is a Mixed Integer Non-Linear Programming (MINLP) problem in nature due to the existence of binary, positive variables and non-linear objective function. A performance evaluation framework has been developed. It is based on implementing the socially aware wireless network and usage of Advanced Integrated Multidimensional Modeling Software (AIMMS) based MINLP solvers for resolving the proposed optimization formulation. A conventional wireless network (i.e. socially unaware network) and conventional optimization formulation for resource allocation in the said network have also been implemented and resolved using the performance evaluation framework [Chapter 5].
- Performance Evaluation: The performance of the proposed socially aware resource allocation scheme has been compared to that of the conventional resource allocation schemes by using performance metrics such as system fairness index, system spectral efficiency and overall network utility under different network operation scenarios. The performance of the proposed scheme using degree centrality metric to determine social metric value of a user is also compared to the performance of the proposed scheme when eigenvalue centrality metric is used [Chapter 6].

1.3 Thesis Organisation

The remainder of the thesis is organised as follows.

Chapter 2 provides a background on resource allocation in wireless networks, multi-hop and relay based wireless networks, social networks and optimization formulations used for resource management. The result of the background study led to the identification of the problem to be solved, the social metrics to be used and the network architecture to be considered.

In Chapter 3, the system model of the downlink OFDMA network used in this thesis has been described in detail. It includes the description of the network architecture and propagation environment implemented for this thesis. The social metrics to be used to characterize the social awareness of the underlying network are described in this chapter. The performance evaluation metrics used to compare the proposed scheme to the conventional schemes are also discussed in detail.

Chapter 4 presents the proposed socially aware resource allocation scheme to allocate the resources (subcarrier and power) in a socially aware downlink OFDMA network. A MINLP optimization problem has been formulated. This chapter also discusses the proposed socially aware utility function in detail.

Chapter 5 presents the verification of the implemented solution model and validation of the proposed utility function.

Chapter 6 defines the several experiments that are conducted under different scenarios and network conditions. The results are presented and discussed in detail. Findings from the results demonstrate that for networks with 6-15 users, usage of social awareness for resource management does not provide significant benefits as compared to conventional resource allocation scheme. However, as the network size increases i.e. when the number of communities (i.e. 5 communities), users per community is large (i.e. 5 and 6) and the individual user minimum data rate requirements are high (e.g. 1Mbps and 2Mbps), using social awareness for resource management helps attain a significant improvement in performance as compared to the conventional resource allocation schemes.

Chapter 7 presents the concluding remarks and suggested directions for future work.

Chapter 2: Research Background

2.1 Introduction

This chapter provides the background to the two-hop socially aware resource allocation scheme proposed in this thesis for a downlink Orthogonal Frequency Division Multiple Access (OFDMA) wireless network. The features of wireless networks, social networks, multi-hop and relay networks are presented in this chapter. Also, the existing optimization based resource allocation schemes for OFDMA networks are reviewed. In order to better understand the proposed work, it is necessary to understand the above mentioned network architectures along with the need to perform resource allocation in such networks.

This chapter is organized as follows. In section 2.2, various network architectures considered in this thesis are discussed. Need for radio resource management (RRM) and quality of service (QoS) support for wireless network is discussed in section 2.3. Features of Orthogonal Frequency Division Multiplexing (OFDM) and OFDMA are discussed in section 2.4. Section 2.5 summarizes various optimization formulations used for RRM purposes in wireless networks. An overview of similarities and differences between the previous work done in literature and the proposed work is provided in section 2.6, followed by a summary of the chapter in section 2.7.

2.2 Network Architectures

2.2.1 Wireless Networks

A wireless network is a network that provides its users with their required services i.e. voice, data and multimedia services on demand, thereby creating a sense of obtaining and sharing "whatever-wherever-whenever" amongst them [2], [7]. Wired and wireless networks are the two types of communication networks used for the purpose of transmitting data from one point to the other [11]-[13]. The main difference between wired and wireless communication systems is that the wired systems use cables (i.e. copper and/or fiber optic) between communicating devices whereas a tetherless link (e.g. a wireless channel) is used by wireless systems. In a wireless network, the communicating devices use radio frequency signals (wireless links) to communicate amongst themselves. A wire or cable has stationary characteristics. In contrast in a wireless network, the propagation environment between the transmitter and the receiver varies constantly thus making the wireless channel change with time. The wireless channel is not only susceptible to noise, interference, and other channel problems, but also to user mobility which causes the channel to vary in unpredictable ways. Wireless networks can be further divided into fixed wireless networks and mobile wireless networks. A fixed wireless network helps connect users present in two fixed locations (e.g. Microwave Networks, Satellite Networks, and Wireless Metropolitan Area Networks (WMAN)). The users in a wireless network are generally mobile hence forming a mobile wireless network. A mobile wireless network can be further divided into an infrastructured and an infrastructure-less wireless network. In an infrastructured network, a centralized controller (e.g. a Base Station (BS) in a cellular network which is a fixed station used for radio communication with mobile users [13]) serves mobile users in a given cell area by performing tasks such as scheduling, resource allocation, power control and hand-off. Whereas, in an infrastructure-less network, a centralized controller is absent and users existing within transmission range of each other communicate with each other in a peer-to-peer manner [7], [11]-[13]. Figure 2.1 shows comparison of an infrastructured and an infrastructure-less wireless network.

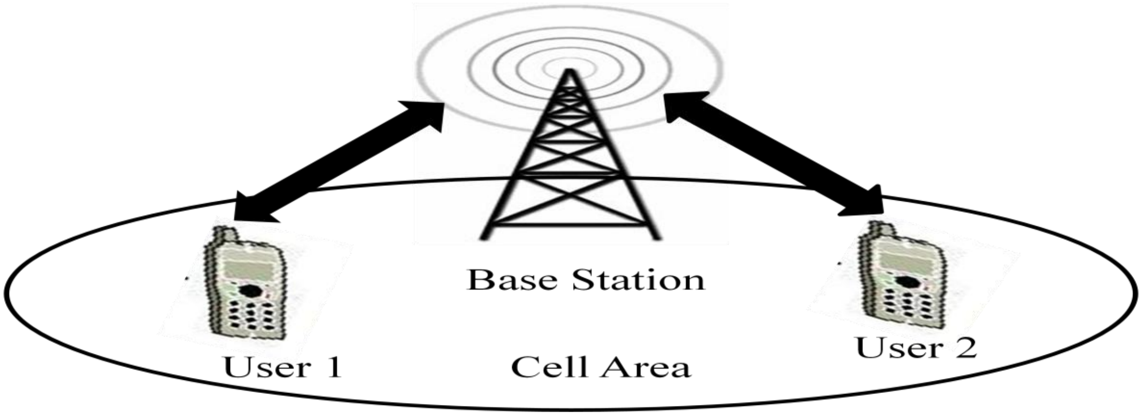

Figure 2.1.a Infrastructure based Wireless network

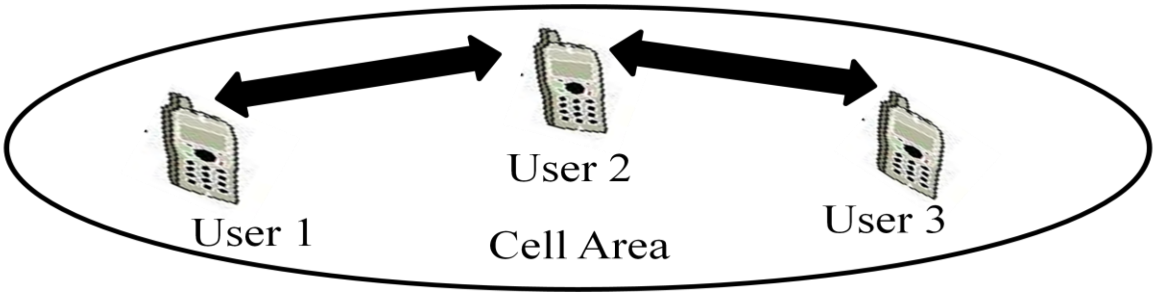

Figure 2.1.b Infrastructure-less Wireless network

2.2.1.1 Features of Wireless Networks

- Support Mobility of network users: Users are free to roam around in the cell area while accessing the network services as no cables are used for communication, hence these networks are convenient to use [7], [11]-[13].
- Fulfill QoS requirements of network users: The centralized controller possess the ability to perform highly computational tasks such as resource management so as to ensure that the requirements of the network users are satisfied [7], [11]-[13].
- Perform handover of calls for users when they move from one cell to another [7], [11]-[13].
- Cost effective: Does not use wires or cables for connectivity, hence cost effective in the long run as no cabling and wire replacements are needed [7], [11]-[13].

- Flexible, scalable and generally compatible with different kinds of networks [7], [11]-[13].

2.2.1.2 Challenges faced by Wireless Networks

- Network resources available are limited, thus meeting the QoS needs of rapidly growing number of users can be very challenging [7].
- Peer-to-peer data sharing may not always be successful as users are mobile and may not be present within each other's transmission range and due to limited availability of mobile device resources.
- Wireless links suffer interference and noise which could lead to poor and inaccurate resource allocation [7], [11]-[13].

2.2.2 Social Networks and Social Network Analysis

Social networks are structures consisting of users connected to each other based on the relationships between them, such as friendships, common interests, etc. They are represented using social graphs, where users are represented by nodes and the relationship between users are represented by edges [6], [8], [14], [15]. When a social network is overlaid on an existing wireless network, the nodes in the social graph formed represent the wireless network user i.e. the user device and the edges represent the communication links between these devices.

Social network analysis examines the social graphs to determine the relations between the individuals and/or organisations, locate central users and study network dynamics [14], [15]. The knowledge of the social behaviour of users incorporates awareness of the underlying social network within the wireless network and helps provide efficient as well as effective network services to the users [1], [2], [3]. Social network analysis techniques use various social metrics to determine the importance of a user in the network [15].

2.2.2.1 Social metrics

Following are some common metrics used for social network analysis. Figure 2.2 [1], [15] shows an example of a network or social graph where the circles represent the network users and the edges represent the communication links between these users.

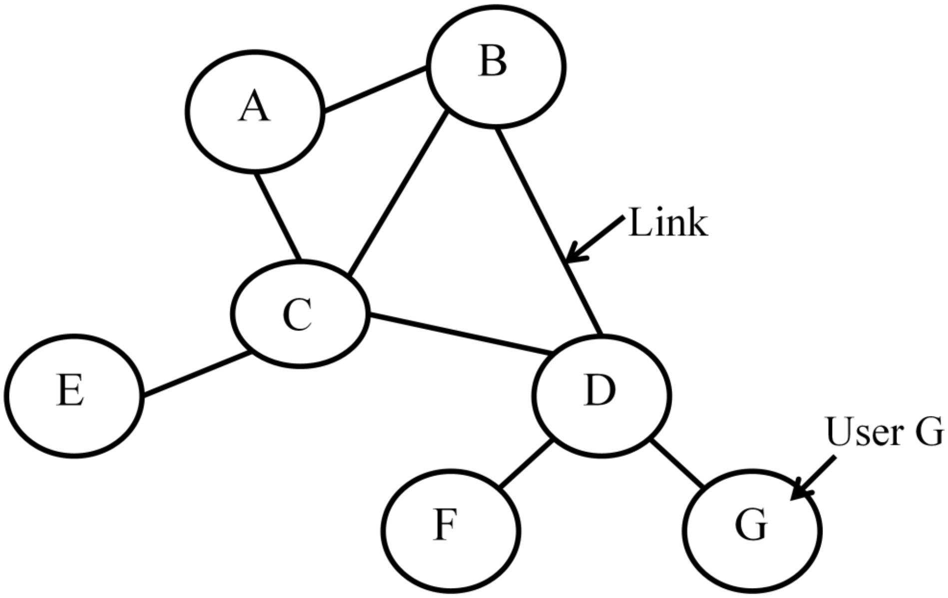

Figure 2.2 Example Network Graph

Centrality is the measure of relative importance of a user within the social network, i.e. how popular a user is within the social network. A highly popular user within a social network has higher probability of connecting to others while the user with low popularity has very low probability of connecting to others [6], [8], [14]-[17]. There are several ways to measure the centrality of users. Four most widely used centrality metrics are as follows.

1) Degree Centrality: This metric determines central users within a community based on their information spreading power in their intermediate vicinity [3], [6], [8], [15]. Degree centrality for a node g, $C_{degree,g}$, is measured as number of other nodes h directly connected to node g where $g \neq h$ (this helps ignore self loops).

Mathematically, $C_{degree,g}$, is given by [6], [8], [15]-[17]:

$$C_{degree,g} = \frac{1}{Total\ Nodes - 1} \sum_{\substack{h=1 \\ g\neq h \\ g,h\in \mho}}^{Total\ Nodes} link\ (g,h) \tag{2.1}$$

where $Total\ Nodes$ is the total number of nodes in the network, $g,\ h\in \mho$,

$\mho = \{1,..,Total\ Nodes\}$ is the set of nodes in the network and $link\ (g,h)$ represents the link connecting nodes g and h. $link\ (g,h)$ exists (i.e. 1) if node g is connected to node h and does not exist (i.e. 0) otherwise.

For calculation purposes, degree centrality only considers local (community based) information and not global (network based) information about the nodes [6], [8], [15]-[17]. In Figure 2.2, nodes C and D have the highest degree centrality as they have the highest number of connections to the other nodes (= 4) in the network.

2) Betweenness Centrality: This metric measures the number of times a node falls on the shortest path or the geodesic path connecting other nodes. It determines the popularity of a user based on its involvement in the communication paths of other network users. Users with higher betweenness have the ability to control communication between multiple other users whereas users with low betweenness have limited influence on social interactions among other users [3], [6], [8], [15]-[17]. The betweenness, $C_{betweenness,g}$ of node g is calculated as [6], [8], [15]-[17]:

$$C_{betweenness,g} = \sum_{\substack{h=1 \\ g\neq h}}^{Total\ Nodes} \sum_{\substack{d=1 \\ g\neq d}}^{h-1} \frac{geodesic_{hd}(g)}{geodesic_{hd}} \tag{2.2}$$

where $geodesic_{hd}$ is the total number of geodesic paths connecting node h and node d; $h, d \neq g$; g, h, $d \in \mho$ and the total number of geodesic paths including node g is represented using $geodesic_{hd}(g)$.

Betweenness helps determine where the network would break apart if the nodes with highest betweenness measure become inactive [3], [6], [8], [15]-[17]. In Figure 2.2, nodes C and D are the nodes with the highest betweenness centrality as they are present on many geodesic paths of the other users. However, the betweenness centrality of node D is greater than that of node C because when node D is inactive, two nodes will lose contact with the network whereas if node C is inactive only one node loses contact with the network.

3) Closeness Centrality: The closeness of a node is the mean length of all the geodesic paths from that node to all the other nodes in the network (i.e. the average number of hops needed to reach every other node). The closeness of node g, $C_{closeness,g}$, is calculated as [6], [8], [15]-[17]:

$$C_{closeness,g} = \frac{Total\ Nodes - 1}{\sum_{\substack{h=1 \\ g \neq h}}^{Total\ Nodes} geodesic(g,h)} \tag{2.3}$$

where $g \neq h$ and $geodesic(g,h) = \ shortest\ path\ between\ nodes\ g\ and\ h.$

Low value of closeness indicates that the node has a more central position in the network. This measure is useful when the analysis focuses on independence of nodes in communication. This measure is useful in cases where the main concern is the speed of information distribution in the network [12]-[15]. In Figure 2.2, nodes C and D have the best closeness as only one hop is needed to reach every other node (except nodes F and G in case of closeness of node C and except nodes A and E in case of closeness of node D) in the network from these nodes.

4) Eigenvalue Centrality: This metric measures the importance of a node in the social network and how well a node is connected to the other well connected nodes in the network. Eigenvalue centrality of a node g, $C_{eigen,g}$, is the proportional sum of the eigenvalue centralities of all nodes directly connected to node g. Mathematically, $C_{eigen,g}$, is given by [10], [15], [18]-[20]:

$$C_{eigen,g} = \frac{1}{\lambda} \sum_{\substack{h \in \mho \\ g \neq h}} (C_{eigen,h}) \tag{2.4}$$

where λ is a scalar (spectral radius of the network's adjacency matrix) and $g \neq h$. The Equation (2.4) can be rewritten as: $C_{eigen}\lambda = AdjC_{eigen}$ where Adj represents the network's adjacency matrix if C_{eigen} represents a vector of centrality scores. C_{eigen} must be an eigenvalue of Adj and if all the values of C_{eigen} are required to be positive, then λ is the spectral radius of Adj [18]-[20]. The eigenvalue centrality, $C_{eigen,g}$ of node g is the gth component of C_{eigen}. This measure considers global information (network based) for calculation purposes [10], [15], [18]-[20]. In Figure 2.2, node C has the highest eigenvalue centrality followed by nodes D and B due to their connections to the most connected nodes in the network.

Following are some other social metrics that exist in the literature [1], [16], [17], [21], [22].

Table 2.1 Social Metrics

Social metric	Description	Use
Tie strength	Measures strength of links between nodes. Indicators: frequency, intimacy, longevity, reciprocity, recency, trust, etc.	Determines weak and strong ties
Similarity	Clustering of nodes if they have common interests	Disperses data among clusters
Neighborhood Nodes Friendship, Associated Nodes Friendship, Community Nodes Friendship	Quantify degree of friendship between a node and its surrounding neighbors	Used at MAC (media access control) layer for efficient data delivery and lowers network usage and data dissemination time
Social pressure metric (SPM) and relative SPM (RSPM)	Measure of a social pressure that motivates friends to meet and share their experiences (based on frequency and regularity of the meetings.) It is computed from the history of encounters	Used for efficient routing in Mobile Social Networks

2.2.3 Multi-Hop and Relay Networks

In downlink transmission, a relay node helps relay data from the BS (source) to the network users (destination). A mobile device or a BS can act as relay nodes. As the user QoS demands evolve and the network size increases, problems faced by the network, namely, constantly varying propagation environment and interference also increase [13]. To counter these issues and improve network coverage and throughput, relay and/or multi-hop networks are implemented [23]. In a relay and/or multi-hop network, the source (BS in a cellular network) communicates with a destination user/node using intermediate nodes/relay devices. The need to use these intermediate nodes generally arises when the distance between the source and destination is greater than the transmission range of both devices. Also, a relay can be positioned flexibly in the network which aids faster network construction [23].

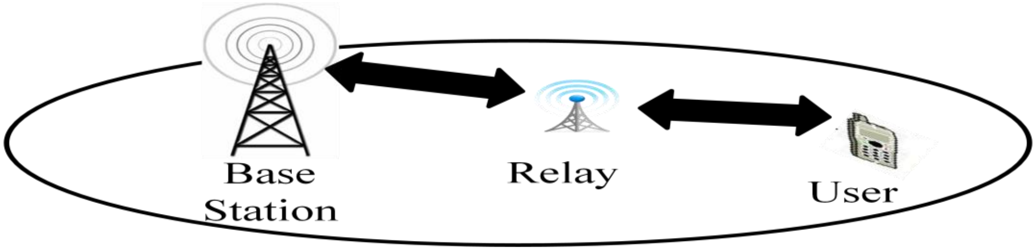

Figure 2.3 Example of a Relay Network

In this thesis, a two-hop infrastructure based (cellular) wireless network has been considered where social metrics are used to determine the popularity of the network users.

2.3 Need for Radio Resource Management and Quality of Service Support for Wireless Networks

Radio resource management in a wireless communication network ensures efficient utilization of the resources available in the network and guarantees a certain level of QoS for different users depending on their traffic profiles [7], [24]. It involves strategies and algorithms that decide the schedule, timing, order, techniques and the amount of resources to be allocated to the users [7]. Owing to the advent of high-definition services such as audio and video applications like Skype, YouTube, etc., users' demand for higher data rate has increased exponentially [23]. To support the various sets of requirements of the network users, the system has to be capable of supporting high data rates in a reliable manner. However, the amount of resources available in a wireless network to support such service demands of the ever growing network users are very limited. Also, the channels in a wireless network suffer from the problems of bottleneck mainly due to the diminished data handling capacity of the channel because of high traffic volume flowing through it, unreliability of the channel caused because of the adverse effects of multipath propagation and severe interference due to the other ongoing transmissions in the neighbouring cells. Thus, resource management techniques have to be implemented to help achieve efficient resource utilization [7].

References [25] and [26] state that QoS is used to capture the performance, qualitative or quantitative, of the contract defined between the server and the client. QoS acts as a guarantee by the network to satisfy a set of predetermined service performance constraints for the users in terms of available bandwidth, end-to-end delay, probability of packet loss, etc. [7], [25]. In a wireless network, the amount of resources such as bandwidth, transmission power, number of antennas, etc., available are limited. Also, the mobile devices are resource constrained in terms of memory, computational power, and power supply [7]. Thus, various resource management techniques have to be employed to ensure that minimal or no wastage of these resources takes place.

2.4 Orthogonal Frequency Division Multiplexing (OFDM) and Orthogonal Frequency Division Multiple Access (OFDMA)

OFDM performs multicarrier modulation where the total available bandwidth B in the network is divided into N orthogonal non-overlapping subcarriers, and the bandwidth of each subcarrier $B_{sub} = B/N$ (Hz). For large values of N ($N \gg 1$), the bandwidth of a subcarrier is smaller than the coherence bandwidth of the channel resulting in a flat fading channel (i.e. information experiences the same channel). Data transmission is done using these subcarriers in parallel instead of doing so in a serial manner over the communication channel. Parallel transmission helps transmit the data at a faster rate than a single subcarrier transmission. At the receiver, these subcarriers are collected and recombined to form one high speed transmission.

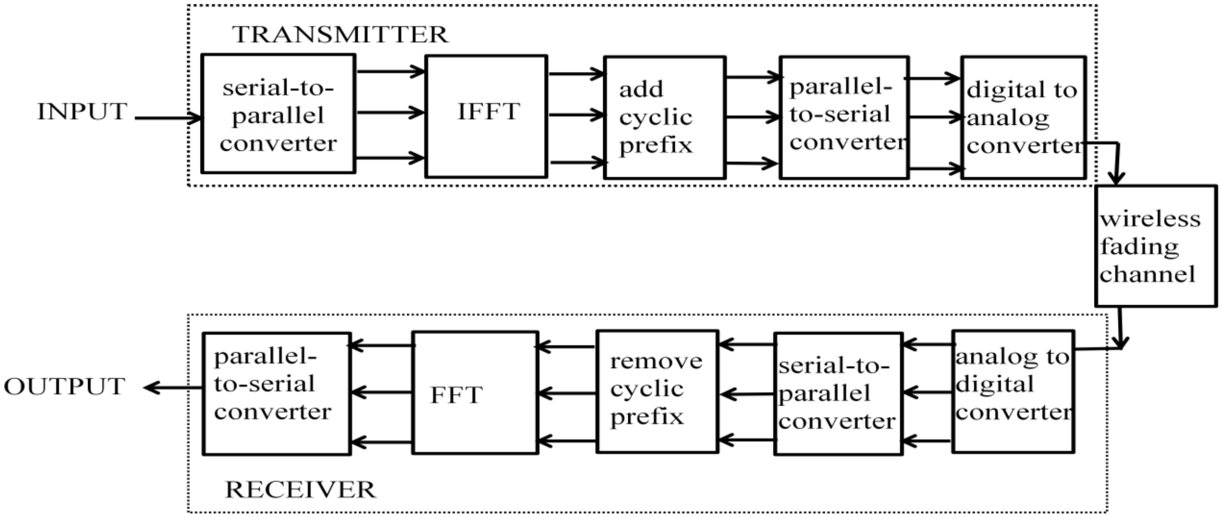

Figure 2.4 OFDM Transmitter and Receiver Block Diagram

In the OFDM system shown in Figure 2.4 [7], [27]-[29], the input data stream is divided into N parallel sub-streams (OFDM symbols) by the serial to parallel converter at the transmitter side. Then an Inverse Fast Fourier Transform (IFFT) operation is performed on the symbols transforming them into time domain. The cyclic prefix block adds a copy of last IFFT samples in front of the

OFDM symbol. The cyclic prefix size is chosen to be greater than the expected delay spread such that one symbol does not interfere with the next symbol; thus introducing guard time for each OFDM symbol which helps eliminate inter-symbol interference (ISI), caused when one symbol interferes with adjacent symbols and acts as distortion making the communication error prone. The resulting signal is transmitted over a wireless channel. At the receiver side, the received signal is distorted and noisy due to varying channel conditions and impairments such as propagation path-loss, shadowing, fading, delay spread, etc.; the receiver performs inverse operation of the transmitter on the received signal and the output is generated [7], [27]-[29].

OFDM is a digital modulation technique and not a multiuser channel access technique. OFDM systems allow only one user to transmit using all the subcarriers at a given time. To support multiple users, OFDM can employ time division or frequency division multiple access [30]. OFDMA is used as the multiplexing scheme in the downlink. It is a multiuser OFDM which distributes subcarriers among multiple users (different users receive different subcarriers) so that all the users can simultaneously transmit and receive data within a single channel; thereby, allowing multiple access on the same channel. OFDMA uses multiple closely spaced subcarriers. Groups of subcarriers are allocated to users in the form of a resource block; the subcarriers used to form resource block do not necessarily have to be adjacent. In the downlink, these resource blocks are allocated to users. The subcarrier allocation is done based on the user's channel condition and service requirements [7], [27]-[29].

2.4.1 Advantages of OFDM schemes

1) The subcarriers are orthogonal making OFDMA a highly bandwidth efficient scheme.

2) Using the guard interval helps avoid ISI.

3) Offers frequency diversity by spreading the subcarriers all over the available spectrum.

4) Each subcarrier undergoes flat fading, hence frequency selective fading can be avoided.

2.4.2 Disadvantages of OFDM schemes

1) Loss in spectral efficiency due to use of guard interval.

2) The amplitude of the OFDM signal is similar to that of noise and has a very large dynamic range, thus, RF power amplifiers with a high peak to average power ratio are needed.

2.5 Optimization Problem Formulation for Radio Resource Management

Resource management problems for wireless networks can be formulated as constrained optimization problems. An optimization problem formulation consists of three major components- 1) objective (or cost) function, 2) constraints and 3) variables. The problem formulation takes the following general form:

$$\min_{qq \in Feasible} or \max_{qq \in Feasible} f(qq) \tag{2.5}$$

$$\text{subject to: } \begin{cases} a_{ii}(qq) \leq 0, for\ ii = 1, \ldots, m \\ b_{jj}(qq) = 0, for\ jj = 1, \ldots, l \end{cases}$$

where qq is the variable used to optimize the resource management problem. *Feasible* is the feasible range for the optimization variable qq. $f(qq)$ is the objective function representing the performance to be maximized or the cost to be minimized. $a_{ii}(qq)$ and $b_{jj}(qq)$ are the inequality and equality constraints for the optimization variable respectively. The goal of the optimization process is to find an optimal $qq^* \in Feasible$ that satisfies the inequality and equality constraints [7], [31].

2.5.1 Different Optimization Formulations for Resource Management in Wireless Networks

In resource management, specifically resource allocation optimization problems for wireless networks, the network resources are considered as the variables. The aim of these problems generally is to maximize user's utility and/or various network capacity performance metrics while satisfying QoS requirements of network users [7], [8], [31]. Existing formulations of resource management based optimization problems for OFDMA networks are mainly classified into the following four categories [7], [9], [27], [28], [31].

2.5.1.1 Sum Rate Maximization

The objective of this formulation is to effectively use the available resources to maximize the performance of the network users in terms of data rate achieved by them [27], [28], [32].

$$\max_{p,s} \sum_{k} \sum_{n} s_{k,n} \times r_{k,n} \qquad (2.6\ a)$$

subject to:

$$\text{C1:} p_{k,n} \geq 0;\ \forall k, n \qquad (2.6\ b)$$

$$\text{C2: } \sum_k \sum_n p_{k,n} \ \leq P_{max} \qquad (2.6\ c)$$

$$\text{C3: } s_{k,n} \in \{0,1\};\ \forall k, n \qquad (2.6\ d)$$

$$\text{C4: } \sum_k s_{k,n} \leq 1\ ;\ \forall k, n \qquad (2.6\ e)$$

where *n* is the subcarrier index, *k* is the network user index, $s_{k,n}$ is the binary subcarrier allocation decision variable i.e. $s_{k,n}$=1 if subcarrier *n* is allocated to user *k* and 0 otherwise. $p_{k,n}$ is the positive power allocation decision variable, indicating the power allocated to subcarrier *n* assigned to user *k*. P_{max} is the total power available in the network and $r_{k,n}$ is the data rate achieved by user *k* who is assigned subcarrier *n*. The data rate $r_{n,k}$ is calculated as follows [7]: $r_{n,k} = \frac{B}{N} \times \log_2\left(1 + p_{k,n} \times \frac{\left|h_{n,k}^{Total}\right|^2}{N_0 \times \frac{B}{N}}\right)$ where N_0 is the power spectral density of the thermal noise and $h_{n,k}^{Total}$ is the channel response for user *k* receiving data on subcarrier *n*.

The objective function in equation (2.6) maximizes the overall data rate of the network under the specified constraints described as follows. Constraint C1 indicates that non-zero power values are allocated to subcarriers. Constraint C2 states that the total power allocated to all the subcarriers should not be greater than the total power available in the network. Constraint C3 specifies that exclusive subcarrier assignment takes place and constraint C4 assures that no two users share the same subcarrier. This is done to avoid intra-cell interference.

2.5.1.2 Margin Adaptive

The margin adaptive approach aims to minimize the usage of the total BS transmission power (i.e. total power available in the network), under the minimum data rate requirement constraints of the network users.

$$\min_{p,s} \sum_{k} \sum_{n} s_{k,n} \times p_{k,n} \qquad (2.7\ a)$$

subject to:

$$\text{C1: } s_{k,n} \in \{0,1\};\ \forall k, n \qquad (2.7\ b)$$

$$\text{C2: } \textstyle\sum_k s_{k,n} \leq 1\ ;\ \forall k, n \qquad (2.7\ c)$$

$$\text{C3: } \textstyle\sum_n s_{k,n} \times r_{k,n} \geq r_k^{req}\ \forall\ k \qquad (2.7\ d)$$

The objective function in equation (2.7) aims at minimizing the cost incurred i.e. transmission power consumed, while ensuring that the minimum data rate requirements of the network users are satisfied. The objective function is subject to the following constraints. Constraints C1and C2 are the same as equations (2.6 d) and (2.6 e), respectively. Constraint C3 in equation (2.7 d) indicates that the data rate achieved by user k should be greater than or equal to its minimum data rate requirement r_k^{req} [27], [28], [32]-[35].

2.5.1.3 Rate Adaptive

The resource allocation formulation in equation (2.6) tends to starve users with bad channel conditions, i.e. users far away from the BS, by allocating more resources to the users with good channel conditions. Thus, rate adaptive approach has been formulated in the literature with the aim of maximizing the minimum data rate achieved by the users. Thus, introducing fairness among the users. This introduces the notion of max-min fairness and leads to the max-min objective function observed in equation (2.8). However, introducing fairness in resource allocation leads to decreased overall data rate of the network as the sum-up data rate is limited by the data rates achieved by users in bad channel conditions [27], [28], [32]-[35].

$$\max_{p,s} \min_{k} \sum_{n} s_{k,n} \times r_{k,n} \tag{2.8}$$

subject to:

Constraints C1-C4 from equation (2.6)

The objective function in equation (2.8) aims to maximize the total system throughput by assigning subcarriers and power to improve fairness among the network users [27], [28], [32]-[35].

2.5.1.4 Utility Satisfaction Ratio Maximization

In wireless networks, utility functions are used to quantify network users' relative satisfaction to the level of service offered by the network [7], [27], [28], [32], [36]-[40].The objective function in equation (2.9) aims to maximize the number of satisfied network users by allocating resources such that a user k is satisfied if its minimum QoS requirement is fulfilled.

$$\max_{p,s} \sum_{n} U(n,k) \tag{2.9}$$

subject to:

Constraints C1- C4 from equation (2.6)

where $U(.)$ is a utility function describing the user's QoS requirement for subscribed traffic types. Logarithmic functions, exponential functions, power functions, etc. are the most commonly used functions in the literature to represent utility functions [7].

2.5.2 Mixed Integer Non-Linear Programming (MINLP) Problems and Non-deterministic Polynomial-time-hard (NP-hard) Problems

In an OFDMA network, resource allocation becomes a complex problem when the multiple users have to be served, as subcarrier and/or power allocation has to be performed to maximize or minimize the objective function which is usually dependent on the data rate achieved by the user. Additionally, the constraint regarding the minimum user data rate requirement further complicates the problem [41]. Several combinations of subcarrier and power allocation exist, out of which the best possible combination which meets the objective and satisfies the constraints has to be determined. Thus, it can be concluded that the resource allocation problem formulated is combinatorial in nature [31].

The optimization problems can be categorized as Linear Programming problem (LP), Non-Linear Programming problem (NLP), Mixed Integer Linear Programming problem (MILP) and Mixed Integer Non-Linear Programming problem (MINLP) depending on the nature of the objective function, constraints and the variables. Most of the problems in wireless networking and resource management are non-linear due to presence of non-linear objective function and/ or constraints [31]. The resource allocation formulations in section 2.5.1 belong to the MINLP category due to the presence of binary and positive variables, non-linear objective function. MINLP problems belonging to the combinatorial category and MINLP problems in general are NP-hard to solve in nature as finding solutions to these problems within polynomial time can be very difficult. This takes place due to the presence of multiple local optimal solutions and the fact that determining the global solution is a very difficult task [31]. In worst case scenarios, the size of the solution time grows exponentially with the problem size [42].

A decision problem is the one where it has to be determined whether a given statement is true or false. An optimization problem is where efforts are taken to determine the best solution possible according to the constraints defined for the problem. Optimization problems can be either maximization or minimization based. Every optimization problem has a corresponding decision problem [42].

A Polynomial-time (P) problem is one whose solution time is bounded by a polynomial and the number of steps needed to finish the solving process for a given input is $O(input^{integer})$ for some non-negative integer *integer* and the input of size *input*. A decision problem, whose solution can be determined in polynomial time is a P problem. For a given connected graph, determining if it is possible for its vertices to be colored using two colors so that no edge is monochromatic is an example of a P problem [43], [44].

The solution time for Non-deterministic Polynomial-time (NP) problem cannot be bounded by a polynomial. A problem is NP if the non-deterministic machine solves the problem and determines the answer for the same using a known polynomial-time algorithm. A problem is NP-complete if it proves to be NP and is poly-time reducible to an existing NP-complete problem. A problem is NP-hard, if it is "at least as" hard as a NP-complete problem [43], [44].

The Hamiltonian path problem in graph theory is a problem where the objective is to determine a path or a cycle that visits each vertex of the graph exactly once. The Hamiltonian problem is a decision problem and an example of NP-complete problem. It is also a NP problem as the existence of the path can be verified in polynomial-time [43], [44].

The Traveling Salesman Problem (TSP) is a problem where, in a given network (a complete graph) or given a set of points, the objective of the salesman is to visit every node (city) only once and return to the starting point, travelling minimum distance or incurring minimum cost. Determining the presence of a Hamiltonian cycle of minimum weight in the above network is the optimization version of the problem. The decision version of the problem is to determine whether a Hamiltonian cycle exists whose combined weight of the edges does not exceed a real number value and it is NP-complete. Optimization problems whose decision versions are NP-complete are NP-hard problems [43], [44].

2.5.3 Global and Local Optimal Solutions

Determining the optimal solution for MINLP problems is difficult because the entire feasible solution set has to be searched. These problems have many local optimal solutions and finding a global optimum to the problem means it has to be proved that a particular solution dominates all feasible points [45].

A global solution (optimum) for a problem or a function is either the overall maximum or minimum value possible (based on the objective of a problem) over the entire given feasible domain. Global optimum is the best solution (optimal) amongst all the possible solutions, whereas a local solution (optimum) is the maximum or minimum value possible within a neighbouring set of solutions. The solution to nonlinear optimization problems is generally locally optimal.

Let F define the feasible set for a problem and assume *f(y)* is a function of variable y. The global minimum for the function *f(y)* is at y^* if value of *f(y)* at y^* is less than or equal to the value at any other point *y* in the feasible set F [46]. Mathematically,

$$f(y^*) \leq f(y) \quad \forall y \in F \tag{2.10}$$

Similarly, the global maximum for *f(y)* at y^* if

$$f(y^*) \geq f(y) \quad \forall y \in F \tag{2.11}$$

The local minimum or maximum for *f(y)* lies at y^* if the equation (2.10) and (2.11) hold true for all *y* existing in a small neighbourhood $Neighbor$ of y^* in the feasible set F.

Neighbourhood $Neighbor$ of point y^* can be defined as a set of points [46]

$$Neighbor = \{(y|y \in F)\; with\;\; \|y - y^*\| < \delta\} \tag{2.12}$$

where δ>0 is a small value. In Figure 2.5, an example of attenuation oscillation curve depicting a general solution pattern and its global and local optimal solutions are shown.

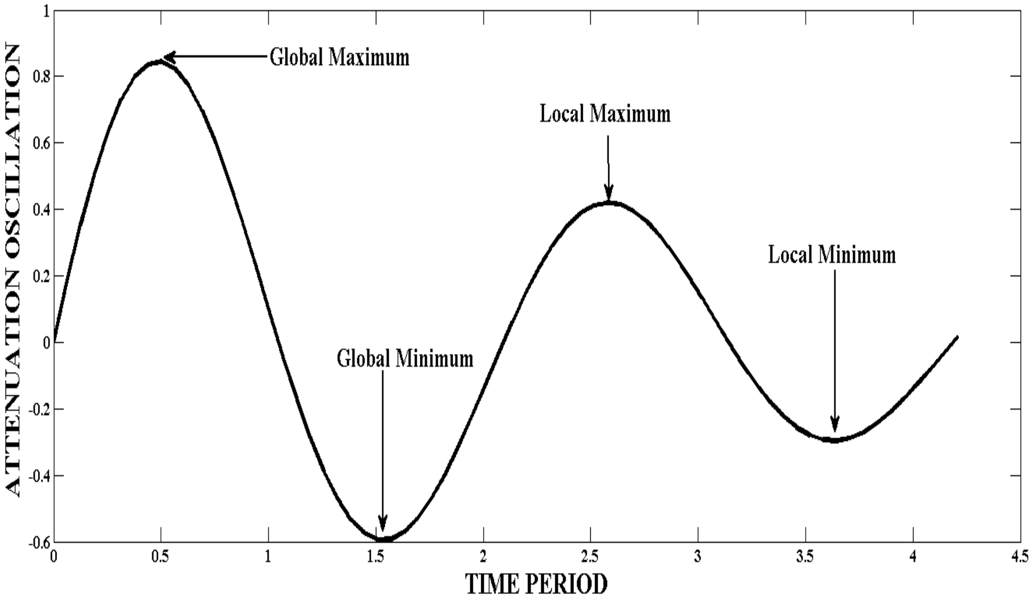

Figure 2.5 Example of Global and Local Optimal Solution

2.6 Previous Work and Proposed Work

2.6.1 Previous Work on Resource Management using Social Network Approach

A community is a group of users that are relatively densely connected to each other but sparsely connected to other dense groups in the network; they are usually formed on the basis of similarity of interests among the users [3], [14].

References [1], [6], [8]-[10] suggest that socio-technical information can be exploited in order to improve the network performance. The socio-technical approach is the process of harnessing the human and the technical aspects of an organization and processes to achieve joint optimization where the aim is to achieve excellence in terms of technical performance and quality in peoples' work. The problem of resource allocation specifically bandwidth allocation in a bottleneck link of a next generation network (NGN) has been considered by the authors in references [6] and [8]. To resolve the considered problem, an optimization problem has been formulated with the objective of maximizing the aggregate network utility. A reformed utility function using social distance parameter which incorporates information about the overlaid social network in the function has been used in [6], [8]. A numerical technique has been implemented to resolve the problem and the results show that the users with higher average popularity are allocated higher bandwidth as compared to other users in the network.

In reference [9], the case of a 802.11e compliant wireless local area network (WLAN), where users in a social network choose to communicate via Voice over Internet Protocol (VoIP) has been considered. The information regarding the effective distance and expected quality requirements of users are integrated in the optimization problem to attain better resource allocation. Results show that exploiting the social awareness of the network achieves almost twice the utility of the network as compared to the case of socially unaware network supporting VoIP traffic.

In reference [10], social distance measure for the entire social network is derived, the utility function used is aware of the social distance of the users and the bounds on the maximum achievable utility are also aware of the social distance. A social distance aware (SDA) allocation scheme has been introduced for a wireless network which is assumed to be IEEE 802.11 e QBSS (QoS service set) and results show that the SDA approach achieves higher network utility than the other schemes considered. In references [47], [48], the issue of content distribution has been investigated. The authors in reference [47] consider a mobile social network, where wireless connection from network operators are bought by multiple content providers to distribute content to their subscribed users. Content providers form coalitions to share wireless connections, which help them reduce the price paid to network operator while the network provider controls the amount of bandwidth to be allocated, as its goal is to maximize the revenue. Hence, to address the joint problems of the coalition formation and bandwidth allocation, a controlled coalitional game has been implemented. In reference [48], broadcasting of dynamic content (e.g., news or traffic information) over a mobile social network has been studied and the issue of optimality and scalability has been addressed. The optimal allocation of bandwidth to provide fresh content to users and scalability of the system have been performed by defining a global fairness objective and solving the optimization problem using the gradient descent method.

2.6.2 Previous Work on Resource Management in Multi-Hop and Relay Networks

In references [23], [49]-[51], resource allocation issues in relay-based wireless networks have been addressed by formulating the issues as optimization problems and proposing techniques to resolve the same. In reference [23], algorithms have been proposed for allocating resources in a downlink OFDMA relay-enhanced network efficiently and feasibly. Resource allocation for centralized and semi-distributed architectures are proposed, in which four representative single-hop scheduling algorithms are extended to attain different levels of fairness in multi-hop scenarios. A trade-off between system throughput optimization and fairness among users is exhibited by the results. Reference [49] addresses the resource allocation problem in a relay-based OFDM network by performing a joint subcarrier-relay and power allocation with the objective to maximize the end-to-end transmission rate when the system has limited total transmission power. The MINLP problem is converted into a convex one and dual decomposition technique is used to resolve it. A suboptimal scheme which performs subcarrier-based relay selection followed by power allocation is also proposed. Results show that the suboptimal scheme is less complex than the joint scheme and is similar to joint technique in terms of performance. Reference [50] proposes a technique to maximize system capacity by performing joint subcarrier matching and power allocation in a two-hop OFDM network. An optimal joint subcarrier matching and power allocation scheme has been proposed by separating the subcarrier matching and the power allocation. A less complex suboptimal scheme has been proposed to understand the effect of power allocation. Reference [51] proposes an adaptive power allocation scheme for an OFDM-TDMA (Time Division Multiple Access) multi-hop network where the objective is to maximize end-to-end capacity and results show that the proposed technique outperforms fixed resource allocation strategy.

2.6.3 Relationship between Previous work and Proposed Work

In this thesis, an optimization based socially aware joint resource allocation scheme for a two-hop downlink OFDMA network has been proposed. Social metrics are used to determine the importance of a user in network similar to the work done previously in literature. This social awareness is used to perform resource allocation in a network where the users are partitioned into non-overlapping communities.

Bandwidth allocation for a bottleneck link in NGN using social distance parameter has been proposed in the literature [6], [8]-[10]. NGN is based on internet technology whereas the current and the future cellular technologies like the Long Term Evolution (LTE) and LTE- Advanced use the OFDMA access technique. Resource allocation (subcarrier as well as power allocation) in an OFDMA network using social awareness about the users has not yet been proposed in literature. Various optimization formulations for resource management in an OFDMA network exist as discussed in section 2.5; however, none of the formulations perform allocation by exploiting social awareness of the users. The previous work done in literature discussed in section 2.6.1, considered a network with users related to each other, but none of them have considered a network partitioned into different communities based on the users' interests.

Similar to the approach used in multi-hop and/or relay networks, a two-hop network has been considered in this thesis, where the most active (MA) user in a network is selected on the basis of its importance in the network and thus acts as a relay for relaying data from the BS to its peers belonging to its community.

2.7 Summary

This chapter provides an introduction to the different network architectures considered in this thesis. This is followed by an overview of the different optimization based resource allocation schemes existing in the literature and the similarities and differences between the previous work done in the literature and the proposed work. Based on the literature survey done in this chapter, the system model to be adopted and the problem to be addressed are identified and formulated in the following chapters.

Chapter 3: System Model

3.1 Introduction

The system model of the downlink Orthogonal Frequency Division Multiple Access (OFDMA) wireless network including the network architecture and the propagation environment to be considered in this thesis are discussed in this chapter. A centralized wireless network overlaid by a social network has been considered. The links between the users of the social network are used to determine central users. System fairness index (SFI), system spectral efficiency (SSE) and overall network utility metrics are used to gauge the performance of the proposed resource allocation scheme in comparison with the ones existing in literature.

This chapter is organized as follows. An overview of the components of the system model is presented in section 3.2. Section 3.3 provides a detailed description of the network architecture considered in this thesis. The social metrics chosen to be used in this thesis are discussed in section 3.4. The propagation environment is presented in section 3.5. The description of the performance metrics to be used in this thesis, along with discussion about the utility functions and different utility functions used for different user applications are presented in section 3.6. Section 3.7 summarizes the chapter.

3.2 System Modelling

Based on the discussion of Orthogonal Frequency Division Multiplexing (OFDM), OFDMA and the advantages of OFDMA stated in section 2.4, and especially due to its robustness in the presence of severe multipath fading, an OFDMA based network for downlink transmissions is considered in this thesis. Social metrics introduced in section 2.2.2.1 are used to incorporate the social awareness of the relationships existing among the network users in the resource allocation scheme. A propagation environment consisting of path-loss, shadowing and fading used to calculate the channel response of the users is described. The base station (BS) uses the channel response of the users to calculate the channel gain, which is used to perform resource allocation for the network users. The performance metrics SFI, SSE and overall network utility based on the data rate achieved by the network users are selected for comparing the performance of the proposed scheme and other schemes.

3.3 Network Architecture

Figure 3.1 exhibits the network architecture considered in this thesis, displaying the social network overlaid on an existing centralized network.

The network considered here comprises of following components.

a) Content Provider

b) Base Station

c) Users (partitioned into communities)

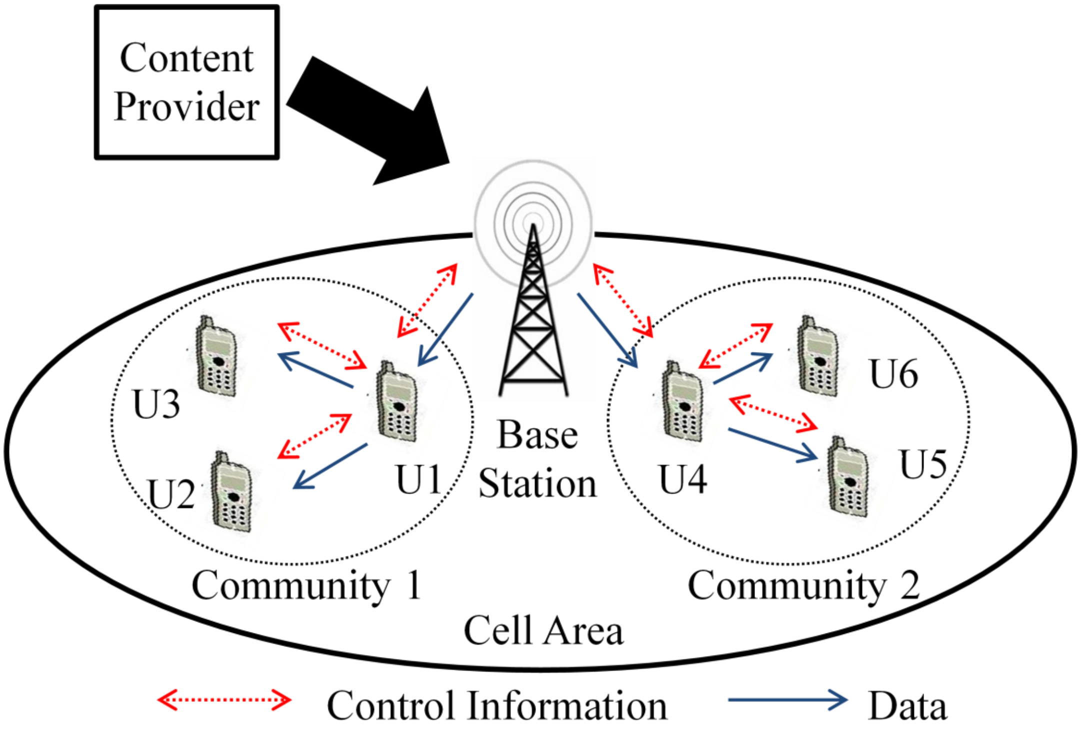

Figure 3.1 The Centralized Socially Aware Wireless Network.

a) Content provider

It is assumed that the network users have subscribed to a social networking application based service (e.g. YouTube, Facebook, etc.). The content provider generates desired content for its subscribed users in the network and utilizes a wireless connection provided by the BS to transfer the desired content/data to the users [47].

b) Base Station

The network is assumed to have a centralized architecture. A centralized architecture is an infrastructure-based wireless network. In an infrastructure-based architecture, the BS is responsible for transmitting data to the network users (refer to section 2.2.1) and is aware of the channel conditions and user demands in terms of quality of service (QoS) support. Alternatively, distributed networks where the users communicate with each other in a peer-to-peer manner without a centralized entity can also be used. However, in general, a centralized architecture is easy to implement and centralized techniques show better performance at the price of higher signalling between users and the BS and such networks are not highly scalable [7], [52].

c) Users (partitioned into communities)

In social networks, users exist in communities, which are formed based on their common interests. In this thesis, as it is considered that the centralized wireless network has been overlaid by a social network, the network consists of users that are partitioned into communities. Selfishness is a social feature displayed by users of a social network [2], [3], [53]-[55]. The major issue faced by the mobile devices is that of power; it is a known fact that more power is spent in transmitting data than the power spent in receiving it. Thus, users behave selfishly by refusing to forward data on behalf of other users while attempting to gain services from others for their own benefit [55]. Social selfishness is exhibited by a user when it is willing to forward data to others with whom it has social ties/links to, especially stronger ties because it has received data from them in the past or expects the same in future [53], [54]. Individual selfishness is displayed by users when they refuse to transmit data to any user, irrespective of the nature of their ties but it will try to receive data from the other users. Users exhibit this behaviour to conserve their own resources [53], [54]. It is assumed that all the network users considered in this thesis display socially selfish behaviour and are only willing to share data with their peers belonging to the same community. Therefore, ties between different communities are not considered and the communities are assumed to be non-overlapping.

3.3.1 Downlink Data Transmission in the Two-Hop OFDMA Network

In this thesis, the case where the network users download data from their subscribed content provider using downlink channel has been considered. Assume that users belonging to the same community are present within the transmission range of each other. They are present in the same location e.g. the mall, and have subscribed to the same social networking application e.g. services such as YouTube, Facebook, WhatsApp[4], WeChat[5], etc. due to their similar interests. When these users demand a certain service from the content provider using the uplink, the content provider provides the data to the BS for downlink transmission.

The BS is placed at the center of the cell area as it is assumed that the communities are uniformly distributed in the cell area [56]. The BS creates virtual First-In-First-Out (FIFO) queues to store the data it receives from the content provider for its subscribed users present in different communities. Before performing the downlink data transfer, the BS uses the bidirectional control information flow as shown in Figure 3.1 and determines the following information about the network users: user location, user transmit power value, friendship list (which indicates which user is connected to whom), minimum user data rate requirement and user channel state information (CSI). Once the BS has all the above information, it determines which user belongs to what community (as location is known for all users and it is assumed that users in same location belong to same community), calculates social metric value of users by using centrality metrics discussed in section 2.2.2.1 and selects the MA user from each community based on the social metric value information determined.

In Figure 3.1, it is assumed that users U1 and U4 are the MA users for community 1 and community 2, respectively. In first hop, the BS transfers the data to these MA users of all the communities determined in the previous step, using the data channel shown in Figure 3.1. The BS informs the MA user about the other users belonging to its community and in the second hop, the

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[4] www.whatsapp.com
[5] www.wechat.com

MA user transmits the data it received during the first hop to these users (its peers) as observed in Figure 3.1.

3.3.2 Additional System Assumptions

No peer-to-peer communication takes place between the community users, due to the centralized architecture of the network. The MA user acts like a relay for forwarding the data it received from the BS to its peers within its community. Downlink direction of communication is considered i.e. a case where users demand data from the content provider they have subscribed to. The BS transmits at full power of P_{max}. This pattern of downlink data transfer also helps ensure that when a fresh data arrives in a community, only the MA user has it and can transfer to its peers without having to check if they have already received it (which would be the case in a peer-to-peer network). This in turn helps reduce wastage of resources in the community as well as computational complexity of the process.

Generally a wireless network supports real time (RT) applications, such as VoIP (voice over Internet Protocol) and non-real time (NRT) applications for example World Wide Web (WWW), email, File Transfer Protocol (FTP) [7], [27]. In mobile social networks, users share data when they are present within their community and/or in vicinity of other community members. However, this may not always be the case as they are mobile and users sharing similar interest may not encounter each other constantly. This leads to the formation of a disconnected social graph. Thus, content dissemination has to be delay tolerant [16], [17]. Therefore, only NRT services are considered in this thesis as they are delay tolerant while the RT services are not as they are delay intolerant in nature.

In a multi-cell OFDM network, users in different cells reuse same subcarriers causing interference between each other. This adds to the complexity of the resource management in wireless networks [27], [28]. Thus, a single cell network has been considered in this thesis to avoid inter-cell interference occurring due to neighbouring cells. Intra-cell interference is avoided by ensuring that no two users in the cell area share subcarriers.

CSI describes the signal propagation from the transmitter to the receiver. CSI describes how the transmitted signal is affected by the surrounding physical elements leading to shadowing, fading and path-loss. The CSI is estimated at the receiver using channel estimation techniques and fed back to the BS using the uplink (reverse channel which is used for transmission of information to the BS) [11]-[13]. In a centralized network, the BS performs resource allocation based on the CSI it receives from the users [7], [11]-[13]. If imperfect CSI is fed back to the BS, the resource allocations performed are not accurate which may lead to unsatisfied network users [28]. Therefore, it is assumed that perfect CSI is available at the BS before it initiates the resource allocation process and CSI does not vary for that particular transmission session (i.e. channel response is flat for a transmission session as the channel coherence bandwidth is greater than the transmission bandwidth). As the CSI depends on the users' physical location too, due to path-loss, it is assumed that the user positions are fixed during an ongoing downlink transmission session [27], [28]. To avoid imperfect CSI feedback, we also assume that new users do not arrive or existing users do not exit a community during an ongoing transmission session.

3.4 Social Metrics

As mentioned in section 2.2.2, social network knowledge helps introduce awareness of the connections among the users in underlying network into the resource allocation scheme. For this purpose, centrality based social metrics have been introduced and discussed in section 2.2.2.1. Social metrics help determine popularity of users. In this thesis, it is assumed the BS transmits the data meant for a community to the MA user of the community. The MA user then transmits this data to its peers within its community. Thus, it is necessary to determine users who have the highest spreading power (i.e. have the ability to spread data to the largest number of their neighbors possible), in a community as well as in the network. In order to do so, based on the discussion of various social metrics in section 2.2.2.1, it is decided that degree centrality (equation (2.1)) and eigenvalue centrality metrics (equation (2.4)) should be chosen. Both these metrics help select the MA users based on their communication activities. Degree centrality helps select the MA user within a community (locally) based on the existing number of ties (links) amongst users whereas eigenvalue centrality helps determine the MA users in the entire (globally) network based on their spreading power and their importance in terms of eigenvalue centrality of its neighbors [6], [8], [10], [15]-[20].

3.5 Propagation Environment

To model realistic conditions for a wireless network, the propagation environment (i.e. wireless channel) is modeled by path-loss, lognormal shadowing and Rayleigh fading. No mobility model for the network users has been implemented as the users' initial positions generated before the transmission begins do not vary for the entire transmission session.

The average path-loss indicates the steady degradation of signal power due to its propagation on the wireless channel. The average path loss is a function of the distance between the transmitter and receiver. It is calculated using the following formula [7], [11]-[13], [27], [28]:

$$h_{PL_{n,k}} = 10 \times \alpha \times log_{10}(d_{tx-rx}) + SysLoss \qquad (3.1)$$

where $h_{PL_{n,k}}$ is the path loss (in dB) experienced by a user k receiving on subcarrier n, α is the path loss exponent, d_{tx-rx} is the distance (in meters) between the transmitter and the receiver i.e. user k and $SysLoss$ is a constant value that accounts for system losses.

Shadowing (also called large scale fading) occurs due to presence of obstacles such as walls, buildings, trees, etc. between transmitter and receiver. These obstacles absorb, diffract and reflect the transmitted signal which causes attenuation of the signal. Shadowing is a random factor for users at same distance from transmitter as the location of the obstacles is random. Lognormal shadowing random variable $h_{S_{n,k}}$ with zero mean, and standard deviation σ has been used here to represent shadowing encountered by users [7], [11]-[13], [27], [28].

Fading (small scale fading) is caused due to scattering and reflecting objects located along the transmitter-receiver communication path. It is assumed that the users are present in an urban environment where a direct line of sight between a transmitter and a receiver may not always be present and multiple reflective paths between the transmitter and the receiver exist. To model this behaviour, small scale fading ($h_{F_{n,k}}$) is modelled as Rayleigh fading [7], [11]-[13], [27], [28].

The total attenuation $h_{n,k}^{Total}$ experienced by the signal carried by subcarrier *n* which has been allocated to user *k* is calculated as:

$$h_{n,k}^{Total} = h_{PL_{n,k}} + h_{S_{n,k}} + h_{F_{n,k}} \tag{3.2}$$

Suppose that subcarrier *n* is allocated to user *k*, the signal-to-noise ratio for user *k* on subcarrier *n* is:

$$SNR_{n,k} = p_{n,k} * H_{n,k} \tag{3.3}$$

where $H_{n,k} = \frac{\left|h_{n,k}^{Total}\right|^2}{N_0 \times \frac{B}{N}}$, $p_{n,k}$ is the power assigned to subcarrier *n* allocated to user *k*, N_0 is the power spectral density of the thermal noise and $h_{n,k}^{Total}$ is calculated using equation (3.2).

The maximum bit-rate user *k* can achieve on subcarrier *n* is calculated using the Shannon`s formula [7]:

$$r_{n,k} = \frac{B}{N}\log_2\left(1 + SNR_{n,k}\right) \tag{3.4}$$

The above formulation also gives the theoretical upper bound for transmission capacity on a single subcarrier.

Let S_k be the set of subcarriers the BS allocates to user k. The total data rate that user k achieves is calculated as follows:

$$R_k = \sum_{n \in S_k} r_{n,k} \tag{3.5}$$

3.6 Performance Metrics

SFI, SSE and overall network utility are the performance metrics employed to compare the performance of the proposed socially aware resource allocation scheme and conventional resource allocation schemes.

3.6.1 System Fairness Index

Fairness shows how well resources are distributed equally among the network users. In this thesis, SFI is calculated using the Jain's Fairness Index formula [57]. It is calculated as follows:

$$\zeta = \frac{(\sum_{k=1}^{K} R_k)^2}{K \times \left(\sum_{k=1}^{K} {R_k}^2\right)} \tag{3.6}$$

where ζ is the system fairness index, R_k is the total data rate achieved by a user k and K is the total number of users in the network.

SFI indicates how much fairness in terms of the minimum data rate required is achieved among the users in the network. The maximum value of SFI that can be achieved is 1, which is possible if all the network users achieve equal data rates.

3.6.2 System Spectral Efficiency

SSE is measured in terms of overall data rate achieved by the entire network and is defined as data rate per unit bandwidth. It is calculated by dividing the total data rate achieved in the system by its total bandwidth. It takes into account the total data rate and not the data rate achieved by individual users in the network. The sum rate maximization resource allocation scheme in section 2.5.1.1 aims at maximizing the total data rate achieved by the network by allocating maximum resources to users with good channel conditions. Highest SSE can be attained by a system if highest possible data rate is achieved by the users, as SSE is proportional to the total data rate achieved by the network users. Spectral Efficiency is calculated using the following formulation [7], [27], [28].

$$SE_{n,k} = \log_2\left(1 + SNR_{n,k}\right) \text{ (bits/s/Hz)} \tag{3.7}$$

where $SE_{n,k}$ is the spectral efficiency of user k receiving on subcarrier n.

In order to achieve highest SSE possible, the BS allocates maximum resources to users with good channel condition and allocates low or no resources to users with bad channel condition. Thus, the users with bad channel conditions are treated unfairly. However, attempting to attain maximum fairness would lead to low spectral efficiency as all users achieve equal data rates. Thus, there is always a trade off between spectral efficiency and fairness while performing resource allocation for a wireless network.

3.6.3 Overall Network Utility

The overall network utility, which is a summation of the individual user satisfaction levels, is also used as a performance metric.

3.6.3.1 Utility Functions

In economics, the term utility is used to describe the amount of happiness/satisfaction experienced by a consumer from consuming certain good or service. Resources in a wireless network are very limited. As many methodologies introduced in economics help manage limited resources, they can also be used for resource management in wireless networks [7]. In wireless networks, utility functions can be used to quantify network users' relative satisfaction to the level of service offered by the network [7], [33]-[36]. These utility functions are used as objective functions in the resource management based optimization problems. When the objective of the optimization problem is in terms of the utility functions, the problem is optimized from the user's point of view.

Utility functions can be expressed in many ways, the most common ones are as follows [58].

1) Exponential function- $U(z) = e^{-\tau z}, \tau > 0$ or $U(z) = 1 - e^{-\tau z}, \tau > 0$ (3.8)

2) Logarithmic function- $U(z) = \log z$ (3.9)

3) Power function- $U(z) = \frac{z^{\tau}-1}{\gamma}, \gamma > 0$ (3.10)

4) Sigmoid function- $U(z) = \frac{1}{1+e^{-z}}$ (3.11)

in equations (3.8), (3.9), (3.10) and (3.11), $U(.)$ is the utility function, z is the variable, τ and γ are positive constant values.

In this thesis, each user has a minimum data rate requirement demand which indicates the QoS level required by the user. Utility is measured as the level of satisfaction attained by network users in terms of total data rate or throughput achieved by them due to the resources allocated to them by the BS. Thus, the utility function maps the resource allocated level to the satisfaction attained. The utility function is a monotonically non-decreasing curve, i.e. application performance level remains unchanged if higher resources are allocated to users. Thus, a trade-off is obtained between the spectral efficiency and fairness. After a certain amount of resources are allocated to the users, there is very little or no increase in the level of satisfaction of the user if more resources are allocated to it.

3.6.3.2 Utility Functions for Different Applications

Different utility functions are used to describe different applications based on the network user's selected application's QoS requirements. As the QoS requirements in wireless networks differ from user to user and from each other based on the application they are trying to access, these applications have to be treated separately. Based on the QoS requirements, the multimedia applications are classified as follows [7], [33], [35]-[37].

1) Elastic (Non-real time) applications

2) Hard real time applications

3) Adaptive real time applications

Details and examples of the above classes of application are given below,

1) Elastic (Non-real time) applications

These applications are delay tolerant (elastic) due to their ability to adapt their transmission rate to maximize the throughput when encountered with delay, bandwidth limitations, etc. This application can buffer and transmit data at a lower rate in case the network is congested. Here, the terms bandwidth and data rate are loosely related to each other as the data rate achieved by users depends on the bandwidth and power allocated to them. Applications such as file transfer protocol (FTP), email, etc. fall into this category.

The utility function for elastic applications is formulated as follows [6], [7], [10], [33], [35]-[37].

$$U(b) = \frac{\ln(b+1)}{\ln(B+1)} \tag{3.12}$$

where b ($b \in [0, B]$) is the actual bandwidth allocated and B is the total bandwidth available in the network.

The curve for the utility function in equation (3.12) is shown in Figure 3.2.

The utility value increases even if the amount of bandwidth allocated to the application is very small as it is elastic in nature and has no strict data rate requirements. From the Figure 3.2 [6], [7], [10], [33], [35]-[37], it is also observed that as the bandwidth allocated increases, the utility diminishes at a marginal rate as discussed in section 3.6.3; this makes the utility function strictly concave. Thus, the utility function is a monotonically non-decreasing concave curve.

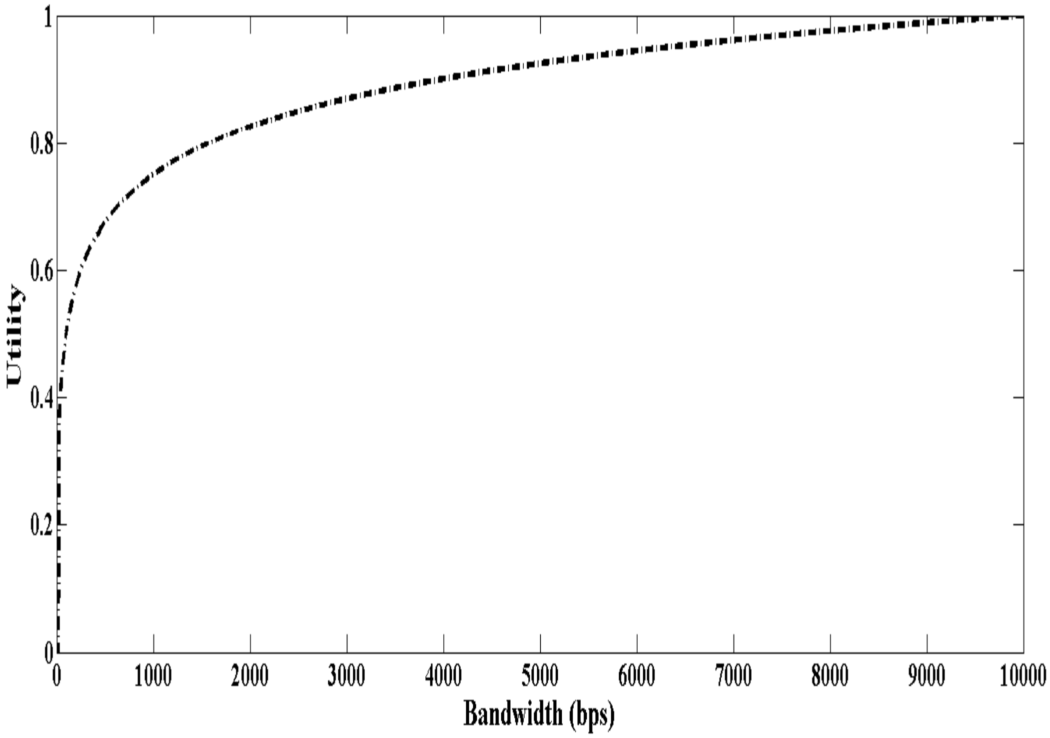


Figure 3.2 The Utility Function for Elastic Applications

2) Hard real time applications

These applications are extremely delay sensitive with strict bandwidth requirements and need performance guarantees from the network. If the required data packets arrive later than the delay bound, poor service is received by the network users. If the minimum bandwidth requirement B_{min} of the said user application is not met, the utility experienced by the users is 0 which means no user satisfaction; whereas, if the minimum requirement of the user is met, the user experiences maximum utility value U_{max}(indicating highest level of user satisfaction) which is usually 1 due to ratio based utility formulations. Generally video and audio applications fall into this category. The utility function is modelled as follows [7], [33]-[37].

$$U(b) = \begin{cases} 0, if\ b < B_{min} \\ 1, if\ b \geq B_{min} \end{cases} \tag{3.13}$$

The curve of the utility function in equation (3.13) is shown in Figure 3.3 [7], [33]-[37].

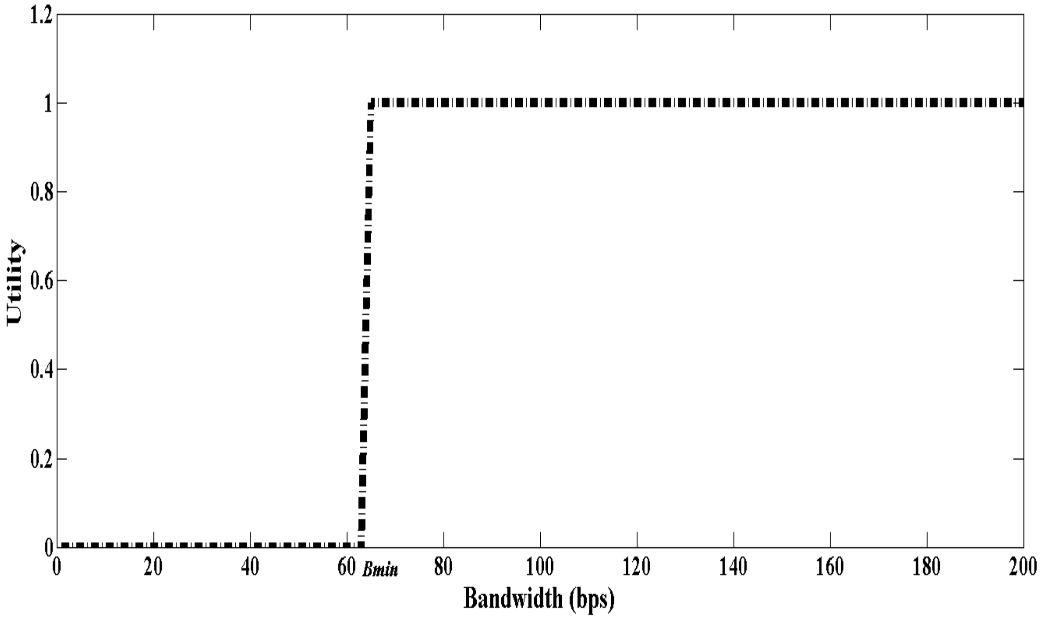


Figure 3.3 The Utility Function for Hard Real-Time Applications

The delay bound or B_{min} values are predefined for different applications. These values define the shape of the utility curve.

3) Adaptive real time applications

These applications have flexible bandwidth requirements. When faced with network congestion, they possess the ability to adapt their transmission rates according to the varying network conditions. This application is tolerant of occasional delay-bound violation and packet dropping occurring due to network congestion. However, they have an intrinsic bandwidth requirement $B_{intrinsic}$ because data generation rate is independent of network congestion. The utility decreases as soon as the allocated bandwidth is less than the intrinsic bandwidth $B_{intrinsic}$ and is unacceptable when it is less than the hard bandwidth requirement of B_{min} [7], [33], [35]-[37], [58]. The utility function of the IPTV traffic is modelled as the "Logistic Model" reflecting S-type curve and represented as follows [37], [59].

$$U(b) = \frac{1}{1+\left(\frac{1}{\varepsilon}-1\right)\times e^{-rr\times b}}, \tag{3.14}$$

where $rr = 2 \times \ln\left(\frac{1}{\varepsilon} - 1\right)/B_{max}$,

ε is the utility value achieved by an IPTV traffic user when the allocated bandwidth is B_{min} and ε helps determine the closeness of the IPTV traffic to that of the hard real time traffic. The lesser the value of ε the closer the IPTV traffic is to hard real time traffic. The curve of the delay-adaptive real time traffic is shown in Figure 3.4 [7], [33], [35]-[37], [58].

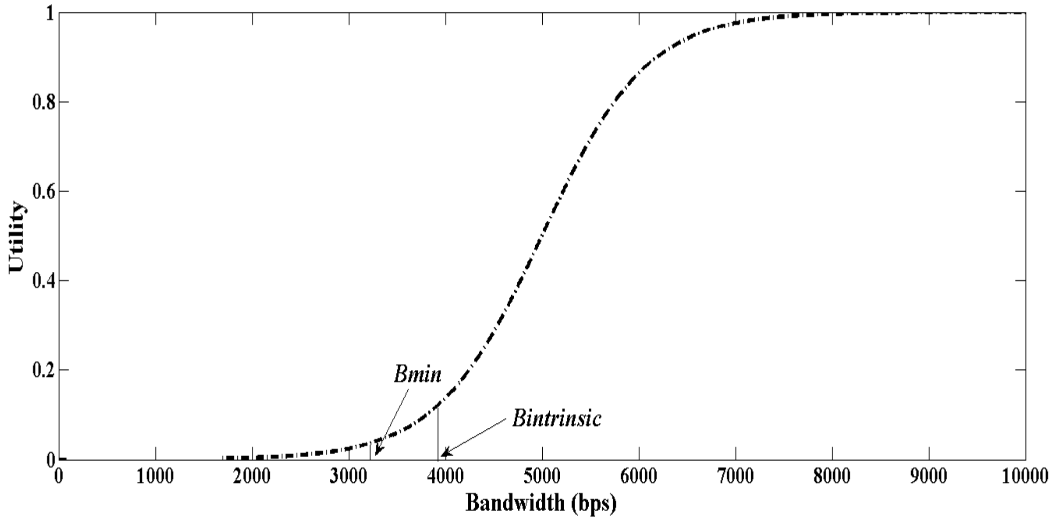


Figure 3.4 The Utility Function for Delay-Adaptive Real-Time Applications

From Figure 3.4, it is observed that the curve is very similar to that of the hard real time application but not as sharp as it. The curve is convex in the neighbourhood of B_{min} indicating that the hard minimum bandwidth requirements is satisfied but is not enough as the intrinsic bandwidth is not satisfied. The curve becomes concave after the bandwidth allocated is greater than $B_{intrinsic}$ as it indicates that the intrinsic bandwidth requirement of the application has been met and the satisfaction levels increases.

3.7 Summary

A two-hop socially aware OFDMA-based downlink network has been implemented. The first hop involves data transmission from the base station to the MA user and the second hop involves data transmission from the MA user to its peers within the same community. The propagation environment modelled helps determine the channel response of the users which is very important for efficient resource management. The MA users are selected on the basis of their popularity in the network using degree centrality and eigenvalue centrality. SSE, SFI and overall network utility are selected as the performance metrics as all of them depend on the data rate achieved by the network users.

Based on the discussion on the different formulations of the utility functions possible, a socially aware utility function is proposed in the following chapter. Also, the optimization formulation depicting the downlink data transmission operation in the two-hop network is proposed in the following chapter.

Chapter 4: Proposed Socially Aware Joint Subcarrier and Power Allocation Scheme

4.1 Introduction

A two-hop socially aware joint subcarrier and power allocation scheme and the optimization formulation for the same to be used for a downlink OFDMA network are presented in this chapter. Conventional i.e. socially unaware resource allocation schemes for wireless networks do not consider the social relationships existing between the network users. In order to introduce awareness regarding the social relations existing among the network users (i.e. social metric value) into the proposed resource allocation scheme, a socially aware utility function has been formulated. The proposed utility function is used as the objective function for the proposed optimization formulation.

This chapter is organized as follows. The proposed socially aware utility function using degree and eigenvalue centrality metrics for incorporating the social awareness about the users in the allocation scheme is discussed in section 4.2. In section 4.3, the proposed resource allocation scheme, the proposed socially aware optimization formulation and the optimization formulations for conventional i.e. socially unaware networks are presented. Section 4.4 summarizes this chapter.

4.2 Proposed Socially Aware Utility Function

As discussed in section 3.3.2, the network implemented in this thesis is delay tolerant in nature. Thus, elastic applications are considered here. The utility function to be used in this thesis should represent elastic applications as shown in equation (3.12) in section 3.6.3.2. In equation (3.12), b is the bandwidth allocated to a network user; however, in this thesis, the utility is measured in terms of the data rate achieved by the network user, as reliable data transmission rate is the most important factor in deciding the user satisfaction in case of elastic applications due to lack of other user requirements [34]. Thus, equation (3.12) is modified as follows.

$$U\left(R_{k,j}\right) = \frac{\ln(R_{k,j} + 1)}{\ln(R_{max} + 1)} \tag{4.1}$$

where $R_{k,j}(R_{k,j} \in [0, R_{max}])$ is the data rate achieved by user *k* belonging to community *j* and R_{max} is the maximum data rate a network user can achieve.

To incorporate the social awareness about the underlying network in the allocation scheme, the social metric value of users is calculated using equations (2.1) and (2.4) from section 2.2.2.1. This social metric value has to be introduced into the existing utility function in equation (4.1) to formulate a socially aware utility function [6], [8]-[10], [15]-[20].

The socially aware utility function curve should exhibit the following properties.

1) The curve should be monotonically non-decreasing concave in shape as that is the property of elastic applications.

2) The utility for a user *k* belonging to community *j*, $U_{k,j} = U_{max}$ when its social metric value $x_{k,j} = x_{max}$, where U_{max} is the maximum utility a user can achieve and x_{max} is the maximum social metric value possible for a user. If this condition is true, it means that *k* is the most active (MA) user in the community *j*. This indicates that the MA user in community *j* is allocated highest amount of resources, which are used by the MA user to transmit content to its peers within the same community.

$U_{k,j} = 0$ when the user's social metric value $x_{k,j}$= 0 indicating that the user *k* in the community *j* has no connections to any other users in the same community or the network, as it doesn't have the ability i.e. the links to transmit content to other users in the network [6], [8]-[10].

3) The minimum value of utility is $U_{min} = 0$, which indicates no user satisfaction is experienced as no resource has been allocated to the user. The maximum value of utility $U_{max} = 1$ indicates highest level of satisfaction a user experiences.

The various ways employed to incorporate the social metric value $x_{k,j}$ of user k belonging to community j into the existing utility function by modifying equation (4.1) are shown in equations (4.2)-(4.5).

$$U(R_{k,j}, x_{k,j}) = \frac{\ln(R_{k,j} \times x_{k,j} + 1)}{\ln(R_{max} \times x_{max} + 1)} \tag{4.2}$$

$$U(R_{k,j}, x_{k,j}) = \frac{\ln(R_{k,j} + x_{k,j} + 1)}{\ln(R_{max} + x_{max} + 1)} \tag{4.3}$$

$$U(R_{k,j}, x_{k,j}) = \frac{\ln(R_{k,j}/x_{k,j} + 1)}{\ln(R_{max}/x_{max} + 1)} \tag{4.4}$$

$$U(R_{k,j}, x_{k,j}) = \frac{\ln(R_{k,j} - x_{k,j} + 1)}{\ln(R_{max} - x_{max} + 1)} \tag{4.5}$$

Figure 4.1 shows the curve plotted for multiplication based socially aware utility function, Figure 4.2 shows the curve plotted for addition based socially aware utility function, Figure 4.3 shows the curve plotted for division based socially aware utility function and Figure 4.4 shows the curves plotted for subtraction based socially aware utility function using equations (4.2), (4.3), (4.4) and (4.5) respectively.

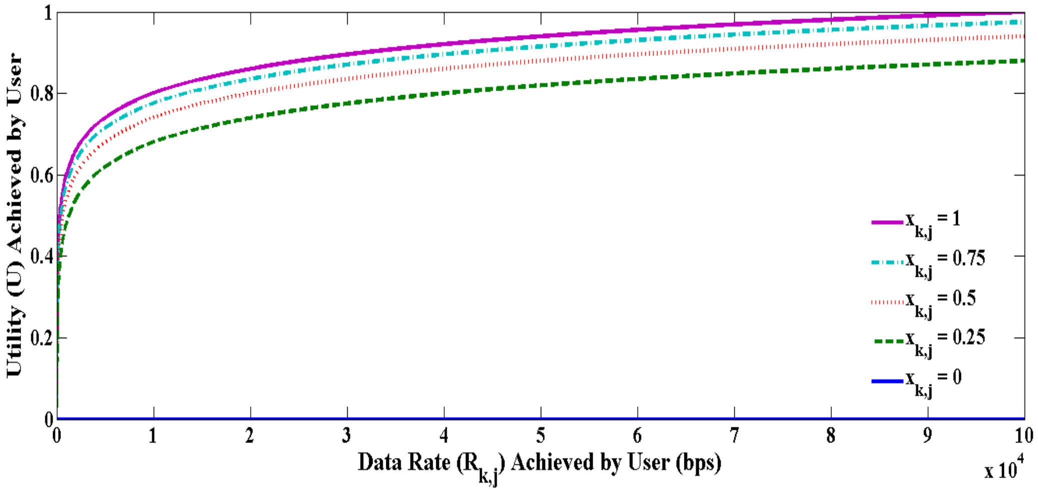


Figure 4.1 Multiplication based Proposed Socially Aware Utility Function Curve

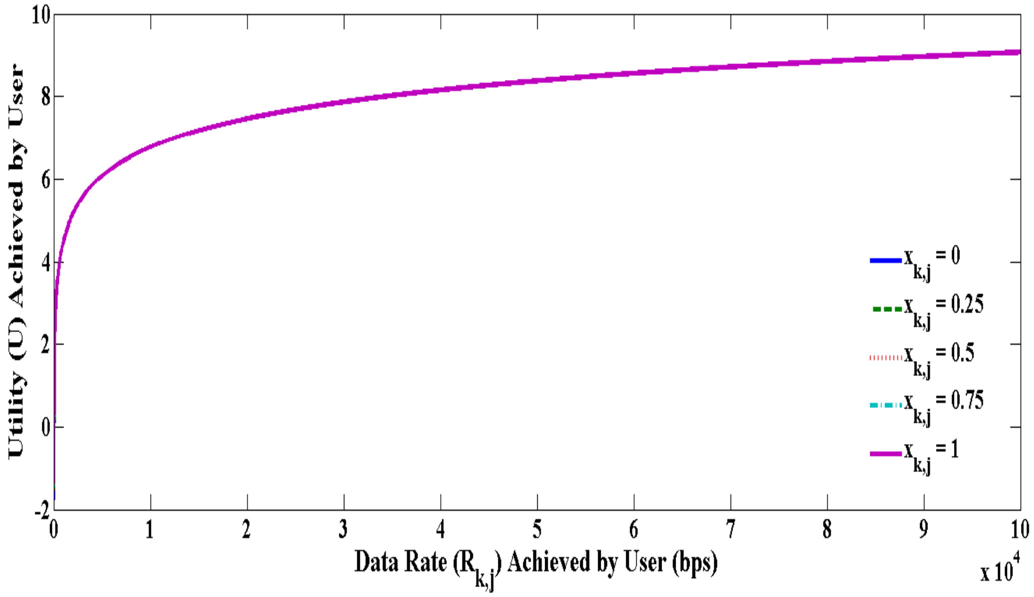


Figure 4.2 Addition based Proposed Socially Aware Utility Function Curve

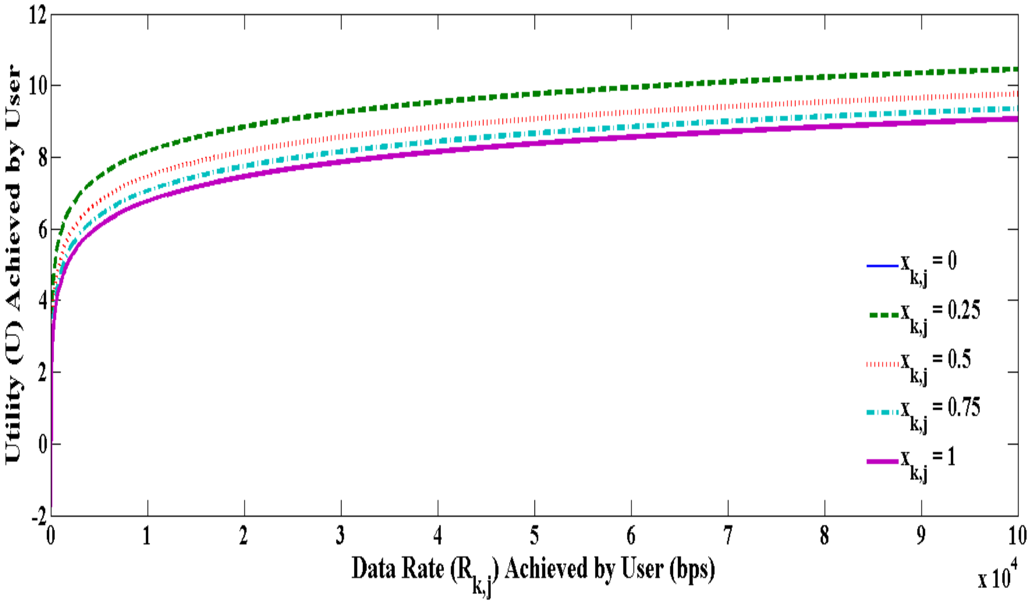


Figure 4.3 Division based Proposed Socially Aware Utility Function Curve

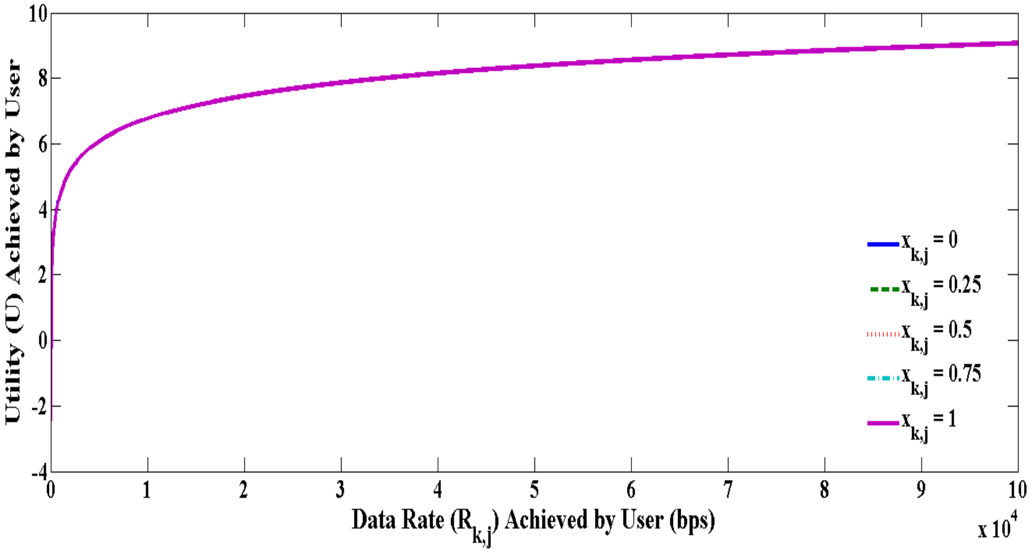


Figure 4.4 Subtraction based Proposed Socially Aware Utility Function Curve

In the Figure 4.1 to 4.4, the utility is plotted against the data rate achieved by a user for different social metric values of the users. From the Figures, it is observed that all the curves are concave in nature. However, apart from the curve in Figure 4.1, none of the other curves meet all the conditions of the socially aware utility function curve enlisted above; hence the multiplication based socially aware utility function in equation (4.2) has been selected to be used in this thesis.

4.2.1 Monotonic Function, Concavity, Convexity and Twice Differentiability

In the selected socially aware utility function (equation (4.2)), the social metric value $x_{k,j}$ is the sensitivity parameter defining the shape of the curve. R_{max} and x_{max} are constant values and $x_{k,j}$ is fixed for each user. The curve of the proposed multiplication based socially aware utility function is monotonic in nature as shown in Figure 4.1.

Lemma 1: The selected proposed socially aware utility function

$$f\left(R_{k,j}\right)=\frac{\ln\left(\,R_{k,j}\times x_{k,j}+1\right)}{\ln(R_{max}\times x_{max}+1)}$$

is a concave function and twice differentiable when $0\leq R_{k,j}\leq R_{max},\ 0\leq x_{k,j}\leq x_{max}$.

Proof: As R_{max} and x_{max} are constant values,

$\ln(R_{max}\times x_{max}+1)$=*constant.*

The first order derivative of the function *f* is as follows.

$$f'\left(R_{k,j}\right)=\frac{x_{k,j}}{constant\times(R_{k,j}\times x_{k,j}+1)} \tag{4.6 }$$

Let $\frac{x_{k,j}}{constant}$ = $constant_1$. Hence:

$$f'\left(R_{k,j}\right)=\frac{constant_1}{(R_{k,j}\times x_{k,j}+1)} \tag{4.7}$$

The second order derivative of function *f* is as follows.

$$f''\left(R_{k,j}\right)=\frac{-constant_1\times x_{k,j}}{(R_{k,j}\times x_{k,j}+1)^2} \tag{4.8}$$

Let $constant_1\times x_{k,j}$=$constant_2$. This gives:

$$f''(R_{k,j}) = \frac{-constant_2}{(R_{k,j} \times x_{k,j} + 1)^2} \tag{4.9}$$

As $f''(R_{k,j}) \leq 0 \ for \ 0 \leq R_{k,j} \leq R_{max}, 0 \leq x_{k,j} \leq x_{max}; f(R_{k,j})$ is a twice differentiable concave function [59].

Lemma 2: As the selected proposed socially aware utility function, $f(R_{k,j})$ is concave function,

$$f_1(R_{k,j}) = -f(R_{k,j})$$

is a convex function and twice differentiable when $0 \leq R_{k,j} \leq R_{max}, 0 \leq x_{k,j} \leq x_{max}$.

Proof: Following the steps shown in equations (4.6)-(4.9),

$$f_1''(R_{k,j}) = \frac{constant_2}{(R_{k,j} \times x_{k,j} + 1)^2} \tag{4.10}$$

As $f_1''(R_{k,j}) \geq 0 \ for \ 0 \leq R_{k,j} \leq R_{max}, 0 \leq x_{k,j} \leq x_{max}; f_1(R_{k,j})$ is a twice differentiable convex function [59].

4.3 Optimization Formulations for Proposed Socially Aware Resource Allocation Scheme

Based on the discussion in section 3.3.1, a two-hop network has been considered in this thesis. The base station (BS) and the network users operate in half-duplex mode i.e. both cannot transmit simultaneously. In a frame-based structure, the timeline contains consecutive frames, each containing downlink sub-frame and uplink sub-frame. The downlink sub-frame is further divided into two sub-frames due to the half-duplex assumption [23]. Full-duplex mode of communication is not considered, as it is hard to implement due to the dynamic range of incoming and outgoing signal [23]. Thus, the resource (subcarrier and power) allocation is performed in two steps, one step for each hop.

In the first hop, the BS performs joint resource i.e. subcarrier and power allocation and determines a subset of subcarriers to be allocated to a community. This subset will be used in the second hop by the MA user to transmit data to its peers within the same community. The BS broadcasts a control message, which notifies the MA user of the corresponding resource allocations [23]. In the first hop, the BS transmit power serves as the power resource. The content is transmitted to the MA user in the first sub-frame, after the allocation process is completed.

In the second hop, after receiving the data successfully in the first sub-frame, the MA user switches from the receiving mode to transmitting mode. A new joint resource allocation is performed using the subcarriers from the subset allocated to the community in the first hop and the transmit power of the MA user acts as the power resource (the BS has knowledge of this value as mentioned in section 3.3.1). The MA user, transmits the control message during the beginning of the second sub-frame, notifying its peers of the resource allocation information, followed by the MA user forwarding data to its peers in the second sub-frame.

The resource allocation in the first and the second hop is done using the channel state information (CSI) gathered by the BS. In the first hop, the BS is the transmitter and all the users are the receivers whereas in the second hop, the MA user acts as the transmitter and its peers in the community act as the receivers. It is assumed that the BS has CSI knowledge of both the links, i.e. from the BS to MA and from MA user to each of its peers, this information is fed back to the BS using a shared broadcast channel (for Long Term Evolution (LTE) networks, the bandwidth of this channel is 1.08 MHz [60]).

Following are the optimization formulations implemented in this thesis, where B is the total bandwidth available in the network, N is the total number of subcarriers present, K is the total number of users in the network and J is the total number of communities in the network.

4.3.1 Socially Aware Joint Subcarrier and Power Allocation Optimization Formulation for First Hop

Over the first hop, the objective of the optimization is to maximize the overall network utility i.e.

$$\max_{s,p} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{n=1}^{N} U\left(R_{k,j}, x_{k,j} \right)$$

which is expanded and expressed as follows:

Problem I) Proposed Socially Aware Joint Subcarrier and Power Allocation Formulation for the First Hop

$$\max_{s,p} \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{n=1}^{N} \frac{s_{n,k,j} \times \left(\ln(x_{k,j} \times \left(\frac{B}{N}\right) \times \log_2\left(1 + p_{n,k,j} \times H_{n,k,j}\right) + 1) \right)}{(\ln(x_{max} \times R_{max} + 1))} \qquad (4.11\ a)$$

subject to:

C1: $s_{n,k,j} \in \{0,1\}$ $\qquad (4.11\ b)$

C2: $\sum_{n=1}^{N} s_{n,k,j} \geq 1;\ \forall\ k, j$ $\qquad (4.11\ c)$

C3: $\sum_{j=1}^{J} \sum_{k=1}^{K} s_{n,k,j} \leq 1;\ \forall\ n$ $\qquad (4.11\ d)$

C4: $p_{n,k,j} \geq 0$ $\qquad (4.11\ e)$

C5: $\sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{n=1}^{N} p_{n,k,j} \leq P_{max}$ $\qquad (4.11\ f)$

C6: $\sum_{n=1}^{N} s_{n,k,j} \times \left(\frac{B}{N}\right) \times \log_2\left(1 + p_{n,k,j} \times H_{n,k,j}\right)\ \geq R_{k,j}^{min};\ \forall\ k, j$ $\qquad (4.11\ g)$

In Problem I (equation (4.11)), the subcarriers ($s_{n,k,j}$) and the transmission power of the BS that can be allocated to the subcarriers, $p_{n,k,j}$ are the decision variables, where *n* is the subcarrier index (*n* ∈ [1,2,.., *N*]), *k* is the user index (*k* ∈ [1,2,.., *K*]) and *j* is the community index (*j* ∈ [1,2,.., *J*]). P_{max} is the total BS transmission power, $\left(\frac{B}{N}\right)$ is the bandwidth of a subcarrier, and $H_{n,k,j}$ is the channel gain calculated for user k belonging to community j receiving over subcarrier n, $H_{n,k,j} = \frac{\left|h_{n,k,j}^{Total}\right|^2}{N_0\frac{B}{N}}$, where N_0 is the power spectral density of the thermal noise and $h_{n,k,j}^{Total}$ is calculated using equation (3.2). $R_{k,j}^{min}$ is the minimum data rate requirement of user k belonging to community j.

The objective function in equation (4.11 *a*), includes the proposed utility function in equation (4.2). The objective of Problem I is to maximize the overall network utility by performing joint subcarrier and power allocation for a socially aware network, subject to constraints C1-C6 given by equations (4.11 b)-(4.11 g) [27], [28], [37], [49]-[51], [61], [62]. S is a subcarrier allocation matrix and P is a power allocation matrix each of size $J \times K \times N$.

Constraint C1 indicates that the subcarrier allocation variable is binary in nature i.e. $s_{n,k,j}$=1 if subcarrier *n* is allocated to user *k* belonging to community *j*, otherwise $s_{n,k,j}$=0.

Constraint C2 states that more than one subcarrier can be allocated to one user.

Constraint C3 indicates that no two users share the same subcarrier, this helps eliminate the intra-cell interference occurring in the network.

Constraint C4 specifies that the power allocated to the subcarriers assume non-zero values.

Constraint C5 certifies that power allocated to the subcarriers is distributed such that the total power allocated to the subcarriers is less than or equal to the total power available in the network.

Constraint C6 ensures that the minimum data rate requirement of each user has been fulfilled (i.e. the quality of service (QoS) requirement of the users is satisfied).

The objective function is a summation over integer set of subcarriers. For a problem to be convex, the domain of the problem should be convex too [27], [28], [59]. The subcarrier allocation variable is a binary variable. The domain of the constraint C1 (i.e.$s_{n,k,j} \in \{0,1\}$) is an integer domain. Integer values are not convex [59]. Thus, the problem is not convex. The domain of the subcarrier allocation variable can be convex if the constraint C1 is relaxed as follows.

C1: $0 \leq s_{n,k,j} \leq 1$ which indicates that the users share the subcarriers. Due to this modification, the domain is now a line segment for the range 0 to 1 which is convex [27], [28], [59]. However, relaxing this constraint will indicate that intra-cell interference which was avoided due to binary subcarrier allocation will have to be considered.

The subcarrier allocation variables are binary and the power allocation variables are positive continuous; making the problem mixed binary integer programming problem. The objective function is non-linear as can be observed in the utility curve in section 4.2, making the problem a mixed integer non-linear programming (MINLP) problem. To determine a global optimum solution for MINLP problems, an exhaustive search technique is needed to search the entire feasible space for the solution, which is very complicated in terms of computation, especially when the number of subcarriers, users and communities are increased (as there are $J \times K \times N$ combinations of allocations possible). MINLP problems are generally NP-hard (Non-deterministic Polynomial-time hard) problems which are very difficult to solve using analytical techniques (section 2.5.2). Thus, heuristics and approximation algorithms have to be used to solve NP-hard problems [18], [27].

4.3.2 Socially Aware Joint Subcarrier and Power Allocation Optimization Formulation for Second Hop

For a two-hop path, the achievable data rate is the minimal capacity of the first hop and the second hop. Assuming the time length of both the sub-frames (section 4.3) is equal, the achievable data rate of a two-hop path, $\mathrm{R}_{\text{end}-\text{to}-\text{end}}$ is calculated as follows [23].

$$\mathrm{R}_{\text{end}-\text{to}-\text{end}} = \frac{1}{2} \min \left\{R_{k^*,j}, R_{k^* \rightarrow k,j}\right\} \qquad (4.12)$$

In equation (4.12), $R_{k^*,j}$ is the data rate achieved by the MA user k^* of community j, $R_{k^*\to k,j}$ is the data rate achieved by user k belonging to community j, when the data transfer takes place from the MA user k^* of the community j to user k of the same community. The factor of $\frac{1}{2}$ accounts the fact that one OFDM symbol is transmitted over two hops.

Problem II a) Proposed Socially Aware Joint Subcarrier and Power Allocation Formulation for Second Hop

$$\max_{s,p}\sum_{j=1}^{J}\sum_{\substack{k=1\\k\neq k^*}}^{K_j}\min\left[\left(0.5\times R_{k^*,j}\right),\left(\sum_{n=1}^{N_j}\left(s_{n,k,j}\times\left(0.5\times\left(\frac{B}{N}\right)\times\log_2\left(1+p_{n,k,j}\times H_{n,k^*\to k,j}\right)\right)\right)\right)\right] \tag{4.13 a}$$

subject to:

$$\text{C1: } s_{n,k,j}\in\{0,1\} \tag{4.13 b}$$

$$\text{C2: } \sum_{n=1}^{N_j}s_{n,k,j}\geq 1;\ \forall\ k\in\ K_j, k\neq k^*, j \tag{4.13 c}$$

$$\text{C3:} \sum_{j=1}^{J}\sum_{\substack{k=1\\k\neq k^*}}^{K_j}s_{n,k,j}\leq 1;\ \forall\, n\in N_j \tag{4.13 d}$$

$$\text{C4: } p_{n,k,j}\geq 0 \tag{4.13 e}$$

$$\text{C5: } \sum_{j=1}^{J}\sum_{\substack{k=1\\k\neq k^*}}^{K_j}\sum_{n=1}^{N_j}p_{n,k,j}\leq P_{k^*,j} \tag{4.13 f}$$

$$\text{C6:} \sum_{j=1}^{J}\sum_{\substack{k=1\\k\neq k^*}}^{K_j}\min\left[\left(0.5\times R_{k^*,j}\right),\left(\sum_{n=1}^{N_j}\left(s_{n,k,j}\times\left(0.5\times\left(\frac{B}{N}\right)\times\log_2\left(1+p_{n,k,j}\times H_{n,k^*\to k,j}\right)\right)\right)\right)\right]$$

$$\geq R_{k,j}^{min};\forall\, k\in K_j, k\neq k^* \tag{4.13 g}$$

In the first hop, the BS performs socially aware resource allocation for the network users, with the objective of maximizing the overall network utility achieved based on the importance of the users within their communities and the overall network. In the second hop, the BS performs resource allocation for the individual communities in the network, where the MA user of the community acts as the transmitter. The social awareness of the peers of the MA user is not considered while performing resource allocation in this hop as they are all connected to only the MA user and not to each other. Thus, the objective of the resource allocation in the second hop is to maximize the end-to-end transmission rate achieved by the peers of MA user by using the resources allocated to the community (subset of subcarriers) by the BS in the first hop.

The objective function in equation (4.13 a) is formulated using equation (4.12). In the minimum function bracket, the first term is the data rate achieved by the MA user in the first hop and the second term is the data rate achieved by the other users within the MA's community during the second hop. The subcarriers ($s_{n,k,j}$) and the transmission power of the MA user that can be allocated to the subcarriers, $p_{n,k,j}$ are the decision variables. In the second hop, resource allocation for each community is independent of the other communities; as during the first hop, the BS assigns independent subsets of subcarriers N_j for each community and the MA user (k^*) of each community are the transmitters with transmission power $P_{k^*,j}$. The channel gain $H_{n,k^*\rightarrow k,j}$, is calculated when the MA user (k^*) is the transmitter and its peer k within community j is the receiver. The constraints C1-C6 equations (4.13 b)-(4.13 g) are the same as the ones for Problem I, i.e. equations (4.11 b)-(4.11 g).

Problem II a) belongs to the MINLP category for similar reasons as stated for Problem I, making determining a global optimum solution for the problem a computationally complex process. The max-min formulation also contributes to the complexity as it makes the problem a multi-objective optimization problem (max and min are generally separate problems).

The max-min formulation in Problem II a) is modified into a maximization problem [63], [64] by introducing a new variable q_k to represent the minimum bracket in the equation (4.13 a) where $k \in K_j$ (total number of users in a community j) and $k \neq k^*$. The minimum of several values is less than or equal to them i.e.,

$$q_k \quad \leq \ \min \left[\left(0.5 \times R_{k^*,j}\right), \left(\sum_{n=1}^{N_j}\left(s_{n,k,j} \times \left(0.5 \times \left(\frac{B}{N}\right) \times \log_2\left(1 + p_{n,k,j} \times H_{n,k^* \to k,j}\right)\right)\right)\right)\right] \quad (4.14\ a)$$

which can be represented as

$$q_k \leq \left(0.5 \times R_{k^*,j}\right) \qquad (4.14\ b)$$

and

$$q_k \quad \leq \left(\sum_{n=1}^{N_j}\left(s_{n,k,j} \times \left(0.5 \times \left(\frac{B}{N}\right) \times \log_2\left(1 + p_{n,k,j} \times H_{n,k^* \to k,j}\right)\right)\right)\right) \qquad (4.14\ c)$$

Problem II b) Modified Proposed Socially Aware Joint Subcarrier and Power Allocation Formulation for Second Hop

$$\max_{s,p,q} \sum_{\substack{k=1 \\ k\neq k^*}}^{K_j} q_k \qquad (4.15\ a)$$

subject to:

$$\text{C1: } s_{n,k} \in \{0,1\} \qquad (4.15\ b)$$

$$\text{C2: } \sum_{n=1}^{N_j} s_{n,k} \geq 1;\ \forall\ k \in K_j \qquad (4.15\ c)$$

$$\text{C3: } \sum_{\substack{k=1 \\ k\neq k^*}}^{K_j} s_{n,k} \leq 1\,;\ \forall\ n \in\ N_j \qquad (4.15\ d)$$

$$\text{C4: } p_{n,k} \geq 0 \qquad (4.15\ e)$$

$$\text{C5:} \sum_{\substack{k=1 \\ k\neq k^*}}^{K_j} \sum_{n=1}^{N_j} p_{n,k} \leq P_{k^*,j} \qquad (4.15\ f)$$

$$\text{C6: } 0.5\times R_{k^*,j} \geq q_k \qquad (4.15\ g)$$

$$\text{C7:} \sum_{n=1}^{N_j} \left(s_{n,k} \times \left(0.5 \times \left(\frac{B}{N}\right) \times \log_2\left(1 + p_{n,k} \times H_{n,k^* \to k}\right)\right)\right) \geq q_k; \forall\ k \in K_j, k \neq k^* \qquad (4.15\ h\ )$$

$$\text{C8:} \sum_{n=1}^{N_j} \left(s_{n,k} \times \left(0.5 \times \left(\frac{B}{N}\right) \times \log_2\left(1 + p_{n,k} \times H_{n,k^* \to k}\right)\right)\right) \geq R_{k,j}^{min}; \forall\ k \in K_j, k \neq k^* \ (4.15\ i)$$

$$\text{C9: } q_k \geq 0 \qquad (4.15\ j)$$

The formulation shown in Problem II b) is used to perform resource allocation for a single community, hence the decision variables considered are subcarriers $s_{n,k}$, the transmission power of the MA user that can be allocated to the subcarriers $p_{n,k}$ and q_k. The objective of Problem II b) is obtained by modifying the equation (14.13 *a*). It maximizes the total data rate achieved by the network users. Constraints C1-C5 (equations (4.15 *b*)-(4.15 *f*)) are the same as constraints C1-C5 (equations (4.11 *b*)-(4.11 *f*)) described for Problem I. Constraints C6 (equation (4.14 *b*)) and C7 (equation (4.14 *c*)) are modifications (decomposition of the minimization function) of equation (4.13 *a*). Constraint C8 ensures that the minimum data rate requirements of community users are met and constraint C9 indicates that the new variable is positive continuous in nature.

4.3.3 Conventional (Socially Unaware) Optimization Formulations

The following optimization formulations in Problems III and IV are used to perform joint subcarrier and power allocation for a network where social awareness of the users is not considered. In this case, direct links exist between the BS and the network users and the transmission of the data takes place over these direct links.

Problem III) Formulation for conventional approach (maximize overall network utility)

$$\max_{s,p} \sum_{k=1}^{K} \sum_{n=1}^{N} s_{n,k} \times \frac{\ln(\left(\frac{B}{N}\right) \times \log_2\left(1 + p_{n,k} \times H_{n,k}\right) + 1)}{\ln(R_{max} + 1)} \qquad (4.16\ a)$$

subject to:

C1: $s_{n,k} \in \{0,1\}$ $(4.16\ b)$

C2: $\sum_{n=1}^{N} s_{n,k} \geq 1;\ \forall k \in K$ $(4.16\ c)$

C3: $\sum_{k=1}^{K} s_{n,k} \leq 1;\ \forall n \in N$ $(4.16\ d)$

C4: $p_{n,k} \geq 0$ $(4.16\ e)$

C5: $\sum_{k=1}^{K} \sum_{n=1}^{N} p_{n,k} \leq P_{max}$ $(4.16\ f)$

C6: $\sum_{n=1}^{N} s_{n,k} \times \left(\frac{B}{N}\right) \times \log_2(1 + p_{n,k} \times H_{n,k}) \geq R_k^{min}\ ;\ \forall k \in K$ $(4.16\ g)$

Problem IV) Formulation for conventional approach (rate maximization based)

$$\max_{s,p} \sum_{k=1}^{K} \sum_{n=1}^{N} s_{n,k} \times \left(\left(\frac{B}{N} \right) \times \log_2 \left(1 + p_{n,k} \times H_{n,k} \right) \right) \qquad (4.17\ a)$$

subject to:

C1-C6 equations (4.16 b)-(4.16 g)

The decision variables in Problems III and IV are the $s_{n,k}$ the subcarrier allocation variable and $p_{n,k}$ the power allocation variable. The transmission power available in the network is the maximum transmission power P_{max} of the BS. The objective of Problem III is to maximize the network utility and is formulated based on equation (4.1). The objective of Problem IV [39] is to maximize the total rate achieved by all users in the network. The constraints C1-C6 for Problems III and IV are the same as those discussed for Problem I.

Based on the discussion in Problem I, Problems III and IV are MINLP in nature and fall under the NP- hard category.

4.4 Summary

In the two-hop socially aware OFDMA-based downlink network implemented; the first hop involves data transmission from the BS to the MA user and the second hop involves data transmission from the MA user to its peers. Based on the discussion of the formulations of the utility functions in equations (4.2)-(4.5), a socially aware utility function is proposed and its monotonicity, convexity, concavity and twice differentiability have been discussed.

An optimization formulation depicting the downlink data transmission operation in the two-hop network is proposed in this chapter. The objective of the proposed optimization is to maximize the overall network performance in terms of utility and data rate achieved by the users of a network constrained by limited bandwidth and limited power, as well as social selfishness of the users. The formulated optimization problems are by nature MINLP problems and belong to the NP-hard category making them computationally complex to solve and achieve global optimal solution. A solution model to solve the proposed optimization formulations is proposed and described in the following chapter.

Chapter 5: Solution of Proposed Optimization Problem Formulation

5.1 Introduction

Development of closed form analytical results for a detailed performance evaluation of resource allocation in a socially aware wireless network is extremely difficult. This is because the proposed optimization problems in sections 4.3.1 and 4.3.2 are Mixed Integer Non-Linear Programming (MINLP) problems in nature. As such, a performance evaluation framework based on determining a numerical solution to the optimization problem, using dedicated solvers is adopted in this thesis. The performance evaluation framework has been established by defining and implementing a wireless network setup which is overlaid by a social network and optimization formulations. The numerical solutions are obtained using MATLAB (Matrix Laboratory) [65], a numerical computing environment and programming language, along with Advanced Integrated Multidimensional Modeling Software (AIMMS) [65] used for modeling and solving large-scale optimization problems. The solution model developed is verified and the outputs are validated to ensure the correctness of the implemented solution and optimization model.

This chapter is organised as follows. Section 5.2 discusses the solution objective. The optimization problem solution is described in section 5.3. The solution model, its inputs and outputs are discussed in section 5.4. The solution model verification and validation are presented in sections 5.5 and 5.6, respectively. The chapter is summarized in section 5.7.

5.2 Solution Objective

The objective of the solution model and optimization problem implementation is to evaluate the performance of the socially aware joint subcarrier and power allocation scheme proposed in sections 4.3.1 and 4.3.2, by solving the proposed optimization formulations (specifically equations (4.11) and (4.15)) under various network scenarios. The performance of the proposed scheme is then compared to the performance of the conventional optimization formulations presented in section 4.3.3 (i.e. equations (4.16) and (4.17)).

Apart from the joint subcarrier and power allocation formulations, fixed power allocation based formulations are also used to compare performance of the proposed socially aware optimization formulations and the conventional optimization formulations. The joint resource allocation optimization problems in section 4.3 are Non-deterministic Polynomial-time-hard (NP-hard) combinatorial optimization problems. Thus, determining optimal solutions within a given time length using extensive search over all possible power and subcarrier allocations is a very complex process. However, by using fixed power allocation, the complexity of solving the optimization problem can be reduced significantly [23]. A fixed value of power is allocated to all the subcarriers to be used in the network. Using the fixed power allocation scheme, the BS has the ability to pre-calculate the data rates achieved by the users. This transforms the problem formulated in section 4.3 into an optimization problem with binary variables (as only subcarrier allocation has to be carried out). Thus, the computational complexity and computation time involved in solving joint optimization problems is reduced using the fixed power allocation scheme. Comparing the proposed and the conventional formulations demonstrates the advantages of the proposed formulation.

5.3 Problem Solution

The proposed optimization problems in sections 4.3.1 and 4.3.2 are MINLP problems in nature and they belong to NP-hard category of problems, i.e. it is highly unlikely that a polynomial-time algorithm exists to solves these problems. The feasible region for the problem is not convex due to the existence of the constraint as discussed in sections 4.3.1 and 4.3.2. This nature of the feasible region, adds to the already existing difficulty in solving the problem. Thus, various heuristics and approximation algorithms have been proposed in the literature to determine a possible solution to such problems.

Heuristics help quickly to determine approximate solutions to problems when methods to determine exact solutions for the same fail. The optimality, accuracy, completeness and execution time of the solution to the problem are traded off while determining the solution [67], [68]. Approximate algorithms determine approximate solutions, generally for NP-hard and NP-complete problems to a certain bound [67], [68].

5.3.1 Algorithms for Solving Mixed Integer Non-Linear Programming (MINLP) Problems

Outer Approximation (OA) [42], [69]-[71] and Branch-and-Bound (B&B) [42], [72], [73] are the two common approaches used in the literature for solving MINLP problems.

B&B forms relaxed MINLP (RMINLP) problems by eliminating the integrality requirements of the discrete variables of the MINLP problem. Each node of the B&B tree represents a solution to the RMINLP with adjusted bounds on the discrete variables [42], [72], [73].

OA technique is generally employed for solving convex problems. OA decomposes the MINLP problem into non-linear programming sub-problem i.e. NLP sub-problem which fixes discrete variables and linear master mixed integer linear programming sub-problem i.e. MILP sub-problem and solves them at each iteration. Provided the first sub-problem is feasible, it gives an upper bound solution to the MINLP problem and the second sub-problem helps determine the lower bound. At each iteration, the algorithm tries to improve the upper and lower bounds. The definition of MILP changes as at each iteration, the OA cuts are added which eliminate the solution of the previous iteration. The algorithm terminates when the two bounds assume same value (within a fixed tolerance value) [42], [69]-[71].

A flowchart of the algorithm is shown in Figure 5.1 [74].

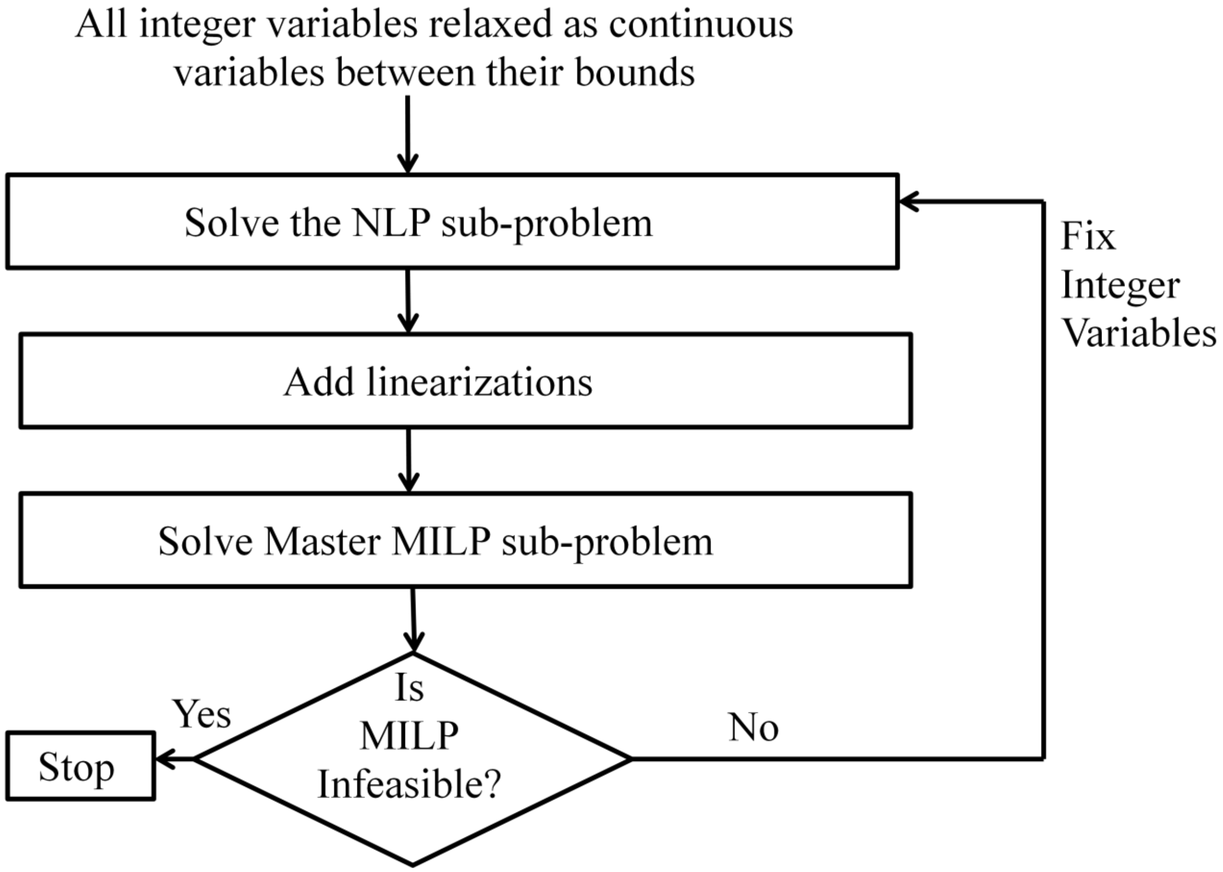


Figure 5.1 Flowchart for the Outer Approximation Algorithm

5.3.2 Optimization Tools

Multiple solvers operating on approximation algorithms, proposed in the literature for solving MINLP problems are available for usage. A solver based approach has been employed in this thesis, as it has the ability to provide an approximate solution to the problem within a tolerable time limit, in spite of the computational complexity involved in doing so. AIMMS is a modeling platform used for modeling and solving optimization problems [66]. AIMMS uses various solvers such as IBM ILOG CPLEX Optimization Studio (CPLEX) [73], AIMMS Outer Approximation (AOA) [69], [75], Branch-And-Reduce Optimization Navigator (BARON) [76], [77], etc. to solve mathematical problems of various types such as linear programming (LP), MILP, NLP, MINLP, etc. AIMMS offers AOA-local solver and BARON-global solver for solving MINLP problems [66].

BARON uses branch-and-reduce algorithm to determine global solution for MINLP problems. It is a computational system for solving non-convex optimization problems to global optimality. Purely continuous, purely integer, and mixed-integer nonlinear problems can be solved with the software. However, the solution time consumed in search of a global optimum for a problem and proving it to be a globally optimum solution for the problem, is very large as compared to the solution time consumed by local solvers to determine a local optimum for the same problem [69], [74], [75].

AOA algorithm determines problem solution using the OA algorithm described in section 5.3.1. It decomposes the MINLP problem into MILP sub-problem and NLP sub-problem and solves them in an alternating sequence [42], [69], [74], [75]. AOA uses two solvers CONOPT (version 3.14) [78] and CPLEX (version 12.5) [73], for solving the NLP and MILP sub-problems, respectively. By default, AOA assumes that the MINLP problem is non-convex and uses the iteration limit as a stopping criteria.

The CONOPT solver from ARKI Consulting and Development [78] is used to solve large-scale NLP problems. CONOPT helps to calculate exact second order derivatives to solve NLP problems more efficiently. CONOPT has been able to successfully solve NLP problems with 100,000 equations. Also, when CONOPT terminates a problem with a locally optimal solution, then the solution is indeed locally optimal [78]. The CPLEX solver from the IBM ILOG [73] is a high performance solver for LP and MIP problems. CPLEX branch-and-bound algorithm for solving MIP problems, uses cutting planes and heuristics to determine integer solutions [73].

B&B algorithm is required to solve multiple NLP sub-problems while searching the feasible area for a solution; whereas, the OA algorithm was designed to minimize the number of NLP sub-problems to be solved to determine a solution. Thus, OA based solver has been used in this thesis, to determine a solution to the optimization problems considered [79].

5.4 Solution Model

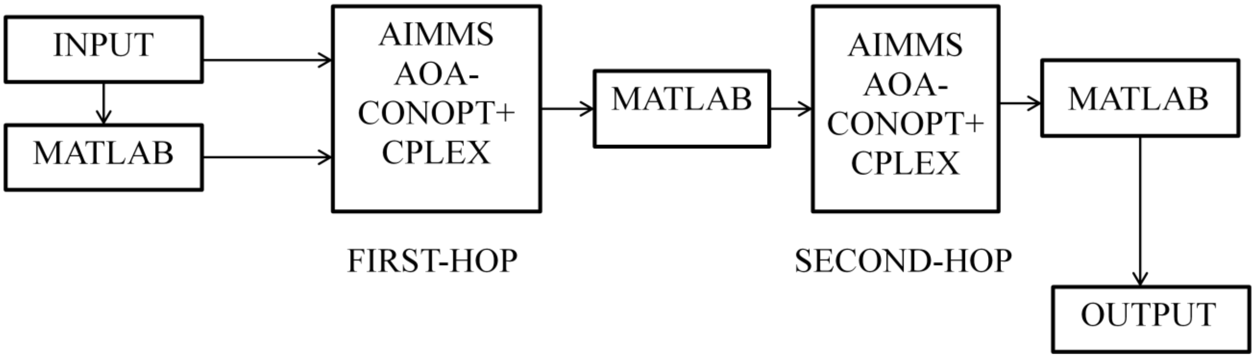
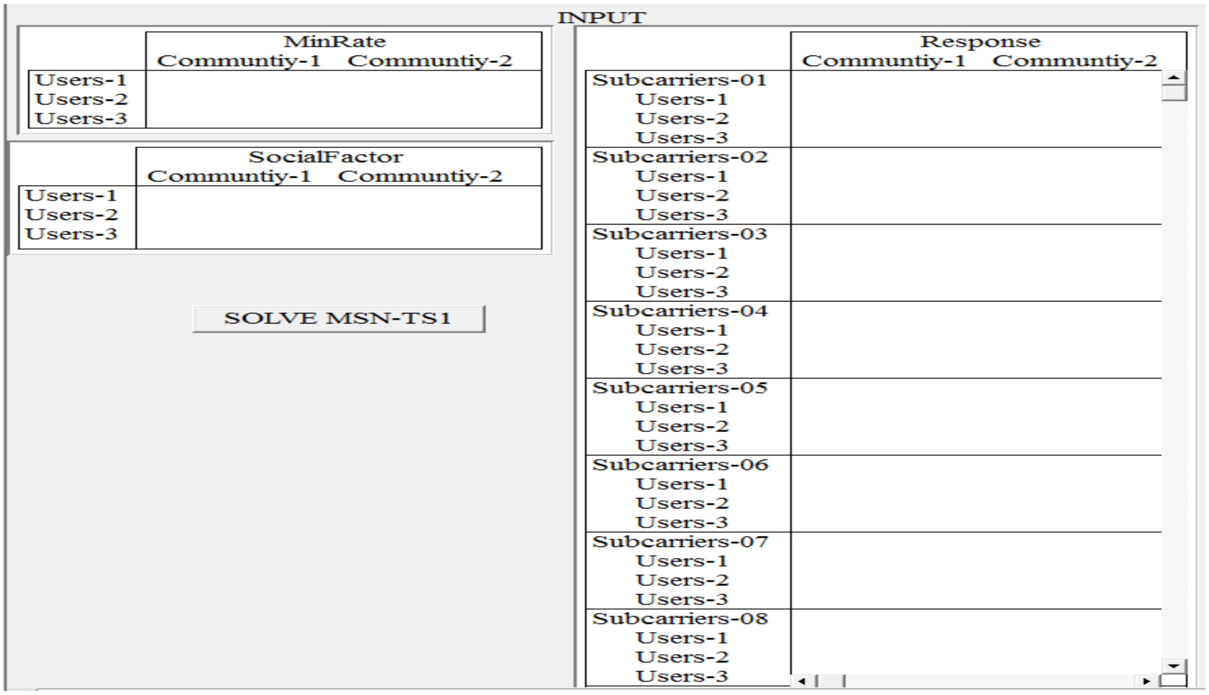


Figure 5.2 High-level Overview of the Solution model

A high-level overview of the solution model implemented in this thesis for resource allocation is shown in Figure 5.2. MATLAB and AIMMS software packages exist at the heart of the solution model. Number of subcarriers, system bandwidth available in the network, total number of users in the network, total number of communities in the network, number of users per community, transmission power of the individual network user and the total base station (BS) transmission power are fed into MATLAB as well as AIMMS.

MATLAB uses the above inputs to generate various socially aware network setups, calculate channel gain for the users and the social metric values of the users. The channel gain is calculated using equations (3.1) and (3.2) in section 3.5 and the social metric values are calculated using equations (2.1) and (2.4) in section 2.2.2.1.



	MinRate	
	Communtiy-1	Communtiy-2
Users-1		
Users-2		
Users-3		

	SocialFactor	
	Communtiy-1	Communtiy-2
Users-1		
Users-2		
Users-3		

	Response	
	Communtiy-1	Communtiy-2
Subcarriers-01		
Users-1		
Users-2		
Users-3		
Subcarriers-02		
Users-1		
Users-2		
Users-3		
Subcarriers-03		
Users-1		
Users-2		
Users-3		
Subcarriers-04		
Users-1		
Users-2		
Users-3		
Subcarriers-05		
Users-1		
Users-2		
Users-3		
Subcarriers-06		
Users-1		
Users-2		
Users-3		
Subcarriers-07		
Users-1		
Users-2		
Users-3		
Subcarriers-08		
Users-1		
Users-2		
Users-3		

Figure 5.3 Input to Advanced Integrated Multidimensional Modeling System (AIMMS)

An input-output Graphical User Interface (GUI) has been created in AIMMS for ease of use. An example with 2 communities, 3 users in each community and 8 subcarriers is observed in the GUI (Figure 5.3). The channel gain (Response), user social metric value (SocialFactor) and user minimum data rate requirements (MinRate) are the inputs to the AIMMS package as observed in Figure 5.3.

The variables (V), objective which is also considered as a variable (V) by AIMMS and constraints (C) of the optimization formulations in equations (4.11), (4.15), (4.16) and (4.17) are coded into the AIMMS platform using the model explorer shown in Figure 5.4. The inputs from MATLAB and the other inputs provided externally are used as parameters (P) and sets (S) in the model.

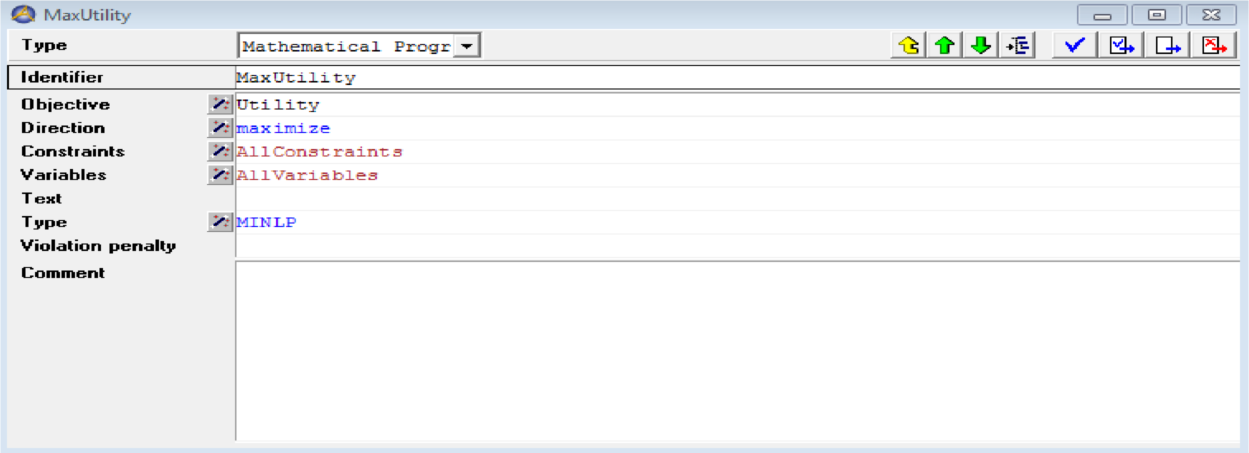

Model Explorer: MSN-TS1.amb

Main MSN TS1
- Declaration
  - subcarrier
  - users
  - communities
  - Response(n,k,j)
  - SocialFactor(k,j)
  - subcarriers(n,k,j)
  - C1(k,j)
  - C2(n)
  - C4(k,j)
  - C3
  - MaxUtility
  - MinRate(k,j)
  - power(n,k,j)
  - Utility
- MainInitialization
- MainExecution
- MainTermination
- Outer Approximation Module [read-only]

Predeclared Identifiers [read-only]

Figure 5.4 AIMMS Model Explorer

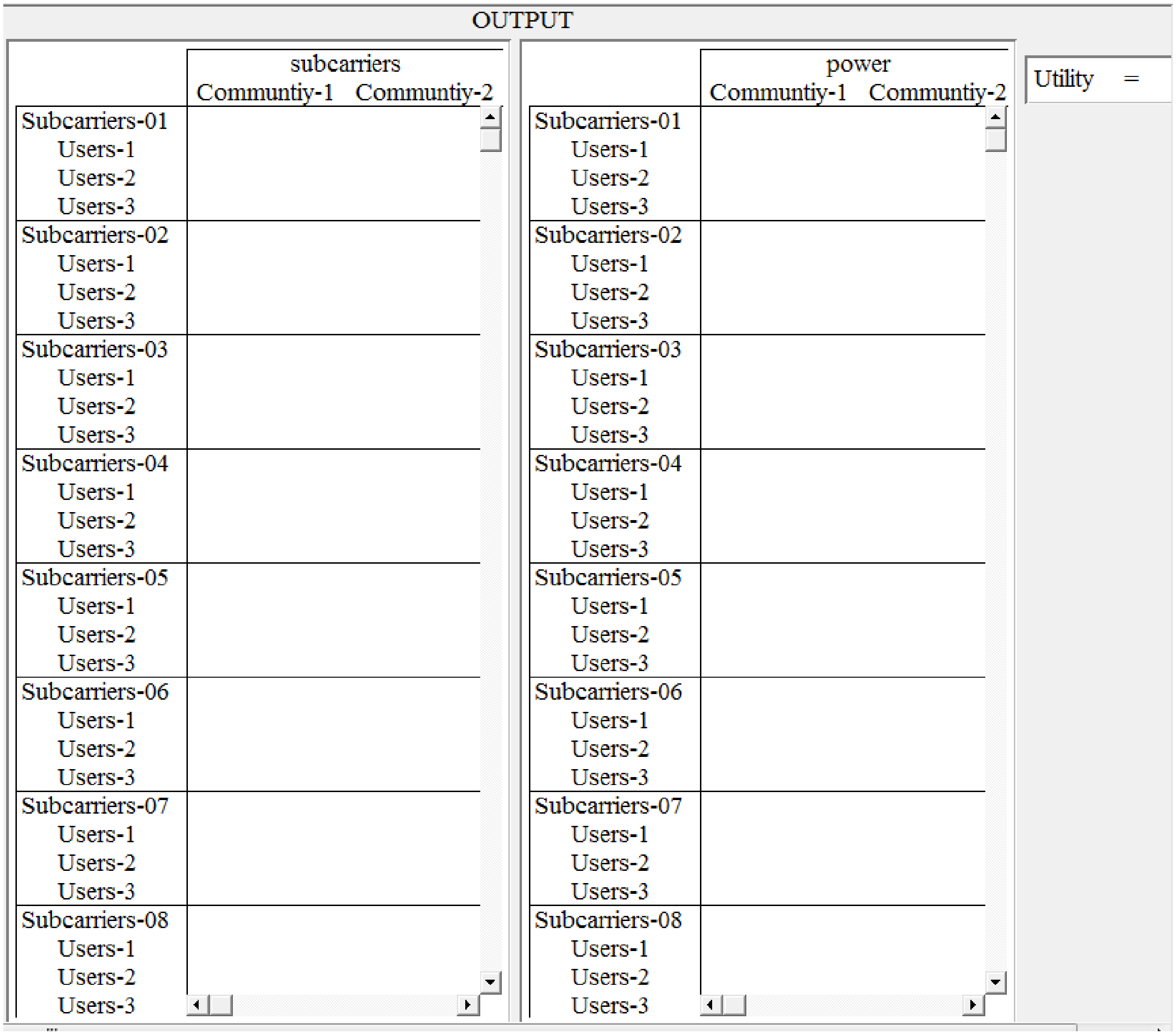
The mathematical program (Mp) as observed in Figure 5.5 provides information such as the objective function, direction of the objective (i.e. whether to maximize or minimize the objective), the constraints along with the variables applicable to the problem and the type of problem to be solved.


MaxUtility

Type	Mathematical Progr
Identifier	MaxUtility
Objective	Utility
Direction	maximize
Constraints	AllConstraints
Variables	AllVariables
Text	
Type	MINLP
Violation penalty	
Comment	

Figure 5.5 AIMMS Mathematical Program

AIMMS uses the AOA algorithm which decomposes the first-hop MINLP problem into NLP and MILP sub-problems and uses the CONOPT and CPLEX solvers to determine a solution to the problem as discussed in section 5.3. The results of the first-hop resource allocation i.e. the subcarrier and the power allocation values can be observed in the GUI developed as shown in Figure 5.6.



OUTPUT

	subcarriers	
	Communtiy-1	Communtiy-2
Subcarriers-01		
Users-1		
Users-2		
Users-3		
Subcarriers-02		
Users-1		
Users-2		
Users-3		
Subcarriers-03		
Users-1		
Users-2		
Users-3		
Subcarriers-04		
Users-1		
Users-2		
Users-3		
Subcarriers-05		
Users-1		
Users-2		
Users-3		
Subcarriers-06		
Users-1		
Users-2		
Users-3		
Subcarriers-07		
Users-1		
Users-2		
Users-3		
Subcarriers-08		
Users-1		
Users-2		
Users-3		

	power	
	Communtiy-1	Communtiy-2
Subcarriers-01		
Users-1		
Users-2		
Users-3		
Subcarriers-02		
Users-1		
Users-2		
Users-3		
Subcarriers-03		
Users-1		
Users-2		
Users-3		
Subcarriers-04		
Users-1		
Users-2		
Users-3		
Subcarriers-05		
Users-1		
Users-2		
Users-3		
Subcarriers-06		
Users-1		
Users-2		
Users-3		
Subcarriers-07		
Users-1		
Users-2		
Users-3		
Subcarriers-08		
Users-1		
Users-2		
Users-3		

Utility =

Figure 5.6 Output from AIMMS

The results of the first-hop optimization obtained using AIMMS act as an input to MATLAB where the number of subcarriers allocated to each community, data rate achieved by the most active

(MA) users of each community and channel gain for the peers of the MA user of a community are calculated. These values are calculated individually for each community existing in the network and act as an input to AIMMS as observed in Figure 5.2.

AIMMS performs resource allocation for each individual community in the second-hop. The results of the resource allocation i.e. subcarrier and power allocation for each community act as the input to MATLAB. This input is used to calculate the performance metrics i.e. overall network utility, system fairness index (SFI) and system spectral efficiency (SSE) using equations (4.1), (3.6) and (3.7) in sections 4.2 and 3.6 respectively.

5.4.1 Inputs and Outputs

Following are the inputs to the MATLAB package and the optimization problems coded into AIMMS.

- System bandwidth (B)
- Maximum BS transmission power (P_{max})
- Number of subcarriers (N)
- Number of network users (K)
- Number of communities in the network (J)
- Number of users per community (K_j)
- Channel Gain ($H_{n,k,j}$)
- Minimum user data rate requirements ($R_{k,j}^{min}$)
- Social metric value of the users ($x_{k,j}$)
- Fixed power value (in case of fixed power allocation)
- Subset of subcarriers as input to the second-hop optimization formulation (N_j)

- Transmission power of the MA user ($P_{k^*,j}$)
- Maximum social metric value possible for a user (x_{max})
- Maximum data rate a user can achieve (R_{max})
- Data rate achieved by most active user of community as input to the second-hop optimization formulation ($R_{k^*,j}$)

Following are the outputs from MATLAB and AIMMS

- Subcarrier allocation ($s_{n,k,j}$)
- Power allocation ($p_{n,k,j}$)
- Subset of subcarriers as output of the first-hop optimization formulation (N_j)
- Data rate achieved by most active user of community as output of the first-hop optimization formulation ($R_{k^*,j}$)
- Overall network utility
- System spectral efficiency
- System fairness index

5.5 Verification of the Solution Model

The objective of verification process is to demonstrate the consistency, completeness and correctness of the solution model. In the following sections, the verification process of channel response and optimization problem solution is described.

5.5.1 Channel Response

As a part of verification of the propagation environment used in this thesis, the channel response generated for the users is verified by comparing the simulated and theoretical probability density functions of Rayleigh Fading and Log-Normal Shadowing models considered.

5.5.1.1 Rayleigh Fading

Rayleigh Fading characterizes the small scale fading experienced by the radio signal transmitted from the transmitter to the receiver [7], [11]-[13]. The signal radiated by the BS arrives at the user device via ($N_{multipaths}$) multiple paths. The received radio frequency signal is expressed as follows [80], [81].

$$received\ (t) = \sum_{w=1}^{N_{multipaths}} amp_w(t)\cos(2\pi f_c t + phase_w(t)) \tag{5.1}$$

where f_c is the system operating frequency, amp_w and $phase_w$ are the amplitude and phase of the w^{th} path respectively. The received signal can be rewritten in terms of inphase and quadrature format as:

$$received\ (t) = received_{in-phase}(t)\cos 2\pi f_c t - \ received_{quad}(t)\sin 2\pi f_c t \tag{5.2}$$

where $received_{in-phase}(t)$ is the inphase component and $received_{quad}(t)$ is the quadrature components and are expressed as follows:

$$received_{in-phase}(t) = \sum_{w=1}^{N_{multipaths}} amp_w(t)\cos\big(phase_w(t)\big) \tag{5.3}$$

$$received_{quad}(t) = \sum_{w=1}^{N_{multipaths}} amp_w(t)\sin(phase_w(t)) \tag{5.4}$$

It is a known fact that the random variable, $Z(t) = \sqrt{A(t)^2 + B(t)^2}$ is Rayleigh distributed, when *A* and *B* are two Gaussian random variables with zero mean and equal variance var^2. Hence, assuming the in-phase and quadrature components are Gaussian with zero mean and variance var^2, the envelope of the received signal r_0 after demodulation,

$$r_0(t) = \sqrt{\left[received_{in-phase}(t)\right]^2 + \left[received_{quad}(t)\right]^2} \qquad (5.5)$$

is Rayleigh distributed with probability density function,

$$f_{rayleigh}(r_0) = \begin{cases} \frac{r_0}{var^2}\exp\left[-\frac{{r_0}^2}{2var^2}\right] & for\ r_0 \geq 0 \\ 0 & otherwise \end{cases} \qquad (5.6)$$

where r_0 is the amplitude of the received signal and $2var^2$ is the pre-detection mean power of the multipath signal.

Figure 5.7 presents an example of simulated versus theoretical Rayleigh Fading probability density functions (pdfs) [81].

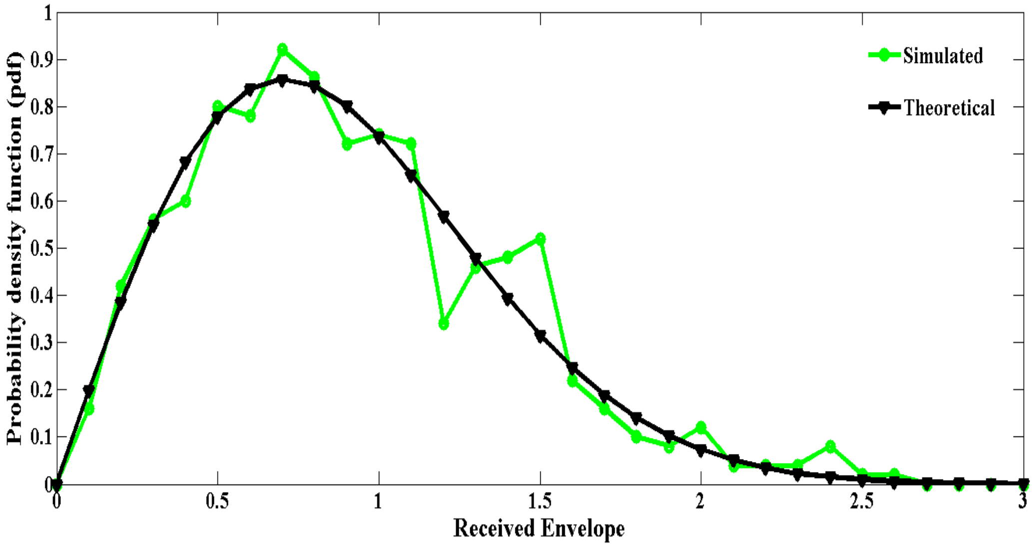


Figure 5.7 Simulated versus Theoretical Rayleigh Fading probability density function

5.5.1.2 Lognormal Shadowing

Large-scale variations caused by shadowing of obstacles are assumed to follow a log-normal distribution [82]-[84]. The shadowing is incorporated into path-loss estimation by the addition of a zero-mean Gaussian random variable, with standard deviation σ.

The probability density function for lognormal distribution is given by [82]-[84]:

$$f_{lognormal}(ls) = \frac{1}{ls\sigma\sqrt{2\pi}} e^{-[\frac{(\ln(ls)-\mu)^2}{2\sigma^2}]} \qquad ls \geq 0;\ \sigma > 0 \qquad (5.7)$$

where μ is the mean and σ is the standard deviation.

Figure 5.8 presents an example of simulated versus theoretical Log-Normal Shadowing probability density functions (pdfs).

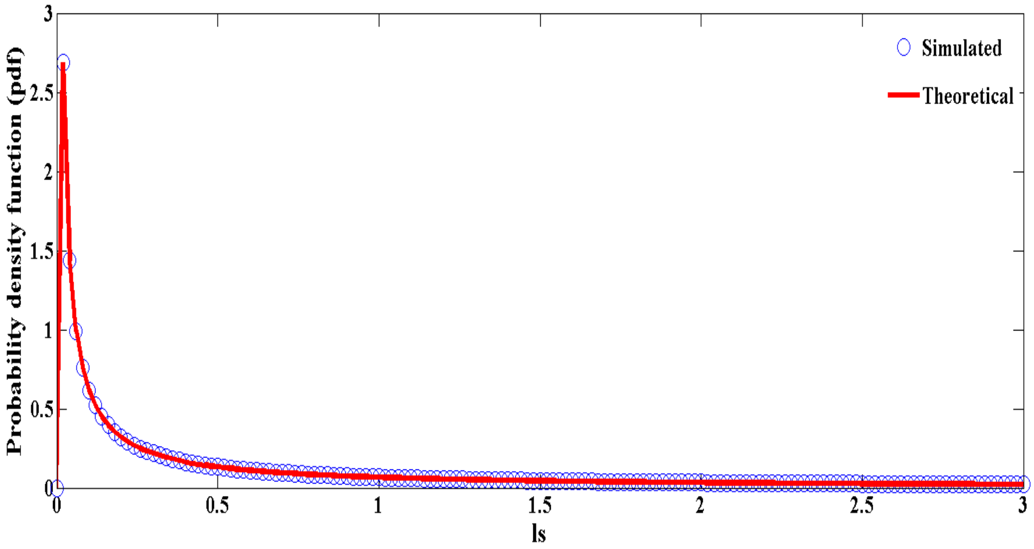
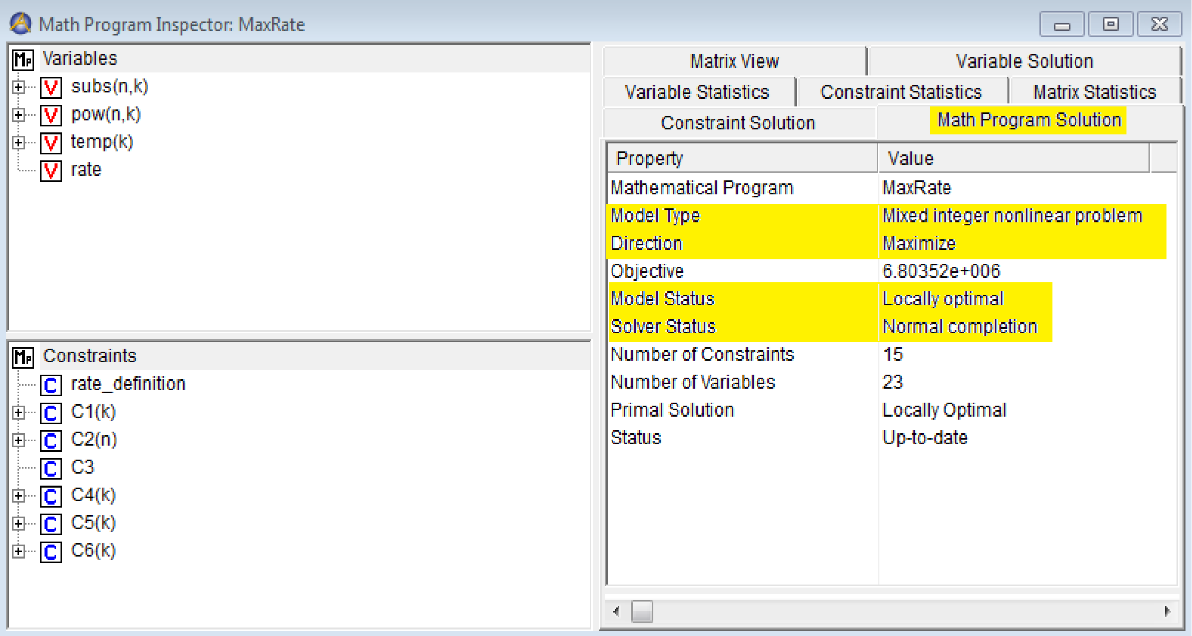


Figure 5.8 Simulated versus Theoretical Log-Normal Shadowing probability density function

5.5.2 Optimization Problem Solution

To inspect the model and verify that the solutions obtained are as expected i.e. locally optimal, the diagnostic tools, i.e. the mathematical program inspector and progress window offered by the AIMMS software are used. Screenshots of the mathematical program inspector and the progress window for different optimization problems are shown in Figure 5.9 and Figure 5.10, respectively [66], [85].

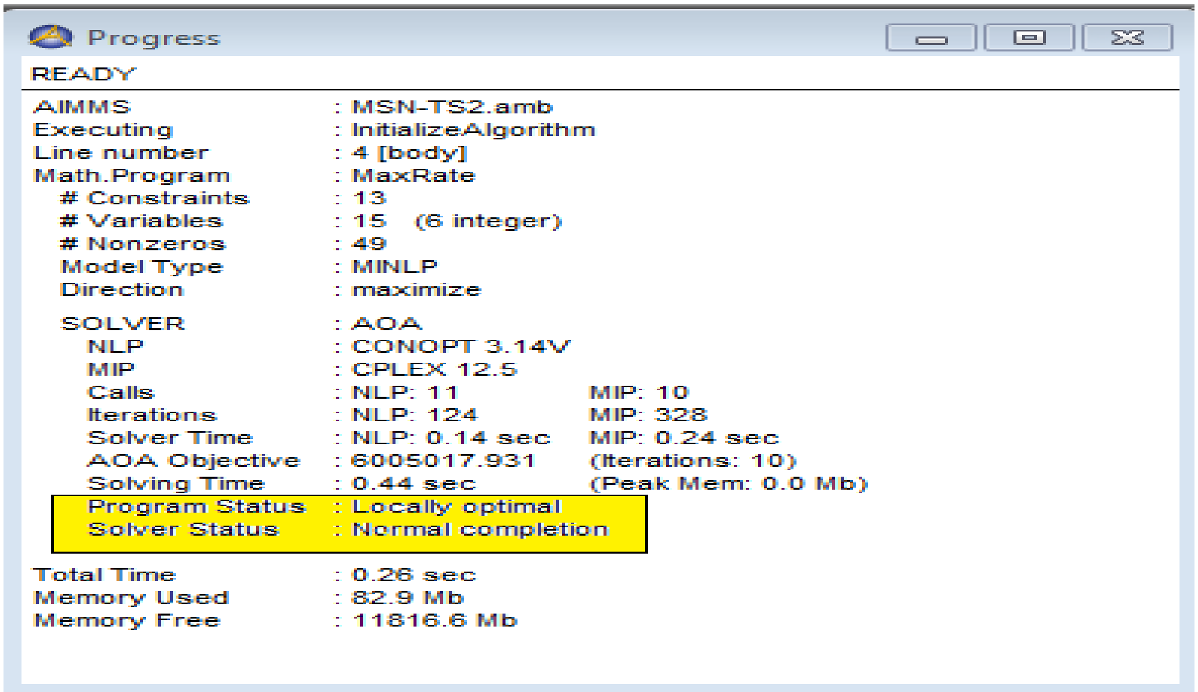


Variables
- subs(n,k)
- pow(n,k)
- temp(k)
- rate

Constraints
- rate_definition
- C1(k)
- C2(n)
- C3
- C4(k)
- C5(k)
- C6(k)

Property	Value
Mathematical Program	MaxRate
Model Type	Mixed integer nonlinear problem
Direction	Maximize
Objective	6.80352e+006
Model Status	Locally optimal
Solver Status	Normal completion
Number of Constraints	15
Number of Variables	23
Primal Solution	Locally Optimal
Status	Up-to-date

Figure 5.9 AIMMS Mathematical Program Inspector



```
READY
AIMMS                       : MSN-TS2.amb
Executing                   : InitializeAlgorithm
Line number                 : 4 [body]
Math.Program                : MaxRate
  # Constraints             : 13
  # Variables               : 15   (6 integer)
  # Nonzeros                : 49
  Model Type                : MINLP
  Direction                 : maximize

  SOLVER                    : AOA
    NLP                     : CONOPT 3.14V
    MIP                     : CPLEX 12.5
    Calls                   : NLP: 11          MIP: 10
    Iterations              : NLP: 124         MIP: 328
    Solver Time             : NLP: 0.14 sec    MIP: 0.24 sec
    AOA Objective           : 6005017.931      (Iterations: 10)
    Solving Time            : 0.44 sec         (Peak Mem: 0.0 Mb)
    Program Status          : Locally optimal
    Solver Status           : Normal completion

Total Time                  : 0.26 sec
Memory Used                 : 82.9 Mb
Memory Free                 : 11816.6 Mb
```

Figure 5.10 AIMMS Progress Window

The Math Program Solution tab shown in Figure 5.9 helps to determine the solution information (brief overview) for the optimization problem solved, while the progress window in Figure 5.10 provides a detailed summary of the problem solution. The program status and the solver status help verify that the resource allocation done by the solvers is indeed locally optimal in nature, which is to be expected as the solvers are local solvers. The progress status window can also help determine the number of constraints and variables the solver generated and the number of iterations needed to reach the local optimal solution.

The results are also verified by checking the allocations (subcarrier and power) performed. It is verified that the allocations done do not violate any of the constraints bounding the objective which are

1) No two users within the same community share the same subcarrier
2) Each user can use more than one subcarrier
3) The total power used is less than or equal to the total BS transmit power available
4) The data rate achieved per user is greater than or equal to the minimum data rate required by the user.

A small scale model consisting of one community, 3 users in the community and 4 subcarriers is considered for verification purpose. Resource allocation for this network using the AIMMS solvers and exhaustive search is carried out for comparing and verifying the performance of the solvers in comparison to the exhaustive search method. It is assumed that equal power is allocated to all the subcarriers in the network and the minimum user data rate requirement is 2 Mbps. The results of the resource allocation are as follows:

Table 5.1 Social Metric Value for the sample community users (Input)

User Index	Social metric value
1	1
2	0.25
3	0.25

Table 5.2.a Subcarrier Allocation using Exhaustive Search Method

	User 1	User 2	User 3
Subcarrier 1	1	0	0
Subcarrier 2	0	0	1
Subcarrier 3	0	1	0
Subcarrier 4	1	0	0

Table 5.2.b Subcarrier Allocation using Advanced Integrated Multidimensional Modeling System (AIMMS) solvers

	User 1	User 2	User 3
Subcarrier 1	1	0	0
Subcarrier 2	0	0	1
Subcarrier 3	0	1	0
Subcarrier 4	1	0	0

Table 5.3 Data Rate Achieved by the users using Exhaustive Search Method and the AIMMS solvers

	Exhaustive search	**AIMMS solvers**
User 1	5.63 Mbps	5.63 Mbps
User 2	3.08 Mbps	3.08 Mbps
User 3	3.51 Mbps	3.51 Mbps

From Table 5.1, it is observed that User 1 is the MA user in its community as its social metric value is the highest. Tables 5.2 a and b show the subcarrier allocation results for the setup using the exhaustive search method and AIMMS solvers, respectively and for the same inputs. The results are exactly the same as the computational complexity of the model is low, the number of resources available to be allocated to the users are limited and the same power value is allocated to all the users. As User 1 is the MA user, it is allocated the highest number of subcarriers and it achieved the highest value of data rate as compared to its peers. From Tables 5.2 a and b, it is also observed that constraints regarding the subcarrier allocation enlisted in section 4.3 are satisfied. From Table 5.3, it is observed that the minimum user data rate requirement is satisfied.

Figure 5.11 shows an example of the verification process for checking the data rate achieved by users for a network where joint subcarrier and power allocation using the proposed allocation scheme is carried out. It is observed in the example that the data rate achieved by users in this example is always greater than the minimum data rate required.

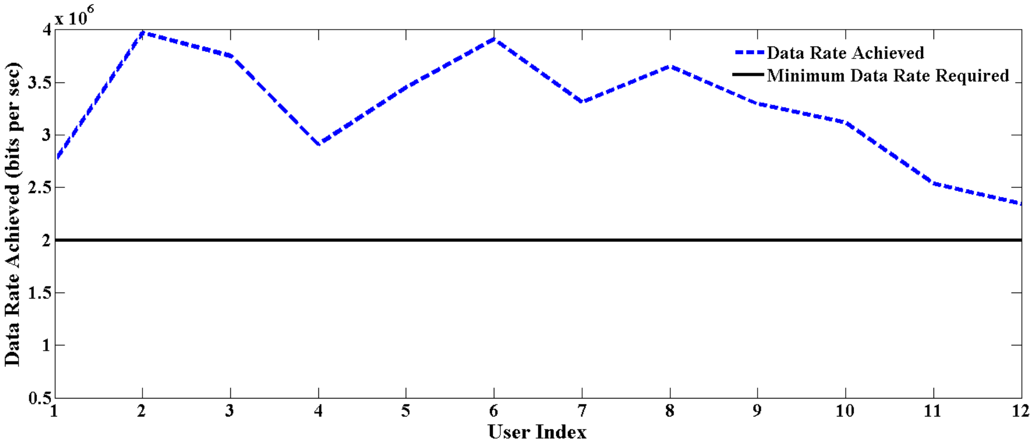


Figure 5.11 Example of Verification Process of comparing the Minimum Data Rate Requirement value to the Data Rate Achieved by Users

5.6 Validation of Solution Model

The proposed socially aware utility function in section 4.2 can be validated by comparing it with the ones existing in the references [6], [8]-[10]. Figure 5.12 compares the proposed socially aware utility function to the socially aware utility function existing in literature. The proposed utility function in equation (4.2) (section 4.2) is in terms of the data rate achieved by users and their social metric values; however, the socially aware utility functions in the references [6], [8]-[27] are in terms of bandwidth allocated to the users and their social metric value. Hence, both the functions shown in Figure 5.12 [24]-[27], are also computed in terms of bandwidth allocated to the user for the sake of fair comparison. The social metric value is represented by x_{kj}, i.e. social metric value of user k belonging to community j.

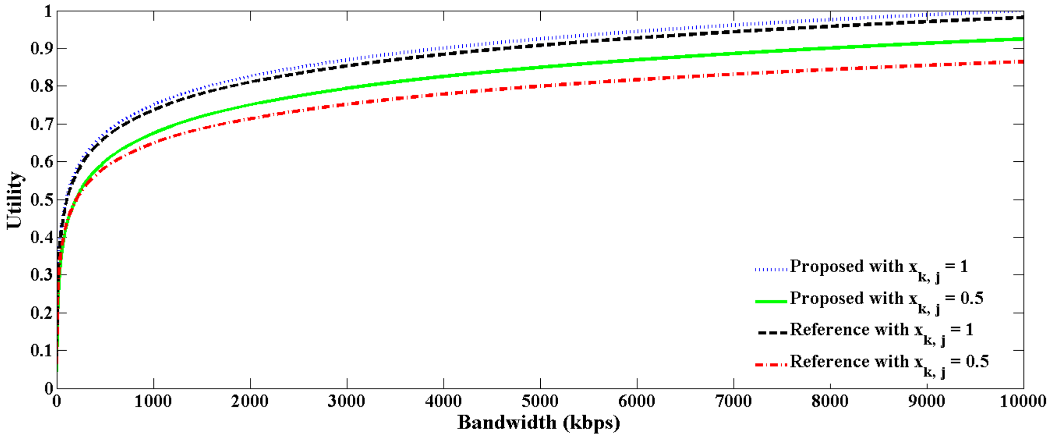


Figure 5.12 Comparing Proposed Socially Aware Utility Function to the Socially Aware Utility Function existing in literature

The results are generated for different values of bandwidth allocated to the network user with different values of social metric values. The closeness of the proposed results to the ones existing in the literature confirms the accuracy of our results.

As there is not much similar work done in the existing literature in terms of resource management (joint allocation) in a socially aware wireless downlink OFDMA network, there are no results that can be used to compare the results of the proposed technique for validation purposes. Hence, major focus has been placed on verification of the solution model and solution results.

5.7 Summary

The objectives of the solution model used to evaluate and solve the proposed socially aware resource allocation optimization problem are presented in this chapter. Due to the MINLP nature of the formulated optimization problems and the existence of non-convex constraint in the formulation, AIMMS based AOA solver is used to determine local solutions for the proposed formulations. MATLAB software package generates inputs for the optimization problem and calculates the performance metrics using the resource allocations generated by the AIMMS solvers as its inputs.

The verification and validation processes help determine the soundness of the implemented solution model. Using the solving method presented in this chapter, resource allocation is performed for various network setups generated and the results for the same are presented in the following chapter.

Chapter 6: Performance Evaluation

6.1 Introduction

The performance of the proposed socially aware resource allocation scheme is evaluated for various network setups. Various network setup scenarios are generated by varying the following: a) number of communities, b) number of users within a community, c) minimum user data rate requirement values and d) number of subcarriers available in the network. The performance evaluation framework uses key metrics such as system spectral efficiency (SSE), system fairness index (SFI) and overall network utility. To gauge the capability of the proposed resource allocation scheme, its performance is compared against those of the existing conventional (i.e. socially unaware) resource allocation schemes available in the literature.

The experiments performed and test scenarios considered are discussed in section 6.2, followed by a summary of the assumed system parameter values in section 6.3. Section 6.4 consists of the performance evaluation and discussion of the results obtained. The chapter is summarized in section 6.5.

6.2 Experiments and Test Scenarios

All the experiments are performed for fixed values of total network bandwidth available, base station (BS) transmission power and most active (MA) user transmission power.

Experiment 1

Objective: Determine the effect of varying number of users in the network (network size)

To determine the scalability of the proposed scheme (i.e. how well the scheme performs when the network size increases), the number of users within each community, the number of communities in the network and the number of subcarriers available for resource allocation are varied.

The minimum number of users in a community is assumed to be 3. In a community with just two users, it will be assumed that both are connected to each other. Thus, both users will have the same social metric value, making them both MA users within their community which is not desired. It is assumed that the total number of communities in the network varies from 2 to 5 and the number of users per community varies from 3 to 6. Thus, total number of users in the network varies from 6 to 30.

For the network setups with 6 to 20 users, the number of subcarriers available for resource allocation is assumed to be 25 [86]. However, when the total number of users in the network is increased to 25 and 30, the number of subcarriers is increased from 25 to 50, because 25 subcarriers are not sufficient resources to serve a network of this size to satisfy the subcarrier based constraint in the proposed optimization problem in section 4.3, which states that one subcarrier is allocated to each user. Note that the total network bandwidth still remains constant, only the bandwidth of each subcarrier varies.

Experiment 2

Objective: Determine the effect of varying the social metric value

The performance of the proposed scheme is evaluated by using degree and eigenvalue centrality metrics (equations (2.1) and (2.4)) to determine the social metric values of the users as discussed in section 2.2.2.1. The degree and eigenvalue centralities are calculated depending on the number of links existing between the network users. Thus, when the number of communities and the number of users in the communities vary, the values of the centrality metrics vary.

Experiment 3

Objective: Determine the effect of varying minimum user data rate requirement

The minimum data rate requirement of the users is varied to evaluate the performance of the proposed scheme and its ability to satisfy user requirements. The performance of each setup (i.e. for a fixed value of communities, number of users per community and social factor value) is evaluated with the minimum data rate requirement of all the network users varying from 64 kbps to 2 Mbps [87]. In social networking applications such as Facebook, Youtube, WhatsApp, WeChat, etc., the users access various types of data services such as audio, video, texts, etc and their minimum data rate requirement varies from 64 kbps to 2 Mbps.

6.3 Assumed System Parameter Values

The assumed parameter values and the justification for choosing them are summarized in Table 6.1.

Table 6.1 Summary of Assumed System Parameter Values

Parameter	**Value**	**Justification**
Network Area	Single cell area	Multiple cells are not considered here to eliminate occurrence of inter-cell interference as discussed in section 3.3.2.
Network Coverage Area	1000m x 1000m	In an urban environment, the cell area is small (up to 2 kilometer radius and the smallest cells cover a few tens or hundreds of meters in radius) [88]. The area is square in shape.
Network Architecture	Centralized	Refer to section 3.3.
Number of Communities (*J*)	2 to 5 (Non-overlapping)	Varied for performance evaluation and refer to section 3.3.

Parameter	**Value**	**Justification**
Number of users per community (K_j)	3 to 6	Varied for performance evaluation.
Total number of users in the network (K)	$\sum_{j=1}^{J} K_j$ It varies in the range of 6 to 30	
BS maximum transmit power (P_{max})	40 dBm (10 W)	Standard value for an OFDMA-based network (e.g. Long Term Evolution (LTE) network) [60].
Most Active user device transmit power ($P_{k^*,j}$)	30 dBm (1W)	Standard value of mobile transmission power.
Total bandwidth (B)	10 MHz	Standard value for an OFDMA-based network (e.g. LTE network) [60].
Noise Spectral Density (N0)	-174 dBm/Hz	[27], [28].
Path loss exponent (α)	2.8	The path loss exponent = 2.7-3.5 for an urban area cellular network.

Parameter	**Value**	**Justification**
Standard deviation for lognormal shadowing (σ)	6 dB	[27], [28].
Minimum Data Rate Required per user ($R_{k,j}^{min}$)	64 kbps, 128 kbps, 256 kbps, 512 kbps, 1 Mbps, 2 Mbps	The minimum bit rate required for MP3 audio application is 128 kbps, video conference applications is 128-384 kbps, various web applications is 1 Mbps [87].
Number of Subcarriers (N)	25 & 50	At a bandwidth of 10 MHz, the 25 and 50 subcarriers correspond to subcarrier bandwidth of 0.4 and 0.2 MHz, respectively. OFDM based IEEE 802.11n uses 52 or 114 subcarriers with the subcarrier bandwidth value being 0.3125 MHz [86].

6.4 Performance Results and Discussion

The results are presented in terms of SFI, SSE and overall network utility, calculated using equations (3.6), (3.7) and (4.1), respectively. They are obtained using joint as well as fixed resource allocation for networks of size 6, 10, 15, 20, 25 and 30 users for different values of minimum data rate requirements of the users.

A maximum of 30 users i.e. 5 communities and 6 users per community have been considered here. If the MA user alone has to serve as a relay for a very large number of its peers, its own resources will exhaust rapidly, which will lead to the MA user exhibiting individually selfish behaviour (refer to section 3.3). If the MA user exhibits this selfishness, the entire community will starve for data as the MA user will stop relaying data to its peers.

The various network configurations are obtained using different number of communities and number of users per community as listed in Table 6.1. In the following results, the legends MAX UTILITY and MAX RATE represent the results obtained for the two conventional allocation problems formulated in section 4.3.3, PROPOSED EIGEN and PROPOSED DEGREE represent the results obtained for the proposed allocation problem formulated in section 4.3.1 and 4.3.2. The results of joint subcarrier and power allocation for the proposed scheme, as well as conventional allocation scheme, are shown in Figure 6.1 to 6.9. For the results shown in Figure 6.1 to 6.6, the number of subcarriers assumed to be available in the network is 25, whereas for Figure 6.7 to 6.9, the number of subcarriers assumed to be available in the network is 50. The results of fixed power allocation performed using 25 subcarriers are depicted in Figure 6.10 to 6.15. A total of 5 different channel realizations were used and the results were averaged.

6.4.1 Joint Subcarrier and Power Allocation Results and Discussions

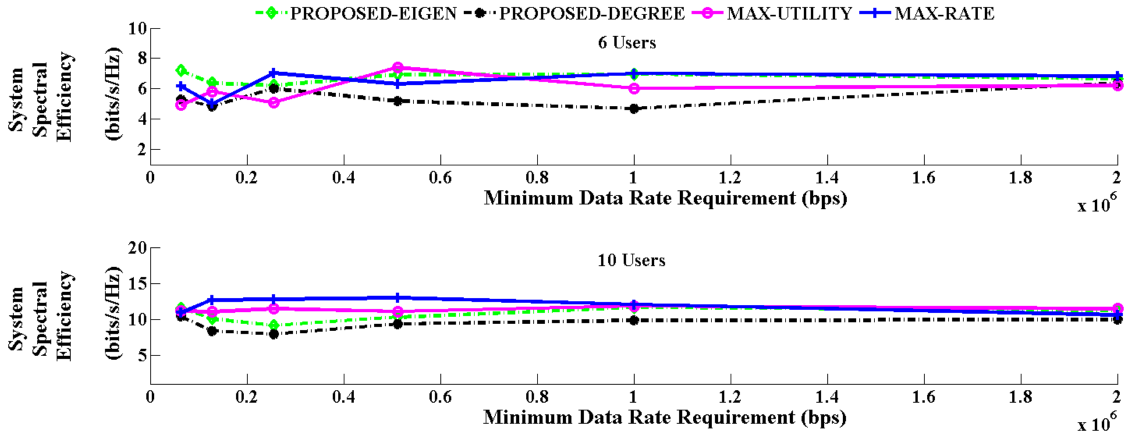


Figure 6.1 System Spectral Efficiency (SSE) for network size of 6 and 10 users when Joint Resource Allocation is performed

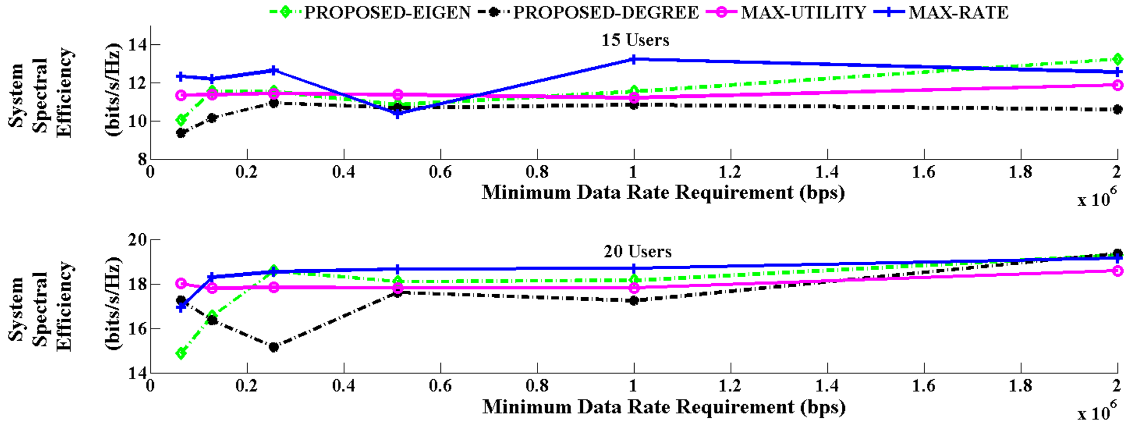


Figure 6.2 System Spectral Efficiency (SSE) for network size of 15 and 20 users when Joint Resource Allocation is performed

Figures 6.1 and 6.2 show the SSE calculated for a network of a given size at different user data rate requirement values.

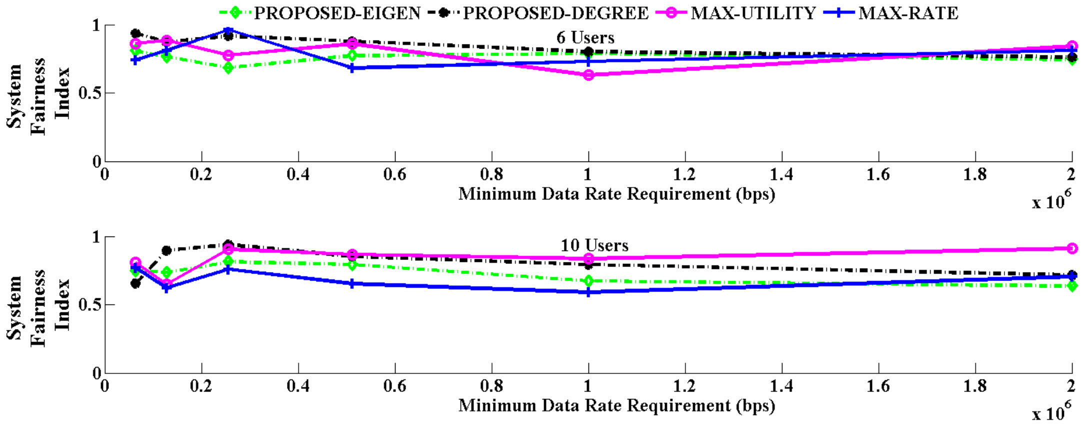


Figure 6.3 System Fairness Index (SFI) for network size of 6 and 10 users when Joint Resource Allocation is performed

Figures 6.3 and 6.4 show the SFI calculated for a network of a given size at different user data rate requirement values. The highest value of SFI possible is 1, in which case, all the network users achieve same data rate.

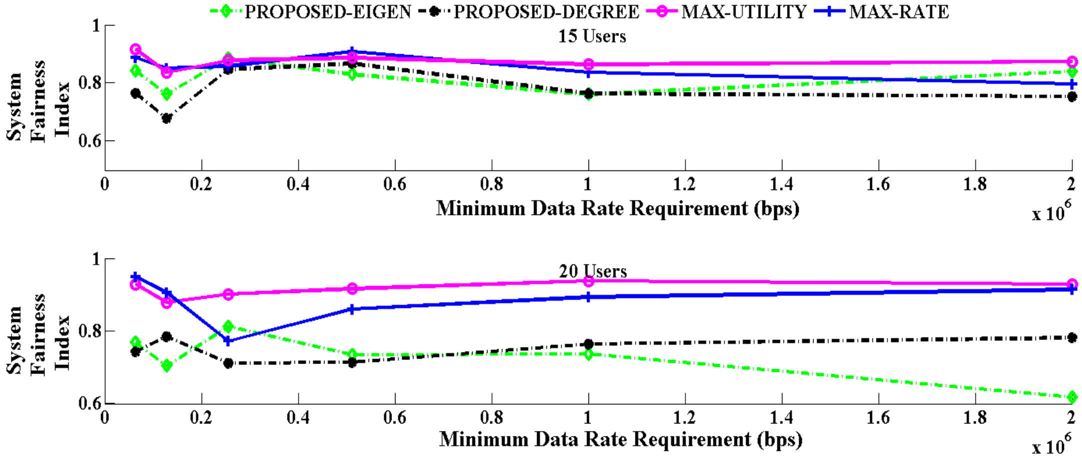


Figure 6.4 System Fairness Index (SFI) for network size of 15 and 20 users when Joint Resource Allocation is performed

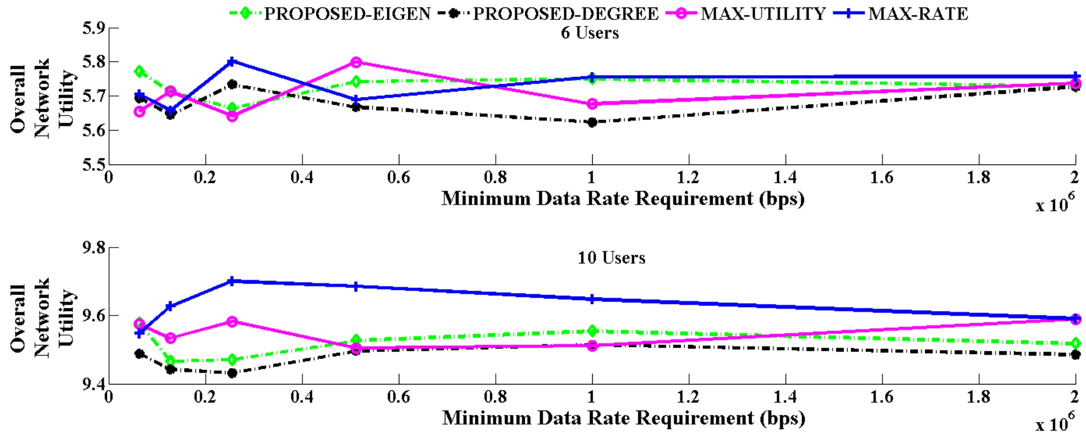


Figure 6.5 Overall Network Utility for network size of 6 and 10 users when Joint Resource Allocation is performed

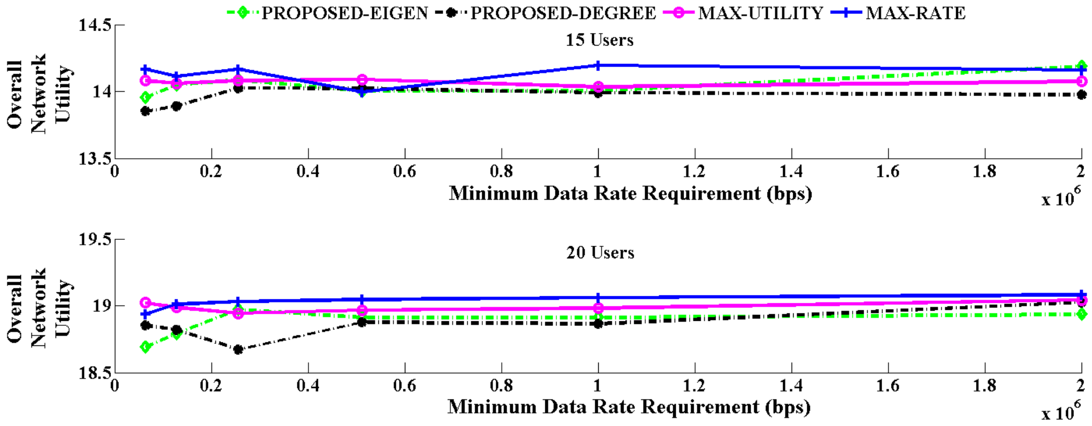


Figure 6.6 Overall Network Utility for network size of 15 and 20 users when Joint Resource Allocation is performed

Figures 6.5 and 6.6 show the overall network utility calculated for a network of a given size at different user data rate requirement values.

Path-loss, which depends on the distance of a receiver from the transmitter, plays a very important role in the channel condition of the receiver. Users that are closer to the BS generally experience a good channel condition and vice versa.

When the number of users in the network is 6, 10, 15 and 20, the user communities are placed closer to the BS. Whereas, when the number of users in the network increases to 25 and 30, the user communities are scattered throughout the cell area and users are closer to the cell boundary. This is done to determine the performance of the proposed scheme when the proximity of the user communities from the BS varies.

When the objective of the optimization formulation is to maximize the overall data rate achieved by the users, the users with good channel conditions are allocated highest amount of resources. Whereas, the ones with bad channel conditions are starved for resources and are treated unfairly. Thus, the SSE in case of MAX RATE is very high and the SFI is low as observed in Figure 6.1 to 6.4.

When the objective of the optimization formulation is to maximize the overall network utility, the BS allocates resource in order to serve users with bad channel conditions fairly. This leads to a decrease in the SSE and an increase in SFI of MAX UTILITY as compared to MAX RATE as observed in Figure 6.1 to 6.4.

The proposed scheme is a combination of two optimization formulations, where the objective over the first hop is to maximize the overall network utility and the objective over the second hop is to maximize the total data rate achieved by the community users. The MA user of a community relays data to its peers. Such relay based networks are very useful for serving users that are placed very far away from the BS and suffer from bad channel condition.

However, as mentioned earlier, when the number of users in the network is small, they are placed within the transmission range of the BS as well as the MA user of their community, thus they do not suffer from very bad channel conditions during the first as well as the second hop transmission. Therefore, the results for PROPOSED-EIGEN and PROPOSED-DEGREE for such a network are very close to the ones of MAX RATE and MAX UTILITY.

From Figures 6.5 and 6.6, it is noted that the highest value of overall network utility possible is less than or equal to the number of users in the network, as the highest value of utility a network user can achieve is 1. It is observed in Figures 6.5 and 6.6 that the overall network utility achieved by the network users when the proposed scheme is implemented using both degree and eigenvalue centrality metrics, is a fairly high value as shown in Table 6.2.

Table 6.2 Highest Overall Network Utility values obtained using the Proposed Scheme

Total network size	**Degree Centrality**	**Eigenvalue Centrality**
6	5.73	5.77
10	9.51	9.57
15	14.02	14.18
20	19.02	18.97

Overall network utility and the SSE achieved by a network are both calculated based on the data rate achieved by the network users as discussed in the formulations in section 4.2 and 3.6. Thus, the SSE curve and the overall network utility curve exhibit similar pattern in the results shown in Figures 6.1, 6.2, 6.5 and 6.6.

In the proposed scheme, over the second hop, the objective is to maximize the total data rate achieved by the community users. This helps achieve high values of SSE and overall utility. In cases where the user data rate requirement values are very high (2Mbps), the allocation over the second hop is performed to achieve the highest possible data rate for the network users. Thus, in Figures 6.1, 6.2, 6.5 and 6.6 we observe high values of SSE and overall network utility for the proposed scheme when the minimum user data requirement is 2 Mbps.

The oscillations observed in Figure 6.1 to 6.6, are due to the additional channel propagation occurring over the second hop for the proposed scheme that has to be taken into account along with the varying values of the minimum user data rate requirements for both the proposed and conventional techniques.

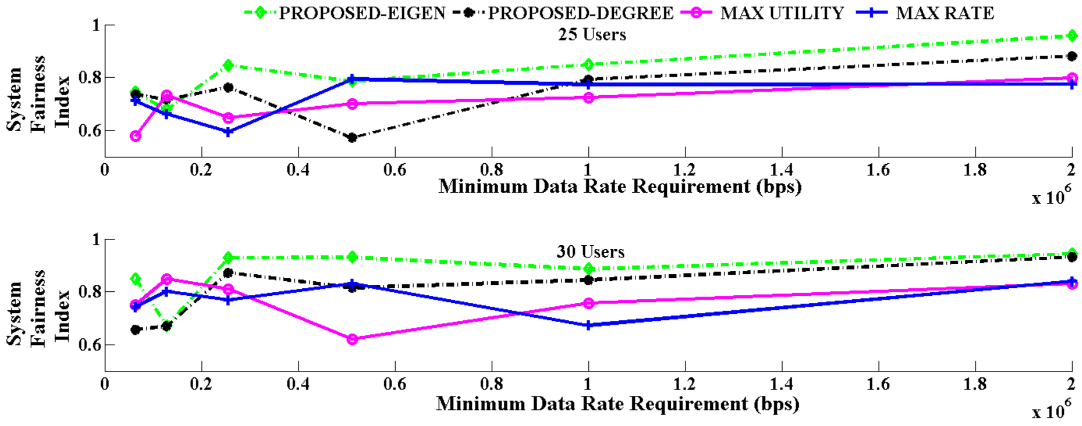


Figure 6.7 System Fairness Index (SFI) for network size of 25 and 30 users when Joint Resource Allocation is performed

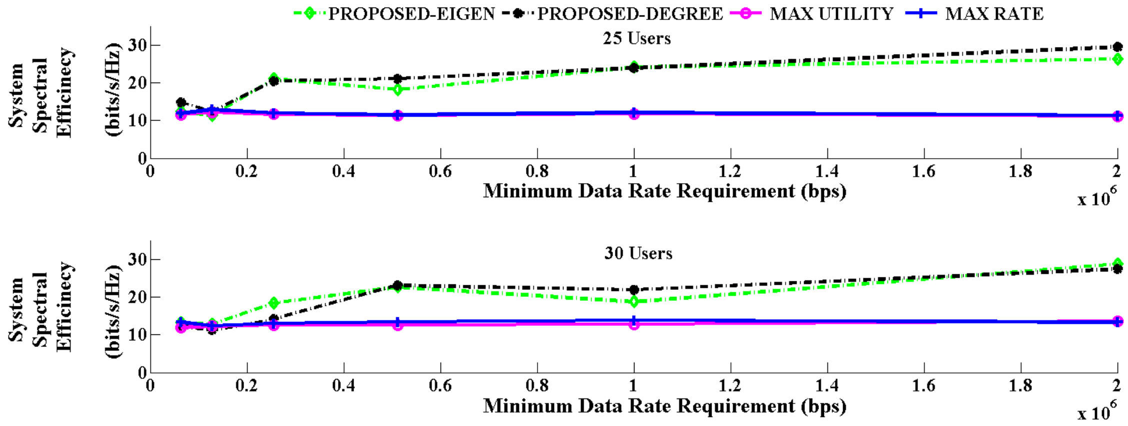


Figure 6.8 System Spectral Efficiency (SSE) for network size of 25 and 30 users when Joint Resource Allocation is performed

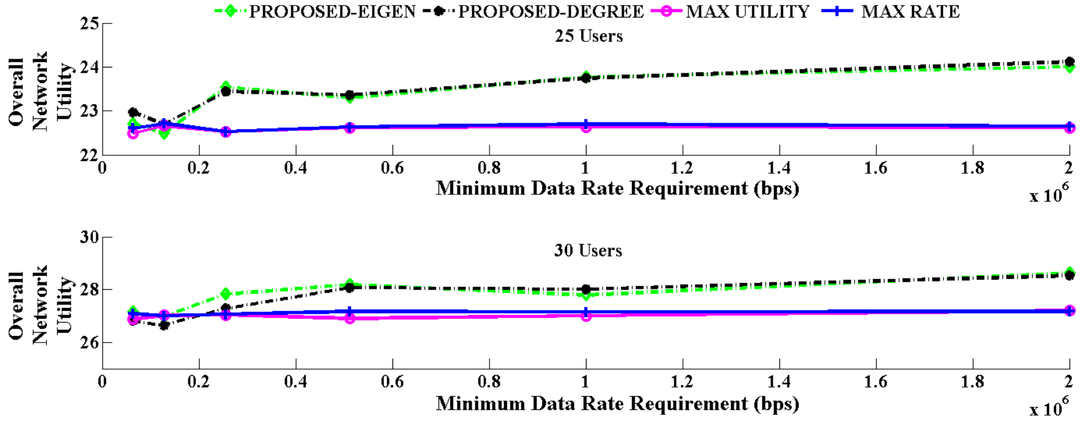


Figure 6.9 Overall Network Utility for network size of 25 and 30 users when Joint Resource Allocation is performed

Figure 6.7 to 6.9 exhibit the results for network size of 25 and 30 users. It is observed that, as the number of users increases, the proposed scheme out-performs the conventional scheme especially in terms of the SSE and the overall network utility. When the network size increases, the proposed two-hop scheme achieves higher data rates than the conventional schemes. This is because the two-hop scheme improves the received signal strength of users in remote areas. In case of large network sizes, there is a high probability that the network users are far away from the BS (i.e. closer to the cell boundary) and much more closer to the MA user of their respective communities. Due to the distance between the BS and the network users, the path-loss between them increases which leads to decreased values of the data rates achieved by the users when the conventional allocation schemes are implemented. On the other hand, as the distance between the network users and their MA users is much smaller, the path-loss experienced is less which helps attain higher data rates for the network users when the proposed scheme is implemented.

The above observation indicates that, as the number of users in the network along with the minimum user data rate requirements increase and when the users are located far away from the BS, the conventional scheme cannot serve the users with a very good level of performance for fixed value of resources (bandwidth and power in this case) available in the network. Hence, it can be concluded that the proposed two-hop socially aware resource allocation scheme helps extend the capacity of the network.

From Figures 6.3, 6.4 and 6.7, it is observed that the SFI attained for the proposed scheme varies as opposed to the SSE observed in Figures 6.1, 6.2 and 6.8. Despite the fact that the fairness experienced by the network users is not taken into account while implementing the proposed resource allocation optimization scheme, Figures 6.3, 6.4 and 6.7 indicates that the SFI experienced by the network using the proposed scheme does not suffer to a great extent when higher values of SSE are attained. This is a consequence of the good balance in the trade-off between the SFI and SSE achieved by implementing the proposed scheme.

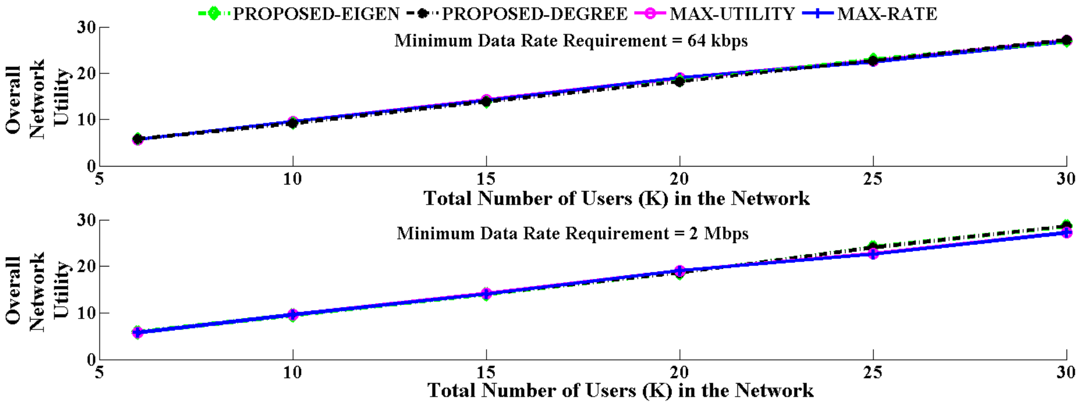


Figure 6.10 Overall Network Utility for network of 6 to 30 users with 64 kbps and 2 Mbps minimum data rate requirements when Joint Resource Allocation is performed

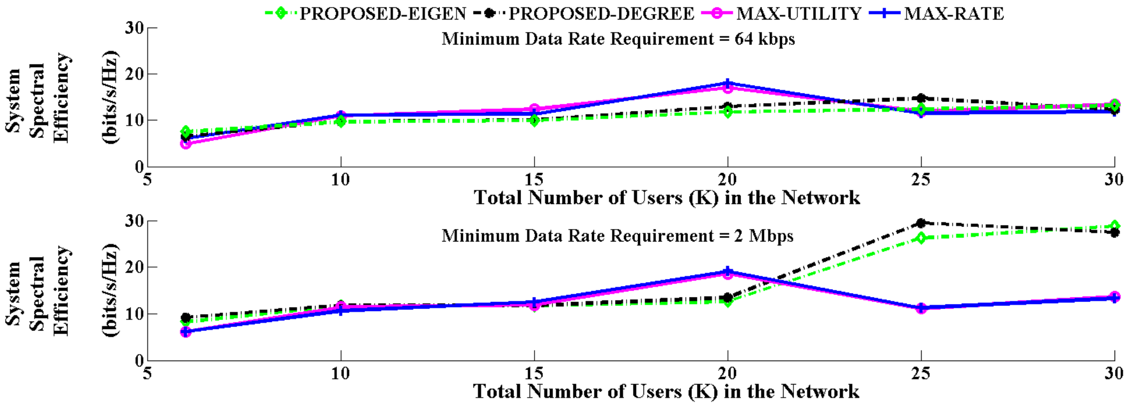


Figure 6.11 System Spectral Efficiency for network of 6 to 30 users with 64 kbps and 2 Mbps minimum data rate requirements when Joint Resource Allocation is performed

The performance of the proposed joint allocation scheme using both degree and eigenvalue centrality is compared to that of the two conventional joint allocation schemes when the number of users in the network increase from 6 to 30 and the minimum data rate requirements of the users are fixed at 64 kbps and 2 Mbps. The results of this comparison are exhibited in Figures 6.10 and 6.11.

From Figures 6.10 and 6.11, it is observed that as the total number of users in the network increase and the minimum data rate requirements of the users increase, the proposed scheme out performs the conventional schemes in terms of SSE and overall network utility as discussed using the results in Figure 6.7 to 6.9. In Figure 6.1 to 6.11, it is observed that the performances of the proposed scheme using degree and eigenvalue centrality metrics are very close to each other. This is because both metrics are calculated on the basis of the communication links existing between the network users for the exact same network setup.

6.4.2 Fixed Power based Resource Allocation Results and Discussions

Fixed power allocation helps determine whether it is necessary to perform joint resource allocation or if just performing subcarrier allocation with fixed power values assigned to the subcarriers is sufficient to achieve a desired level of performance. Fixed power allocation is less computationally complex as compared to the joint allocation scheme, as the former only allocates subcarriers, whereas in the latter case, subcarrier and power allocations have to be performed.

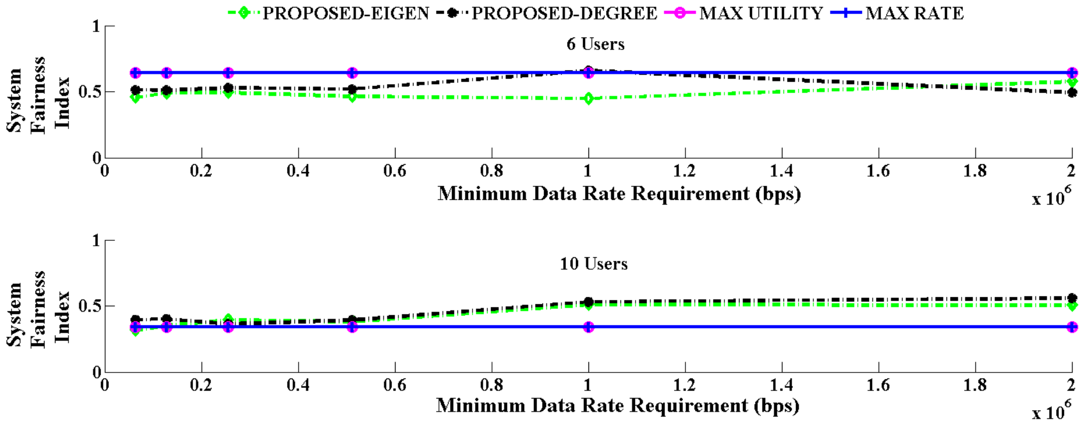


Figure 6.12 System Fairness Index (SFI) for network size of 6 and 10 users when Fixed Power Resource Allocation is performed

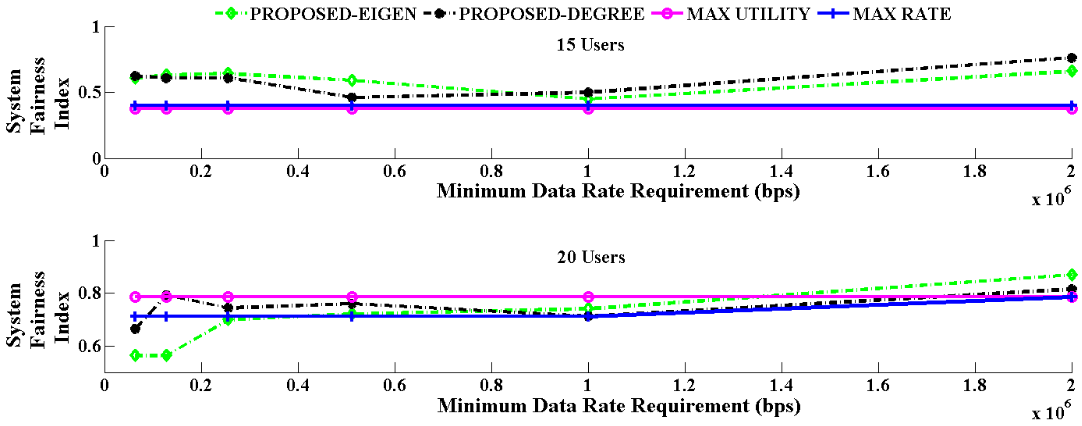


Figure 6.13 System Fairness Index (SFI) for network size of 15 and 20 users when Fixed Power Resource Allocation is performed

Figures 6.12 and 6.13 show the SFI calculated for a network of a given size at different user data rate requirement values using fixed power allocation.

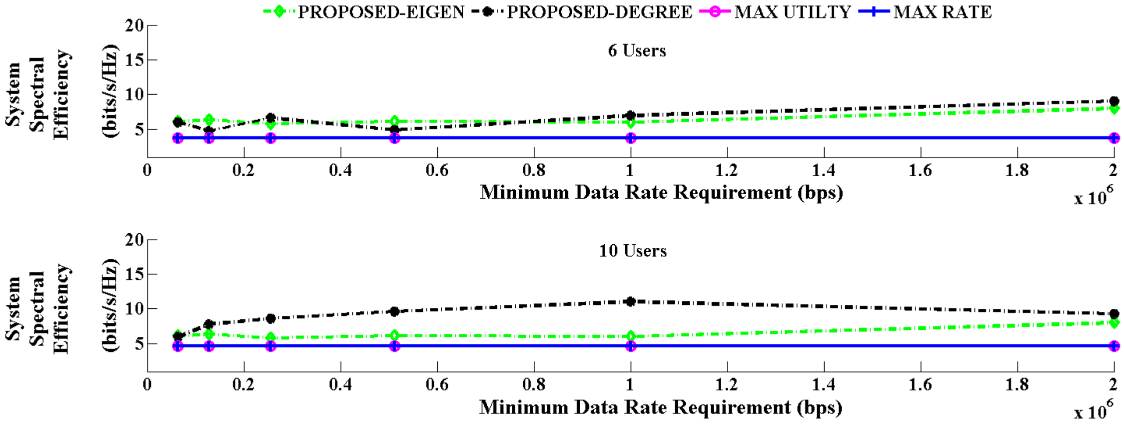


Figure 6.14 System Spectral Efficiency (SSE) for network size of 6 and 10 users when Fixed Power Resource Allocation is performed

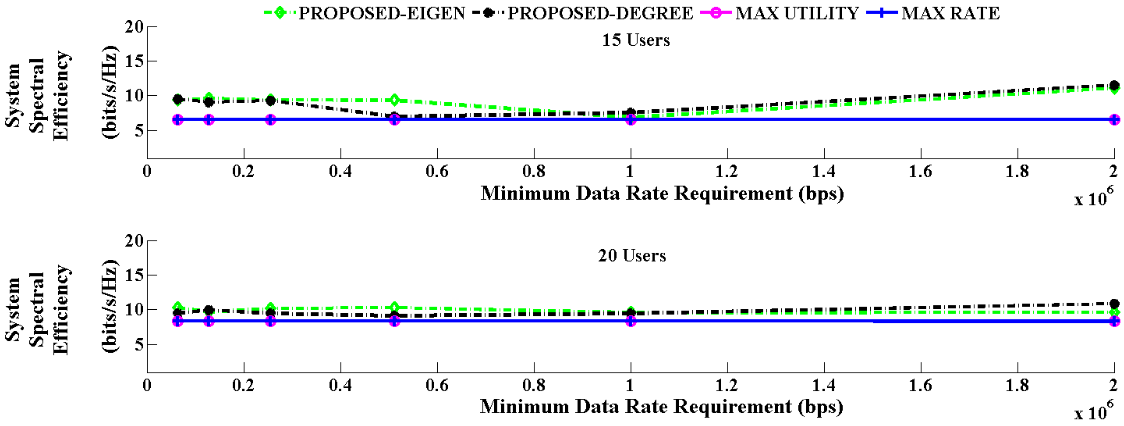


Figure 6.15 System Spectral Efficiency (SSE) for network size of 15 and 20 users when Fixed Power Resource Allocation is performed

Figures 6.14 and 6.15 show the SSE calculated for a network of a given size at different user data rate requirement values using fixed power allocation.

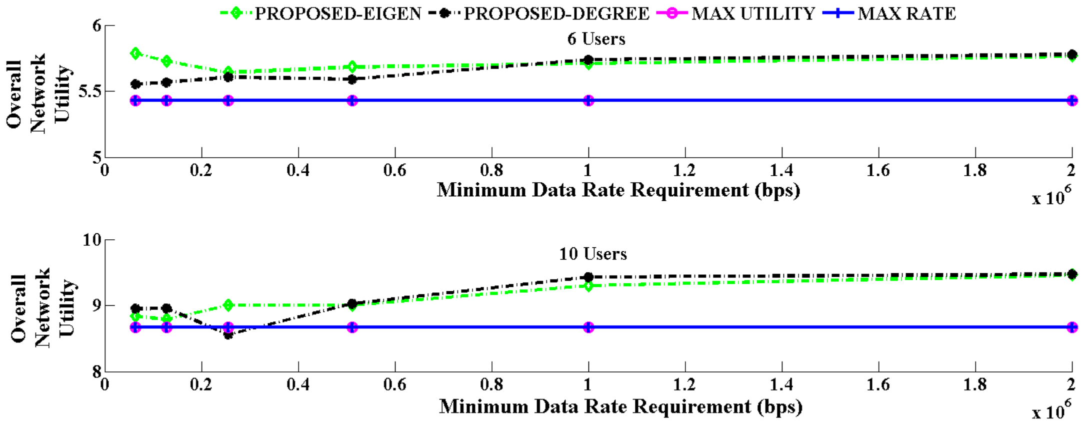


Figure 6.16 Overall Network Utility for network size of 6 and 10 users when Fixed Power Resource Allocation is performed

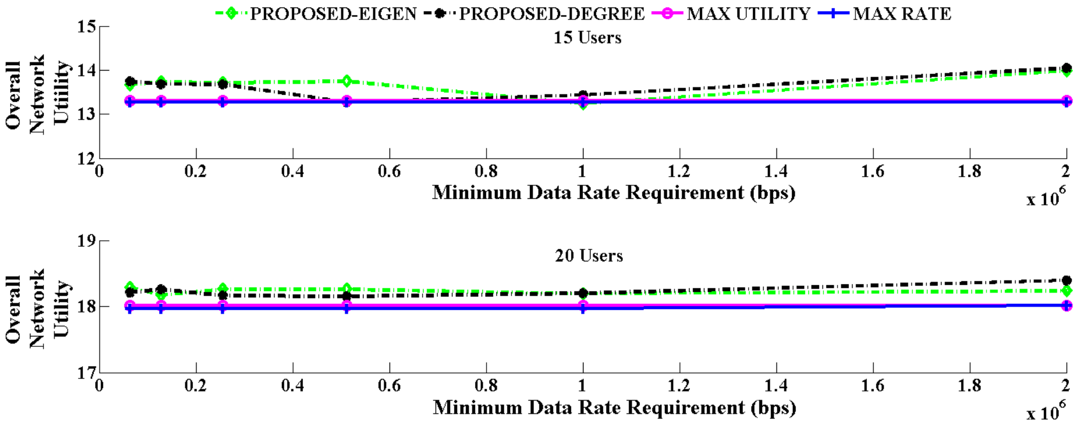


Figure 6.17 Overall Network Utility for network size of 15 and 20 users when Fixed Power Resource Allocation is performed

Figures 6.16 and 6.17 show the overall network utility calculated for a network of a given size at different user data rate requirement values using fixed power allocation.

When the fixed power allocation scheme is implemented, the data rate that can be achieved by a subcarrier is pre-calculated and is constant. Based on this information, the subcarrier allocation is performed. The data rates pre-calculated for the conventional as well as proposed schemes are greater than all the values of minimum user data requirements due to the high bandwidth value of each subcarrier. Thus, the minimum data rate requirements of the user are satisfied by the fixed power allocation scheme as observed in Figures 6.16 and 6.17 exhibiting the overall network utility.

As discussed in section 6.4.1, over the second hop while using the proposed scheme, higher data rates are achieved by the users as the distance between the network user and the MA user is lesser than the distance between the network user and the BS. Along with this, the value of the fixed power allocated to the subcarriers also varies twice (once over the first-hop and then over the second-hop) when the proposed scheme is implemented as compared to the conventional schemes which are only one hop based. The power value plays a very important role in determining the pre-calculated data rates over subcarriers, when it is high, the data rates achieved by the network users are high. Thus, fixed allocation results show that the proposed scheme out-performs the conventional schemes in terms of the SSE and the overall network utility as observed in Figure 6.14 to 6.17. The trade-off existing between the SSE and the SFI attained by the network is also observed while comparing Figure 6.12 to 6.15.

It is also observed that the results obtained using fixed power based resource allocation are lesser in value than the ones obtained using joint resource allocation formulations. When joint resource allocation is performed, the BS can vary the power allocated to the subcarriers to achieve the best possible objective value possible. However, as the data rates achieved by the network users are pre-calculated using fixed power allocation at a fixed power value, the BS does not have the flexibility to vary the power. It can only perform binary subcarrier allocation which is the reason behind the constant values of SFI, SSE and the overall network utility attained by the network users observed in Figure 6.12 to 6.17. Similar to the discussion in section 6.4.1, in Figure 6.12 to 6.17, it is observed that the performances of the proposed scheme using degree and eigenvalue centrality metrics are very close to each other.

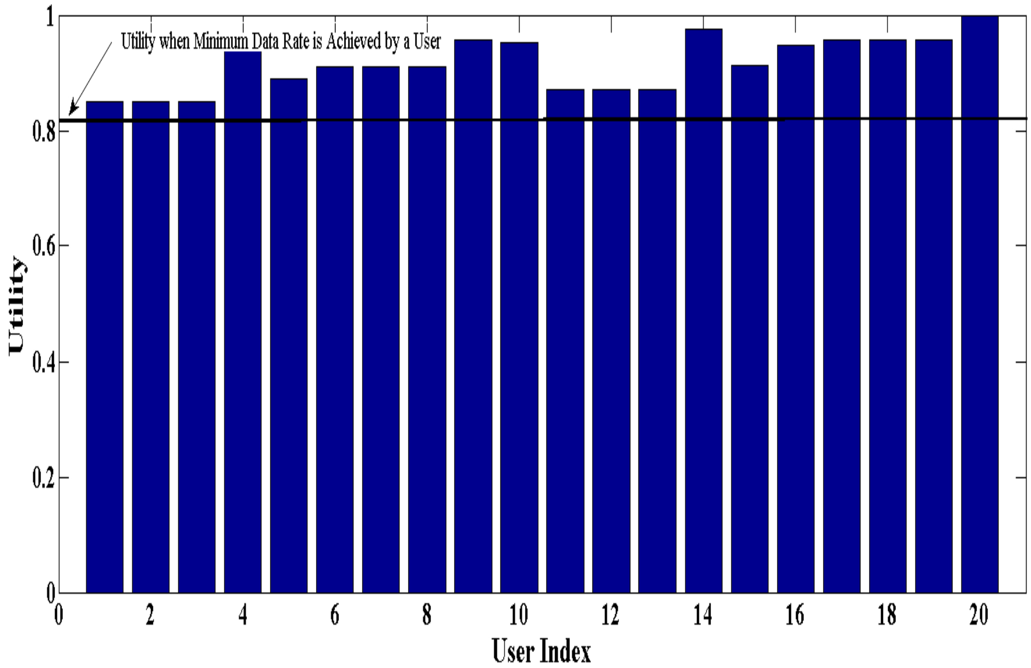


Figure 6.18 Utility Achieved by each user for a network of 20 users when Proposed Socially Aware Joint Resource Allocation Scheme is implemented

Figure 6.18 shows the utility achieved by each network user when the proposed resource allocation scheme is implemented for a network. It is observed that the users achieve very high utility values (with 1 being the highest). This indicates that no user is starved for resources and it is also observed that the minimum data rate requirements of the users are satisfied.

6.5 Summary

In this chapter, the performance evaluation of the proposed two-hop socially aware resource allocation scheme is presented. For networks with small number of users, the use of social metric values of the users for resource allocation does not achieve significant improvement in the performance as the results of the SFI, SSE and overall network utility of the proposed allocation scheme are very close to that of the conventional allocation schemes. However, using the social metric values for resource allocation for networks with large number of users (i.e. dense networks) and when the user data rate requirements are high achieves a significant improvement in performance compared to the conventional schemes. The proposed scheme also ensures that the minimum data rate requirements of the network users are satisfied and no user starves for resources.

Fixed power based resource allocation scheme can also be adopted for socially aware networks as it is less computationally complex to implement. However, its performance is degraded as compared to the joint resource allocation scheme which in turn is highly computationally complex to implement. A trade-off exists between the SFI and SSE attained by the network users. In a network made up of disjoint communities, when the MA user has to be selected based on its communication activities, degree and eigenvalue centrality metrics based results exhibit similar performance levels.

Based on the findings in this chapter, conclusions drawn are discussed in the following chapter.

Chapter 7: Conclusions and Suggestions for Future Work

The main objective of this thesis is to determine the impact of utilizing social awareness about the network users for resource management on the overall network performance. To achieve this objective, a two-hop socially aware resource allocation scheme for an Orthogonal Frequency Division Multiple Access (OFDMA) based wireless network, partitioned into non-overlapping communities has been proposed and its performance has been evaluated.

7.1 Thesis Contributions

In summary, this thesis makes the following contributions.

- A socially aware utility function has been proposed in section 4.2.3. Generally, utility functions used in relation to wireless networks help gauge the network users' satisfaction level, when a certain amount of resources are allocated to them. The existing utility functions depend on the data rate achieved by network users and do not reflect the social positions of the users in the network. In order to integrate the popularity of a user in the network, the existing utility function is modified by introducing the social metric value of a network user into it. The social metric value used in this thesis reflects the relative popularity of the users in the network and within their communities. The utility function is modified such that users with no connection to any other user in the network are not allocated any resources by the Base Station (BS) i.e. they do not experience any satisfaction. Whereas, the user with the highest number of connections in the network is allocated the highest amount of network resources i.e. they experience a very high level of satisfaction.
- An optimization problem has been formulated for performing resource allocation in the considered centralized OFDMA wireless network overlaid by a social network. The optimization is performed over two hops as discussed in section 4.3. The network resources

act as the decision variables in the problem. In the first hop, the overall network utility achieved by the users is maximized. This utility is calculated using the proposed socially aware utility function. In the second hop, the allocation is performed to maximize the data rate achieved by users of the individual communities.

- This thesis implements and evaluates the proposed socially aware resource allocation scheme and the optimization formulation for the same in chapters 5 and 6, respectively. Advanced Integrated Multidimensional Modeling Software Outer Approximation (AOA) optimization solvers provided by Advanced Integrated Multidimensional Modeling Software (AIMMS) for resolving Mixed Integer Non-Linear Programming (MINLP) problems are used to solve the optimization problems formulated. Resource allocation in a conventional (i.e. socially unaware) wireless network has been performed using the optimization formulation in section 4.3 for comparing the performance of the proposed scheme with it. System fairness index (SFI), system spectral efficiency (SSE) and overall network utility are the key performance metrics used for comparing the performance of the proposed and the conventional resource allocation schemes. The social metric values used in the proposed scheme are calculated using degree and eigenvalue centrality metrics. The proposed scheme is implemented using these two metrics and the performance of these two implementations are also compared to each other.

7.2 Thesis Conclusions and Engineering Significance

Based on the thesis research study and its findings, the following conclusions can be drawn.

The proposed socially aware resource allocation scheme is beneficial for a wireless network of at least 15 users each user requiring 1 Mbps data rate. From the results in section 6.4, it is concluded that the proposed scheme when implemented for large size networks (i.e. 25 and 30 users), achieves performance improvement of up to approximately 50% in terms of SFI, up to approximately 7% in terms of overall network utility and up to 75% in terms of the SSE as compared to the conventional allocation schemes. Thus, it is concluded that the proposed two-hop scheme extends the network capacity and network coverage when the BS has to serve a large number of users.

Individual network users experience a very high level of satisfaction (very close to 1) in terms of utility when the proposed scheme is used. This also indicates that the minimum user requirements in terms of the service provided by the network are satisfied. High level of performance is obtained by using the computationally expensive proposed joint resource allocation scheme. While determining most active (MA) users in a wireless network consisting of non-overlapping communities, degree centrality metric should be used to determine the popularity of a user in its immediate neighbourhood.

The findings of this thesis can be used as a foundation for developing resource management protocols for wireless networks which have been overlaid by social networks. The proposed two-hop optimization based socially aware resource allocation scheme and the proposed socially aware utility function can be used to design new resource management protocols for mobile social networks.

7.3 Limitations of the Proposed Work

Following are the limitations of the proposed work.

- The proposed problems are MINLP problems (refer to sections 4.3.1 and 4.3.2), solving these problems is computationally complex and not scalable especially when the number of subcarriers, communities and number of users per community increase. The complexity makes it difficult for the network designers to implement the proposed scheme for very large size networks. To resolve this, sub-optimal schemes, where the resource allocation is performed in two step i.e. subcarrier allocation is performed assuming equal power allocation in step 1 and the knowledge of subcarrier allocation is used for power allocation in step 2 can be implemented [6].

- Despite the fact that the resource allocations are fair from network users' point of view, the data rate achieved by the network users is much larger than the minimum data rate required by the users, which occurs due to the objective to maximize the performance in second hop (equation (4.15 a)) and the minimum data rate requirement constraint (equation (4.15 i)). This indicates a waste of network resources from the service provider's point of view. This is unavoidable as the minimum data rate requirement constraint representing the elastic applications considered in this thesis cannot be varied.
- The centralized architecture can suffer from single point of failure at the BS as well as the MA user. Thus, architecture is also not scalable.
- The maximum number of users that can be considered to be present within a community is restricted. This is done so as to stop the MA user from displaying individual selfishness which would deprive the community users from the data they want to obtain from the content provider.

Thus, proposed scheme is not highly scalable due to the following reasons a) the network architecture is centralized, b) the computational complexity of the proposed MINLP problem increases as the number of users, communities and subcarriers increases and c) MA user will turn individually selfish.

7.4 Suggestions for Future Work

As logical extension to the work reported in this thesis, the following three major research directions are considered as future work.

- Overlapping communities

  In this thesis, non-overlapping communities have been considered, i.e. it is assumed that the users exhibit socially selfish behaviour, and are connected to their peers within their own communities. However, users belonging to different communities do not share any connection. Such an assumption ignores the fact that users belonging to different communities may have a few common interests i.e. user 1 from community 1 may share a connection to user 1 from community 2. Considering these connections will help faster dissemination of data to a larger number of users. However, to achieve this faster data dissemination, a multi-hop resource allocation scheme will have to be proposed as opposed to the two-hop scheme proposed in this thesis.

- Distributed/Hybrid architecture and Multiple Most Active users

  In this thesis, it is assumed that the BS performs all the allocations for both hops. The advantage of this centralized architecture is that the BS is equipped to perform highly complex computational tasks and possesses high transmission power. Implementing a centralized architecture is simpler and highly efficient due to presence of centralized control. However, a centralized architecture may not always be feasible, as a single point of failure in the architecture may cause congestion at the BS when multiple communities try to access its services at the same time. Also, centralized architectures are not scalable. In such situations, distributed and/or hybrid networks can be introduced as a potential alternative.

The MA users also serve as a single point of failure as discussed in section 7.3. Thus, to increase the reliability, a multiple MA users based scheme can be adopted. In this scheme, every user will have to determine which MA user they are connected to and share and/or accept data with and/or from them in a distributed manner.

- Selfishness

  Selfishness is a negative social feature [2]. In this thesis, the users are assumed to exhibit socially selfish behaviour, so as to allow users to share information with their peers belonging to the same community [1]. However, as the resources of a user are limited, the MA user may exhibit individually selfish behaviour as discussed in section 7.3, and virtually disconnect the community from the network and deprive them of the data they demand. Further research needs to be done in order to overcome this individual selfishness exhibited by users.

- Uplink and downlink scenario

  In this thesis, a data downlink scenario has been considered. A scenario where users belonging to different communities who share similar interests but are physically separated can be considered for extending the proposed work. Resource allocation for the case where user 1 from community 1 uploads data to the server and the users from community 2 which have similar interest as those of community 1, download the data from the server should be addressed.

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