BOTSWANA INTERNATIONAL UNIVERSITY OF SCIENCE & TECHNOLOGY

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IMPROVEMENT OF CELL EDGE USER ADMISSION USING A USER-CENTRIC APPROACH

by

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Abstract

The increase in the number of linked technological devices, coupled with devices with new multimedia based services has resulted in the growing demand for high data rate communication and a spectrum crisis. Non-orthogonal multiple access (NOMA) is a promising candidate for better utilisation of spectrum and to address the high data demands in current and future communication systems. This work addresses the utilization of NOMA under power minimization and user admission strategies. The problem is formulated as an optimization problem which is solved through a novel auction based approach for power allocation at the base station. The main problem under investigation is an under researched case wherein the system is modelled as a auction mechanism that allows for multiple auctioneers, multiple bidders, and multiple items. The solution is user-centric which accommodates heterogeneity in the wireless network in terms of the network topology, participants, items or services being offered. The results demonstrate that at a particular channel the proposed user centric solution outperforms the existing algorithm in terms of average admitted users and average generated revenue. It is observed that in general there is either more user admission or a different user admission set. The NOMA based solution improves cell edge user admission with reduced average transmitted power. Ultimately, the revenue of the service provider is equally improved. However there are limitations due to the presence of errors in the auction link, lack of incentive for users performing SIC and the NOMA scheme compromising physical layer security,and often, over satisfying user's target rate.

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I sincerely appreciate God for His grace, strength and sustenance throughout this journey. I express my deepest gratitude to Dr. Bokamoso Basutli and Professor Joseph Chuma for their guidance, criticisms and above all his patience. Lastly, I am indebted to my family who encouraged and supported me throughout.

List of Abbreviations

5G	**F**ifth-**G**eneration
6G	**S**ixth-**G**eneration
AP	**A**ccess **P**oint
AWGN	**A**dditive **W**hite **G**aussian **N**oise
APP	**A**daptive **P**reference **P**rofile
BWA	**B**id **W**ait **A**uction
BER	**B**it **E**rror **R**ate
BS	**B**ase **S**tation
FDMA	**F**requency **D**ivision **M**ultiple **A**ccess
FPA	**F**air **P**ower **A**llocation
FSPA	**F**ull **S**earch **P**ower **A**llocation
FTPA	**F**ractional **T**ransmit **P**ower **A**llocation
HU	**H**ost **U**ser
MIMO	**M**ultiple-**I**nput **M**ultiple-**O**utput
MISO	**M**ultiple-**I**nput **M**ultiple-**O**utput
NOMA	**N**on-orthogonal **M**ultiple **A**ccess
OFDMA	**O**orthogonal **F**requency **D**ivision **M**ultiple **A**ccess
OU	**O**pen **U**sers
QoS	**Q**uality-of-**S**ervice
SC	**S**uperposition **C**oding
SIC	**S**uccessive **I**nterference **C**ancellation
SINR	**S**ignal-to-**I**nterference-plus-**N**oise **R**atio
UE	**U**ser **E**quipment

Mathematical Notations

$\log_a(x)$	The logarithm of x using the base $x \in \mathbb{R}_+$.
$x \in S$	If S is a set x is a member
$\forall x$	Means that a statement holds for all x

Chapter 1

Introduction

Traditional wireless networks were designed to provide only voice services however, contemporary wireless communication services, have become an essential part of everyday life providing a wide variety of high rate multimedia services. The evolution of wireless technology has significantly contributed to enhancing the life style of the people in the automotive, health, logistics and merchandise tracking sectors, as well as enabling the concepts such as smart society, smart grids and many other scenarios where wireless communication is imperative [1,2]. The telecommunications industry along with academia have already made advancements in the path towards the next generation technologies. Some emerging features and technology being proposed and implemented for fifth generation (5G) and beyond include: multi-tier dense heterogeneous networks, device to device (D2D) and machine to machine (M2M) communications, extensive use of small cells and relays, cloud based radio access network, integrated use of multiple access technologies, massive and 3D multiple input multiple output (MIMO), millimetre wave (mmWave) and full duplex communication [3–5]. The evolution of wireless communications systems and technology is centered around using different multiple access schemes. Specifically time division multiple access (TDMA), frequency division multiple access (FDMA), code division multiple access (CDMA), and orthogonal frequency division multiple access (OFDMA) were and still are the driving access schemes in first generation (1G), second generation (2G), third generation (3G) and fourth generation (4G) systems respectively. This thesis will focus on non orthogonal multiple access (NOMA). This multiple access scheme is envisaged to address some of the challenges laid out before [6].
The challenges of 5G include heterogeneity and dense deployment of devices, the heterogeneity of network resources and the rationality and self interested behaviours of network agents [7].

The wireless architecture has evolved towards a network of multiple nodes/users which interact, engage in mutual resource exchanges, and reach agreements to promote their interests where their decisions ultimately affect each other. this provides an opportunity for devising distributed, dynamic and adaptive algorithms for ensuring network operation over time-varying conditions and optimising decisions on network services and resource allocation [8–10]. The resources present in wireless communication systems (i.e.,power, bandwidth, spectrum, etc.,) form the backbone of which such systems operate. The scarcity of these wireless resources requires that the design objectives of such systems include resource allocation mechanisms. The benefits that result from resource allocation mechanisms in cellular networks include improving network performance, satisfying differing quality of service (QoS) requirements, as well as saving energy. A general radio resource optimisation problem consists of a utility as the objective function, a set of constraints, and variables to be optimised. The utility is usually a performance metric while the constraints represent some physical limitations in wireless network. In general, the aim is to find optimal solutions or near-optimal solutions which will improve the network performance.

Auction theory has been identified as a tool for network design, optimisation, and resource allocation while taking into account economic properties. The features of the auction enable it to model interactions among entities and provide incentive mechanisms that are essential in determining the value of network resources and services. Auctions can also support the differing objectives and provide various other desired properties. Furthermore, auctions are able to provide the allocation of bundles of diverse resources while satisfying the dynamic demands and improving resource utilisation.

1.1 Motivation

Resource allocation enhance the performance of wireless networks by sharing the spectrum and optimising parameters such as the transmitting power, symbol transmission rate, modulation scheme, coding scheme, bandwidth, or combinations of these parameters. Emerging technologies introduce new challenges in the design and optimisation of network resource management.

- Current wireless networks consist of billions of devices with requirements of making optimal decisions with minimal human interaction. Given the constrained and dynamic nature of network resources and the wireless environment this leads to issues in the efficient control and management of devices.

This presents a necessity for approaches with higher efficiency and more flexibility to adapt to the dynamic network.

- Traditional radio resource management techniques require a central entity to perform the overall network optimisation. This presents a challenge for current networks which have become decentralised and adhoc in nature resulting in a necessity for the development of resource allocation schemes that are suitable for distributed and autonomous decision making. Furthermore, the decentralisation of wireless networks increases the need of resource sharing and reallocation among network entities. The dynamic and unpredictable nature of the resource demands, in time and space, presents a need for the consideration of scalable resource management schemes.
- The high density and large scale nature of the wireless network make the obtaining of perfect global network state information too costly and impractical. Thus radio resource management (RRM) decisions need to me made with partial or no knowledge of the parameters of the optimisation problem.
- The entities in the wireless environment may be rational and selfish seeking to maximise their own utilities and in turn may affect the social optimality and global resource allocation within the network. This selfish trait may also affect the spectrum utilisation as well as the revenue of the seller. The described behaviour can be modelled and understood through game theoretic mechanisms that promote truthfulness and cooperation.
- The differing objectives of network entities i.e., low latency, cost minimisation, utility maximisation, high data, may conflict with each other. Traditional methods merely consider system performance metrics rather than economic factors. Thus, RRM methods that incorporate economic implication into the solution need to be adopted.

The descriptions above indicate that the wireless environment is similar to real markets. In particular, the existence of various participants in the system and their ability to perform in the transaction of items or commodities, including sharing information and network resources under certain regulations. Thus business and economic management approaches are easily applicable and can be used to dynamically and efficiently manage the radio resources. Auctions are one kind of economic approach that has the ability to guarantee the efficiency of the resource management by allocating resources to those that value them the most. Auction mechanisms can further address RRM in the cellular networks in the following ways [11–14]:

- The complex interactions of networks entities can be modelled and analysed through the use of auctions as a game. These interactions enable network entities to observe, learn and predict the actions of other entities and then make the best decision based on the equilibrium analysis.The auction is able to cope with the distributed autonomous decision making and the diverse and conflicting interests of the network entities.

- Auction based mechanisms can be designed in a manner that copes with the different objectives of network entities. The objectives range from revenue maximisation, social welfare maximisation and other various desired properties that can be concurrently solved using am auction based solution.
- Based on demand and supply in the market, an auction can offer the flexibility of dynamically and efficiently setting prices for items and commodities.
- Auctions can provide RRM decision under conditions of limited or no network state and node utility information

In the view of complex requirements of wireless networks, we observe that modern wireless networks aim to improve the spectrum utilisation along with a reduction in power levels. Also, the growth of wireless networks in devices results in an increase in energy consumption therefore modern wireless networks need to provide higher data rates with increased power limitations. There is an urgent need for efficient techniques to be incorporated into the networks to overcome the above challenges. Keeping in view the above requirements, this thesis presents an auction approach in power allocation that takes into account the `SINR` targets of users in the network and aims at minimising the total transmit power at the base station.

1.2 Problem statement

The Cisco visual index states that by 2023 there will be 29.3 billion mobile connected devices up from the 18 billion in 2018. In addition the mobile data traffic is projected to increase by seven fold between 2016 and 2021. However, with spectrum being a finite and scarce resource the tremendous growth and the demand in spectrum is likely to affect capacity and hence result in dropped calls, slower data speeds and increased prices for both consumers and providers. Most networks experience outages at the cell edges, hence a degraded service provision at those locations. The demands of these increasing devices can be met by the efficient use of the available spectrum. Motivated by this, the thesis addresses radio resource allocation problems in power domain NOMA communication systems.

1.3 Research objectives

The main aim of this thesis is to formulate and develop a novel auction based power allocation scheme that improves system performance in a NOMA based downlink network. The specific objectives being;

- To formulate a power allocation algorithm that minimises the total transmit power at the base station and uses the auction as an allocation mechanism.
- To achieve users SINR demands, increase cell edge user admission and increase network revenue.

1.4 Research Publications

- **T. Jacob**, A. Sanenga, B. Basutli and J. M. Chuma, "NOMA Assisted Communication for Cell Edge User Admission: A User-centric Approach," submitted to MDPI (under revision).
- A. Sanenga, G. A. Mapunda, M.**T. L. Jacob**, L. Marata, B. Basutli, and J. M.Chuma, "An Overview of Key Technologies in Physical Layer Security," Entropy, vol. 22, no. 11, pp. 133, Nov. 2020.

1.5 Outline of the thesis

- Chapter 2: Discusses the relevant fundamentals of auction theory and gives a literature review that is associated with the scope of this thesis. Classic utility functions, are first defined and discussed.
- Chapter 3: This chapter gives the background theory and literature review on Non Orthogonal Multiple Access. A comparison between NOMA and orthogonal frequency division multiple access (OFDMA) in terms of the energy efficiency and spectral efficiency. The different pairing techniques, power allocation techniques are discussed with a comparison of the achievable sum rate in the different power allocation techniques. An overview of multiantenna NOMA is given with the formulation of a convex power minimisation problem solved using semi definite programming (SDP).
- Chapter 4: A power allocation technique for power minimisation in a downlink MISO NOMA system is considered. The resource allocation problem is first formulated then the proposed algorithm is described. The chapter first describes the system model and the user centric auction model with multiple auctioneers, multiple bidders and multiple items. It continues to propose a NOMA based solution and then the numerical results are discussed.

- Chapter 5: Finally, in Chapter 5 we have provided the conclusions of the research works presented in each chapter. Then, possible future extensions of the problems considered in this thesis are briefly described.

Chapter 2

Convex optimisation techniques and auction theory

In this chapter, convex optimisation techniques and game theory are reviewed.The basic concepts of these techniques are briefly discussed. The chapter further discusses the basic concepts of auctions and reviews their application in wireless network environments.

2.1 Techniques for modelling and analysis of radio resource allocation methods

2.1.1 Optimisation techniques

Optimisation is a branch of mathematics that deals with problems of decision making. The use of optimisation methods is present in communications and signal processing. Optimisation formulations consist of a measurable objective and a variable that can control the optimisation of the objective. Optimisation problems may be constrained or unconstrained. The constraints restrict the feasibility of the variables. An optimisation problem has the form:

$$\underset{x}{\texttt{minimise}} \quad f_0(x) \tag{2.1}$$

$$\text{subject to} \quad f_i(x) \leq b_i \quad i = 1, \cdots m \tag{2.2}$$

where x is the optimisation variable $f_0(0)$ is the objective function and $f_i(0)$ is the i^{th} constraint. After the modelling and formulation there are various methods that can be used to find the solution of an optimisation problem. These include linear optimisation, mixed integer programming, convex optimisation, and quadratic optimisation. In this work we focus on convex optimisation where the objective function is assumed to be a convex function. Under this assumption the optimal solution is expected to be unique. Many signal processing and communication problems can be considered as or converted into convex optimisation problems. This helps in finding analytic and numerical solutions. The structure of the obtained solutions, often reveals design insights. There exists numerical algorithms to solve for the optimal solution of convex problems efficiently. There are various convex optimisation methods to solve the original problem. The methods include linear programming, second order cone programming, semi-definite programming, conic programming and geometric programming. Used in this thesis is semidefinite programming in solving problem in chapter 3, with the help of cvx, a matlab based package for convex optimisation.

2.1.2 Game theory

In a setting where several decision makers/players exist, game theory enables the modelling and analysis of the interactions between their conflicting or common objectives [15–17]. The objectives of the players are tightly coupled that is to say that the benefits or cost experienced by each player not only depend on its own decision but also on those taken by other players. Each player has a set of strategies and a preference whose characteristics are captured by a utility function. The utility function determines whether the equilibrium solution that exists is unique and the associated distributed algorithm is robust or not [18]. There are three components to any game:

- A player set $k = \{1, ..., N\}$
- A set of strategies $A_1 \times A_2 \times ... \times A_N$
- A utility function set $u = \{u_1, ..., u_N\}$

Games can be classified as cooperative games or non-cooperative games. In cooperative games there is coordination between players and their strategies and the payoff is shared among them. Non-cooperative games resolve conflicts among players who behave selfishly to optimise their own well being. Distributed radio resource allocation schemes can be modelled as non-cooperative games such that each radio node takes a decision using its computational and learned infrastructure. Each user seeks to choose its strategy in such a way as to maximise its own utility. Two important concepts can be defined for such a game. The concept of Nash equilibrium (NE) and pareto optimality. A NE corresponds to a steady state in Non-cooperative games. NE is discussed in the following section.

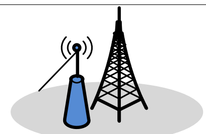
Auction component	Description	Wireless Network Environment
 Buyer/Bidder	• The bidder wants to buy commodities in auctions. The word bidder and buyer may be used user as synonyms	 • In the wireless environment bidder is a user who wishes to buy radio resources in order to complete tasks of transferring data, the user compete for the resources with other user
 Auctioneer /seller	• The auctioneer is as an intermediary and conducts the auction processes. A seller can be an auctioneer it.	 • in wireless systems, a base station or an access point can conduct resource auctions
commodity	• Commodity refers to the object being traded between a buyer and a seller. Each commodity has a value at which the buyer/seller wants to buy/sell.	• Power • Timeslot • Frequency • Modulation code etc.,
 Bidding cost/ valuation	• buyers and sellers have different valuations for a commodity depending on their preferences. A valuation can be private or public	• Latency, • Sum rate • Power consumption etc.,

FIGURE 2.1: Components mapping of auction approach in wireless networks

Furthermore the utility function is highly related to the network performance such as throughput, delay, and outage. Research in the context of game theory and wireless communications has been applied to wireless communications such as 3G/4G wireless cellular networks, MIMO/OFDM wireless technologies. Figure 2.1 encompasses a large number of wireless communication scenarios. The mobiles in the figure may represent secondary users and primary users, they may belong to macrocells and small cells or they may represent network nodes that are also receivers as is the case of device to device communications.

Solution concepts

The goal of this subsection is to provide an overview of the solution concepts encountered in the literature within the space of game theory applications. However, the discussion is not exhaustive and does not cover all existing solution concepts.

Solution concepts are a rules that predict how the will be played. They describe players adopted strategies and thus predict the outcome of the game. Equilibrium concepts, like the one discussed below, are the most commonly used solution concepts. Other equilibrium solutions, include the stackelberg equilibrium, evolution equilibrium and correlated equilibrium.

Nash equilibrium: John Forbes Nash formulated one of the most fundamental concepts in non cooperative games, the Nash equilibrium. The Nash equilibrium involves two or more players, where no player has anything to gain by changing his strategy unilaterally. The NE is the most fundamental concept in non-cooperative strategic games. Games can admit zero, one or multiple Nash equilibria. The key points of interest are existence of the NE, its multiplicity and efficiency.

DEFINITION

An NE is a set of strategies $(a_1^*, ..., a_k^*)$ such that no user can unilaterally improve its own utility $i.e$,

$$U_i(a_i^*, a_{-i}^*) \geq U_i(a_i, a_{-i}^*), \quad \forall a_i \in A_i \quad and, \quad i = \{1, 2, ..., N\}, \tag{2.3}$$

where U_i is the utility of the i^{th} player , A_i is the action domain of the i^{th} player, N is the total number of players.

Dominant strategy equilibrium The concept of dominant strategy is an important notion in non-cooperative games. The use of dominating strategies simplifies the solution of a game by eliminating some strategies.

DEFINITION

A strategy $a_i \in A_i$ is said to be dominant for player i if,

$$U_i(a_i, a_{-i}) \geq U_i(a_i^*, a_{-i}), \quad \forall a_i^* \in A_i \quad \text{and}, \quad \forall a_{-i} \in A_{-i}, \tag{2.4}$$

where $A_{-i} = \prod_{j \neq i} A_i$ is the set of all strategy profiles for all players except for player i A dominant strategy $a^* \in A$ is the dominant strategy equilibrium if every element a_i^* of a^* is a dominant strategy of player i.

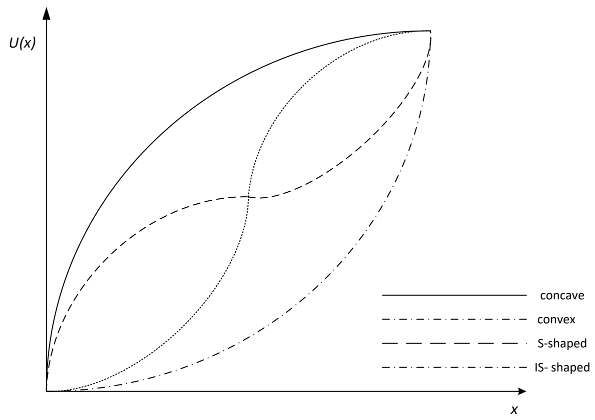


FIGURE 2.2: Different types of utility functions

Classic utility functions

Research shows that the management of radio resource is preferred to be controlled in an automated, self optimised manner rather than centralised or manual. An automated approach can be achieved by using different distributed algorithms performing optimisation. One challenge in the distributed approach is the formulation of the utility function. Utility, in terms of economics, is a measurement of usefulness or preferences over some set of goods and services. It represents a satisfaction level experienced by consuming a good or a service and may be a function with respect to a resource. The derivative of the utility function, represents the marginal utility. In the context of wireless networks, utility functions provide a measure of user quality of service whose function is related to metrics such as frequency, SINR, time slots or power. Often times, the more resource allocated the more satisfied the user. The criterion used to pick utility functions is based on application traffic elasticity [19, 20], efficiency of resource allocation and fairness among competing users. The commonly used utility functions in network utility maximisation are concave, convex, S-shaped, and inverse-S-shaped (IS-shaped) functions, as shown in Figure 2.2. As stated above, the utility function is the objective functions and can represent a performance metric or a variable to be optimised. The constraints are usually QoS requirements or some limitations present in wireless networks. Summarised below are some classic utility functions, including those used in this thesis.

- Power: The sum of the transmit power allocated to users served in the network is a typical objective function in wireless networks.
- Throughput: Throughput can be referred to as sum-rate utility and it sums up the data rate of the users. The expression of the utility function is of the form

$\sum R_i$. R_i represents the data rate achieved by user i.

- Weighted sum-rate and fairness: Some application scenarios prefer to priorities and maintain fairness among users instead of only considering maximum throughput. To achieve this, a weight W_i is introduced and a utility function is formulated as a function of the minimum achievable rate between all users.
- Spectrum efficiency: The expression of this utility function is in bits per second per Hz and quantifies throughput in unit bandwidth. This utility considers the sum of the users data rate, normalised to the bandwidth.
- Energy efficiency: Energy efficiency is a metric that tries to find a balance between the achievable data rate and power consumption. It is defined as the number of bits that can be reliably transmitted per Joule of energy consumption.
- Probability of success: In the case where each user has specific QoS requirements the corresponding utility function is expressed by the probability of success. Sigmoid utility functions in [21] are used to represent different modulation schemes. The utility represents the probability of successfully transmitted packets per unit power consumed, when using a certain modulation scheme. Earlier work of the sigmoid function in resource allocation is seen in [22].

2.2 Auction theory fundamentals

Auctions facilitate designing wireless resource allocation algorithms which can be analysed within the mathematical framework of strategic non-cooperative games. All players are viewed as selfish and wanting to maximise their payoff. The rules that govern auction participation can be translated into mathematical formulations where game theory can be used to analyse the behaviours of buyers and sellers.In general auctions are viewed as games with incomplete information. Game theory can be used in studying the efficiency of a given design, revenue comparison and the optimal and equilibrium bidding strategy. The view of auctions from a game theoretic perspective provides a framework for auction analysis and it has resulted in a volume of research contributions. This sections reviews the fundamental concepts of auction theory.

Auctions are widely used in wireless networks and date back from the use of spectrum license distribution. In an auction there are bidders, sellers and auctioneers. The traditional auction mechanisms include English and Dutch auctions, and the first price and second price sealed bid auctions.

2.2.1 Auction classification

There are various existing auctions and we categorise them in terms of of the characteristics of items, bidders timing and payment rules. Some simple categorisations follow.

- *forward and reverse auction*: A forward auction is the most common type of auction that involves one seller and multiple buyers that compete to offer a price the seller will accept. The bid begins at a minimum price and continues to increase and offer higher prices. The reverse auction reverses the traditional roles of buyer and seller (see Figure 2.3). There is one buyer and multiple potential sellers. The competition is between the sellers who compete for the attraction of the buyer. The submitted bids refers to the price that the seller is willing to receive for trading the items. In reverse auctions, the price decreases to the lowest price that the buyer can accept.

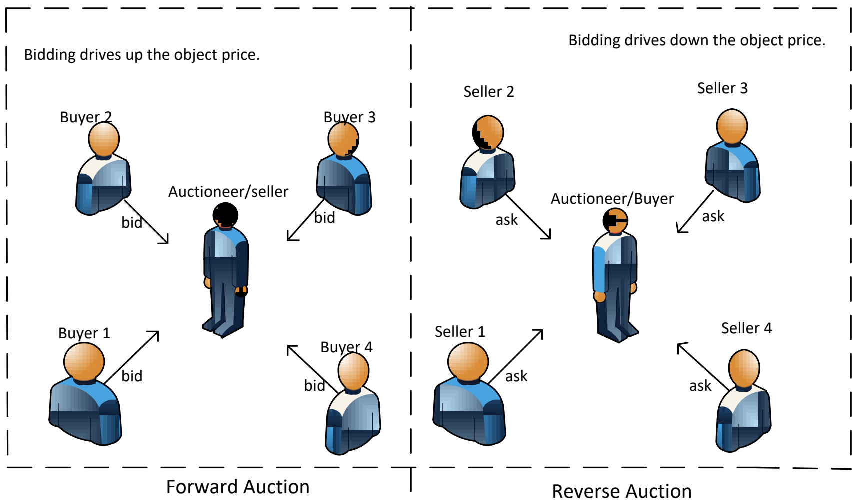


FIGURE 2.3: Different types Auctions:.

- *Open-cry and sealed bid auction*: In the open cry auction the announcement of bids is made in an open market. The bids of bidders are disclosed to the other bidders. The sealed bid auction is contradictory and the bidders submit their bids simultaneously to the auctioneer. No bidder knows how much the other bidders bid.
- *Single item and multi item auction*: The single object auction is the simplest auction setting consisting of a single seller selling one indivisible item. In the setting of multi-object auctions multiple related items are to be sold. The objects may be physically identical or they may be physically distinct.

Aside from the categorisation described above, a typical approach is based on the auction rules. As stated above there are four traditional auctions in this regard.

- *English auction*: This is the most common form of auction and can also be referred to as the open ascending bid auction. The auctioneer initially sets a reserve price for the item. The buyers place their bids for the item. The auctioneer continues to accept increasingly higher bids until are accepted until a higher bid isn't received and only one buyer is left. The remaining buyer pays a certain amount declared by the auctioneer.
- *Dutch auction*: Different from the English auction, the Dutch auction may be considered as a descending price auction. The auctioneer sets a ceiling price and gradually decreases the price until one of the bidders accepts the price. The winning bidder pays the final price and pays a price at which the last second bidder dropped out.
- *First-price sealed-bid auction (FPSB)*: The asks submitted in the FPSB auction are known only to the auctioneer and the bidder. The bidder with the highest bid wins the auction.
- *Second-price sealed-bid auction (SPSB)*: The auction framework of the SPSB auction may also be referred to as the Vickery auction. The bidders each submit a sealed bid to the seller. The highest bidder is sold to the item however, the winner pays the second highest bid for the item. This setting provides a mechanism in which it is a dominant strategy for bidders to bid their true valuations of the goods.

There are other auctions such as the double auction and combinatorial auction. Each of these have different objectives and various desired properties

- *Double auction*: Double auctions allow buyers and sellers to submit bids/asks simultaneously. The double auction has desired properties such as truthfulness, individual rationality, balanced budget and economic efficiency. In wireless architecture, the double auction may be applied where each node can be both resource provider and consumer.
- *Combinatorial auction*: Combinatorial auctions are multi item auctions used when complementaries or substitution effects exist between different items. This allows bidders to better express their preferences compared to traditional auction formats. Combinatorial auctions are suitable in environments where a set of items have greater utility than the sum of the utilities of the individual items.

2.3 Auction theory for radio resource allocation

There are various survey papers that present auction-based applications and resource management techniques in wireless systems. The authors in [23, 24] provide an overview of auction theory in terms of the concepts, categorization and objectives. Furthermore, they explain the motivation of using auction approaches in radio resource management while introducing design issues. Discussed below are the auction based techniques found in the literature categorized by the most prevalent wireless networks in the literature.

Cognitive radio

Auctions in cognitive radio (CR) networks provide a motivation for secondary users (SUs) to maximise their spectrum usage. The free channels in the system are items to sell, the bidders are the secondary users and the seller is the primary user (PUs) and the auctioneer is a regulator. Cognitive radio networks provide a setting where double auctions are applicable. One of the earliest work on the application of the double auction framework to wireless networks is documented in [25]. The authors propose a truthful double auction to support dynamic multi-party spectrum trading. A truthful auction mechanism for efficient resource allocation (TERA) is proposed in [26]. The auction framework is modelled as a hierarchical auction and the authors consider a cooperative cognitive wireless network. The framework considers the joint allocation of spectrum and secondary relay nodes because of their fundamental role in the performance of CR. The authors in [26] improve TERA by ensuring that all buyers who pay for the same resource are charged with a unique price and that the groups of buyers that pay for the same resource do not interfere with each other. The work in [27] investigates the combined effort of the double auction framework and dynamic spectrum leasing. The double auction framework (DAF) [28], presents a primary framework to be utilised for dynamic and static communication of cognitive radio. The framework also focuses on the security of the Secondary users.

In the CR landscape SUs use unused spectrum holes under strict requirements of the level of interference that they would cause towards the PUs. As such, high accuracy sensing is required to determine there is no ongoing primary communication that they would potentially interrupt. Spectrum sensing addresses the efficient spectrum management for the secondary user-primary user coexistence. An auction framework in [29] was applied to the spectrum sensing hidden PU problem. The hidden PU problem occurs when a PUs signal is shadowed or experiences multi-path fading and the SU cannot sense the presence of the PU. This detection can be made easier by SUs cooperating and enables the detection of PUs which would not be detected by one SU independently. The authors in [30] incentivise cooperation by introducing a virtual currency that can be used to reward spectrum sensing cooperation. They propose a three dimensional Vickery auction mechanism.

Device to device communication

Device to Device (D2D) communication is considered as an essential component to 5G networks and enables the communication between two devices outside of the engagement of the base station or the evolved node B (eNB). A truthful double auction for device to device communication in cellular networks (TAD) [31], designed by authors Peng *et al.*, presents a double auction in a multi-cell multi channel consisting of a number of users. TAD attempts to achieve the three economic properties described of individual rationality, truthfulness and budget balance. One problem associated with D2D communications is the data offloading problem. The randomised auction approach for data offloading (RADO) considers the problem of offloading and constructs an auction to encourage the exchange between the eNB and helpers. The eNB buys messages from the helpers and helpers get payments for sharing messages [32]. The auction is modelled as a combinatorial auction.

2.3.1 Auction based NOMA power allocation

This thesis focuses on power allocation in a NOMA setting. Hence, discussed below are the current applications of auctions in the NOMA landscape. The factors that affect power allocation in NOMA include channel condition and power restrictions. Power allocation in NOMA aims to increase number of served users and sum data rate with a limit on consumed power. Most of the work that has been applied to NOMA that relates to auctions is in the form of games. The authors in [33] propose a stackleberg game to model the interaction between basestation and users in a NOMA cellular network. As the team leader, the base station sets the transmitted power price for each user with the aim of maximising revenue. Similar to [33], the authors in [34] propose a stackleberg game for downlink NOMA and exhibits better performance in terms of revenue and sum rate. A Glicksberg game model was proposed in [35] where the authors formulate a price based utility function unlike [33, 34] their focus was on maximising sum rate. In [36] a super modular game model was used to model subchannel matching to improve energy efficiency. The utility function is designed to maximise energy efficiency and power is allocated equally.

Chapter 3

Multi-antenna and power allocation techniques for NOMA

In this chapter, the NOMA background techniques are reviewed. To comprehensively understand the motivation of these background techniques, an overall review of the NOMA technique is provided. Finally, power allocation methods for downlink NOMA communications are introduced.

3.1 Overview of non-orthogonal multiple access (NOMA)

The techniques for NOMA find their roots in principles like successive interference cancellation (SIC) and superposition coding (SC). SC is performed at the base station while SIC decoding happens at the user. SC is a multi user transmission scheme that simultaneously transmits information of multiple users at the same time. SIC is the ability of a receiver to receive two or more signals concurrently . SIC is possible because the receiver decodes the stronger signal first and subtracts it from the combined signal and then decodes the difference as the weaker signal [37, 38]. NOMA provides a balanced tradeoff between spectral efficiency and user fairness [39–43]. Various forms of NOMA techniques exist and are categorised based on the domain in which non-orthogonality is achieved [44, 45].
In general two categories can be made, power domain NOMA and code domain NOMA as illustrated in Figure 3.1. Power domain NOMA achieves multiplexing based on different power levels while code domain NOMA achieves multiplexing based on different codes. Code-domain NOMA is similar to conventional CDMA in that users share the available resources (time/frequency), the contrast is introduced by the use of user-specific spreading sequences in code domain NOMA [46]. In this thesis the focus is on power domain NOMA. The fundamental contrast of NOMA from other multiple access schemes is that each user operates in the same band and time but at different by their power levels. When compared with other orthogonal multiple access techniques, NOMA exhibits better spectral efficiency, user fairness,

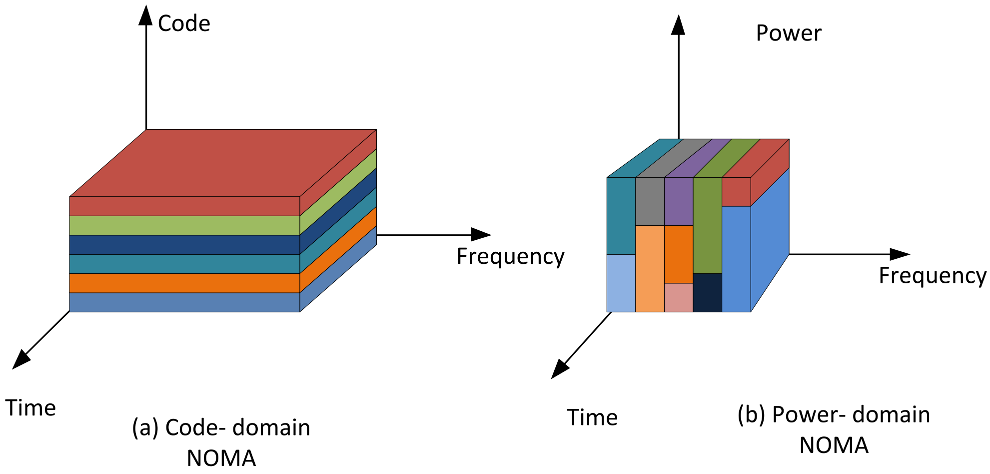


FIGURE 3.1: Resource allocation in code domain and power domain NOMA : colours represent different users.

lower latency and higher massive connectivity. There are various limitations and implementation issues that hinder the exploitation of NOMA. Such hindrances include receiver complexity at each user and the limitation of the number of users in a cluster due to error in SIC [7].

3.1.1 Downlink NOMA

The principle of NOMA is best exhibited when considering the case of two users in a SISO NOMA system. The BS serves the two users denoted UE_1 as a far user and UE_2 as a near user, with transmit power $P_1 > P_2$ as illustrated in Figure 3.2. Assuming that the desired signal for UE_1 and UE_2 are x_1 and x_2 respectively. To obtain the desired signal at the first user, UE_1 decodes its message by treating UE_2's message as noise while the second user firstly decodes UE_1 message, and then decodes its own message after removing UE_1 message. The channel coefficient of UE_i is denoted by h_i. The transmitted signal by the base station is given by

$$x(t) = \sum_{i=1}^{2} \sqrt{\alpha_i P_T} x_i(t) \tag{3.1}$$

where $x_i(t)$ is the information signal, α_i is the power coefficient corresponding to user i, and P_T is the total available power at the basestation. The power allocated to each user, $P_i = \alpha_i P_T$, is allocated according to distance hence UE_1 receives more power than UE_2. The received signal at the user is written as

$$y_i(t) = x_i(t)h_i + n_0, \tag{3.2}$$

where n_0 is the additive white Guassian noise with variance σ^2. The $\texttt{SINR}$ of UE_1, can be written as

$$\texttt{SINR}_1 = \frac{P_1 h_1^2}{\sigma^2 + P_2 h_1^2}. \tag{3.3}$$

while for the nearer user, with the assumption of perfect cancellation, is given by

$$\texttt{SINR}_2 = \frac{P_2 h_2^2}{\sigma^2}, \tag{3.4}$$

The achievable rate of UE_1 and UE_2 are given respectively as

$$R_1 = \log_2(1 + \texttt{SINR}_1) \tag{3.5}$$

$$R_2 = \log_2(1 + \texttt{SINR}_2) \tag{3.6}$$

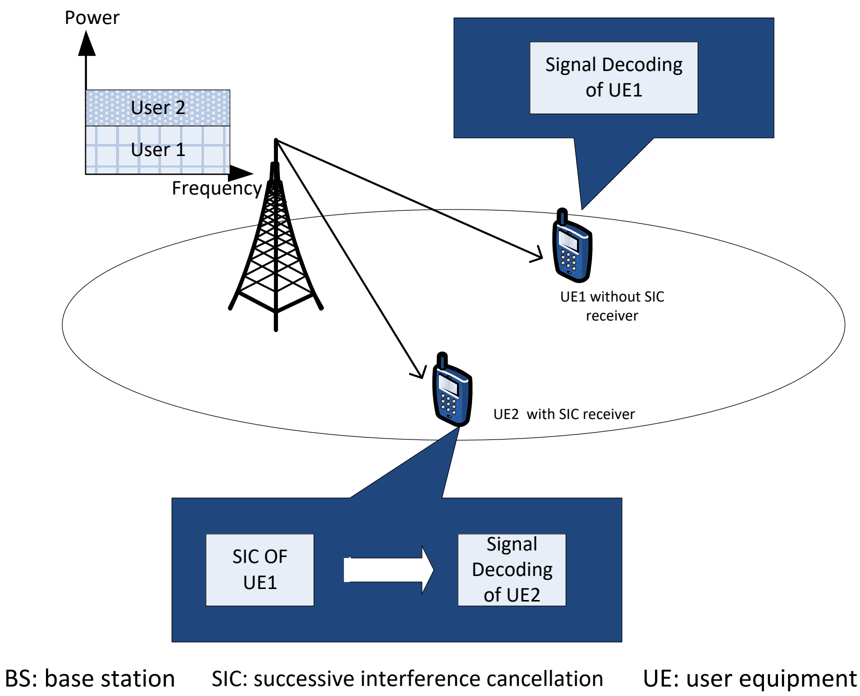


FIGURE 3.2: Illustration of a 2-user downlink NOMA transmission with SIC at user ends.

When multiple users are considered, with a user order $UE_1, ..., UE_K$. The application of SIC is such that UE_1 sequentially decodes the messages of $UE_1, UE_2, ..., UEi$ while decoding UE_j messsage $(j \leq i)$ the interference from $UE_1, UE_2, ..., UE_j$ is removed based on previous decoding results and interference from $U_{j+1}, ..., U_K$ is treated as noise. Figure 3.3 considers two users in a downlink network with symmetric channel conditions and the users are equal distance from the basestation. The depiction shows the boundaries of the achievable rate regions. It can be seen that NOMA achieves higher rate pairs than OFDMA. Figure 3.4 compares the energy efficiency (EE) and sepctral efficiency (SE) of NOMA with OFDMA. The network is a downlink network with two users with different gain. The EE and SE curves shows that NOMA achieves higher spectral effeciency and energy effeciency than OFDMA.

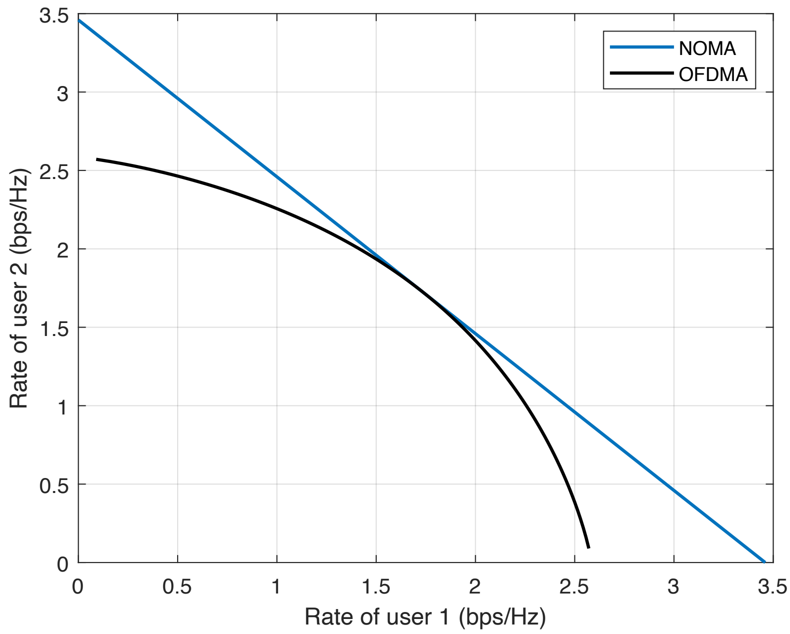


FIGURE 3.3: Rate pairs for downlink OFDMA and NOMA.

3.1.2 Uplink NOMA

The principle of uplink NOMA is different to that of downlink NOMA. The illustration in Figure 3.5 shows UE_1 and UE_2 transmit their signals x_1 and x_2. The received signal at the BS is given by

$$y(t) = \sum_{i=1}^{2} x_i h_i + n_0 \tag{3.7}$$

The first signal decoded by the BS will be the signal from the nearest user and then the signal from the farthest user will be decoded. The SINR for the nearest user and

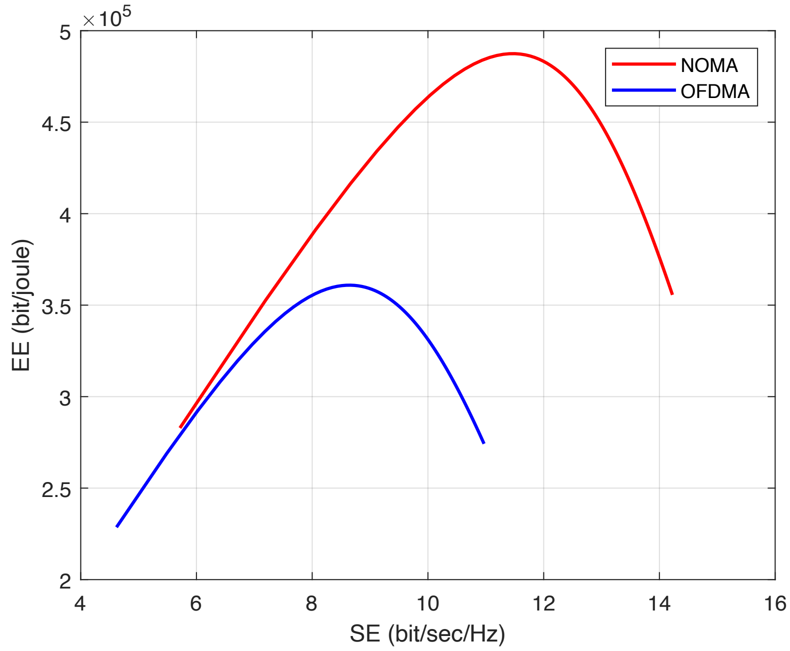


FIGURE 3.4: Energy efficiency and spectral efficiency trade off curves for NOMA and OFDMA.

farthest users which are UE_2 and UE_1 respectively are written as

$$\mathtt{SINR}_2 = \frac{P_2 h_2^2}{\sigma^2 + P_2 h_1^2}, \tag{3.8}$$

$$\mathtt{SINR}_1 = \frac{P_1 h_1^2}{\sigma^2}. \tag{3.9}$$

The achievable rate is then given as

$$R_1 = \log(1 + P_1|h_1|^2), \quad R_2 = \log\left(1 + \frac{P_2|h_2|^2}{1 + P_1|h_2|^2}\right). \tag{3.10}$$

The superiority of uplink NOMA to its OMA counterpart can be shown by comparing the achievable data rate and sum capacity. Due to more computing power and energy at the base station, uplink NOMA can accomodate more users than downlink NOMA. The principle of NOMA states that users with a distinct difference in their channel conditions should be paired together [47]. Thus, discussed below are the pairing techniques present in the literature.

3.1.3 Pairing techniques

User pairing in NOMA is performed based on the desired outcome, deployment environment and the implementation complexity. The easiest user pairing algorithm is a random one where the BS selects user pairs without considering their channel

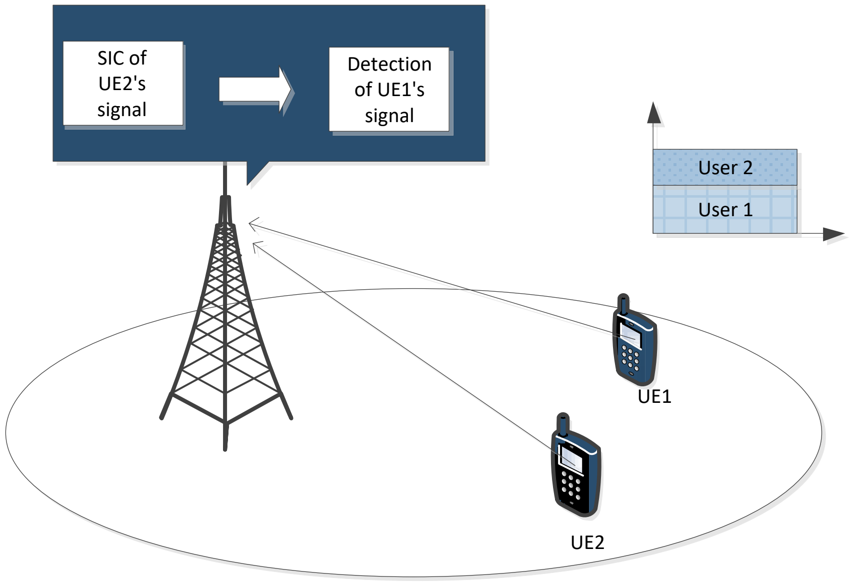


FIGURE 3.5: Illustration of a 2-user uplink NOMA transmission with SIC at the Base Station.

gains. This algorithm is low in complexity however it exhibits sub-optimal sum rate performance. Research has shown that increasing the difference in channel gains between users increases the performance gains of NOMA when using fixed power allocation schemes. This means pairing the user with highest channel gain with the user with lowest channel gain and, the user of second highest channel gain should be paired with a user with the second lowest channel gain, and so on. This algorithm is referred to as the next-largest-difference based user pairing algorithm (NLUPA) [47]. Cognitive inspired NOMA proposes a next best diversity pairing algorithm (NBDPA). In contrast to NLUPA, the user with the highest channel gain is paired with the user with the second highest gain, the user with the third highest gain is paired with the user with the user of the fourth highest channel gain and so on [47, 48], [20]. Figure 3.6 clarifies the above described algorithms. The optimal user pairing solution requires an exhaustive search to form a NOMA cluster [49]. That is to say that for for all users all the grouping combinations have to be considered. As such the computational complexity of optimal user clustering may not be practical for systems with large number of users.

3.1.4 Power allocation in NOMA

Transmission power is a valuable resource in cellular communications which directly impacts the interference management, rate distribution and users admission.

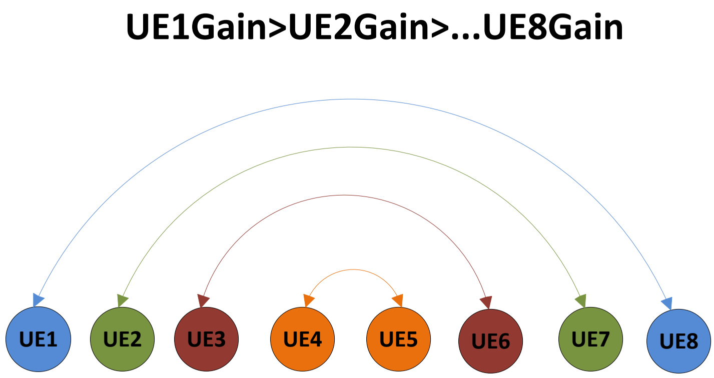


FIGURE 3.6: Next Largest difference based user pairing (NLUPA)

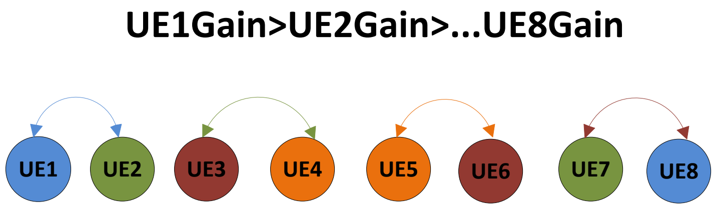


FIGURE 3.7: Next best diversity pairing algorithm

How to assign power is a significant issue in the design of wireless communications. To guarantee a certain quality of service (QoS) a specif $\mathtt{SINR}$ should be achieved.The importance of power allocation in NOMA is further enhanced by the fact that users are multiplexed on the power domain. The key factors that affect power allocation in NOMA include user channel conditions, availability of channel state information, QoS requirements, the total power constraint and system objective. Unsuitable PA may lead to consequences such as the unfair rate distribution among users and system outage due to SIC failure. The performance metrics associated with power allocation include number of admitted users, sum rate, user fairness, outage probability and total power consumption. This thesis analyses the number of admitted users. A variety of PA strategies exist in the literature which target different aspects of NOMA.

The NOMA principle states that the user with the highest channel gain is allocated the lowest amount of power, and vice-versa. There are several intra-sub-band power allocation techniques, the most basic being the fixed power allocation (FPA) [50]. In this instance a coefficient α controls the power allocated to each user. Equation (3.11) and (3.12) show the FPA formulation in the two user scenario.

$$P_1 = \alpha P_T, \tag{3.11}$$

$$P_2 = (1 - \alpha)P_T. \tag{3.12}$$

A more complex technique, called fractional transmit power allocation (FTPA) [51, 52], divides P_T between paired users. The power allocated depends on the channel gains of the users as given by equations (3.13) and (3.14) for the two user scenario.

$$P_1 = \frac{\left(\frac{h_1^2}{no}\right)^{-\alpha}}{\left(\frac{h_1^2}{no}\right)^{-\alpha} + \left(\frac{h_2^2}{no}\right)^{-\alpha}} P_T, \tag{3.13}$$

$$P_2 = \frac{\left(\frac{h_2^2}{no}\right)^{-\alpha}}{\left(\frac{h_2^2}{no}\right)^{-\alpha} + \left(\frac{h_1^2}{no}\right)^{-\alpha}} P_T. \tag{3.14}$$

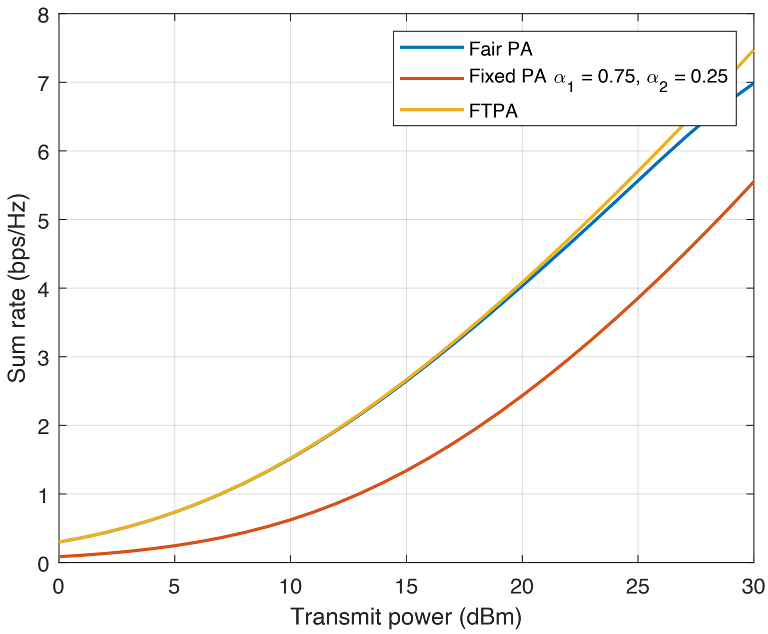


FIGURE 3.8: Sum rate of FPA, FTPA and fixed power allocation

where $0 \leq \alpha \leq 1$ represents a factor that controls the amount of power allocated to every user. The two techniques, FPA and FTPA, can be extended to any number of paired users such that the sum of all powers remains equivalent to the total power. Full search power allocation (FSPA) [53], is another intra sub band technique that is very complex compared to its counterparts mentioned above. It chooses power values that result in the highest achieved throughput by searching through all possible

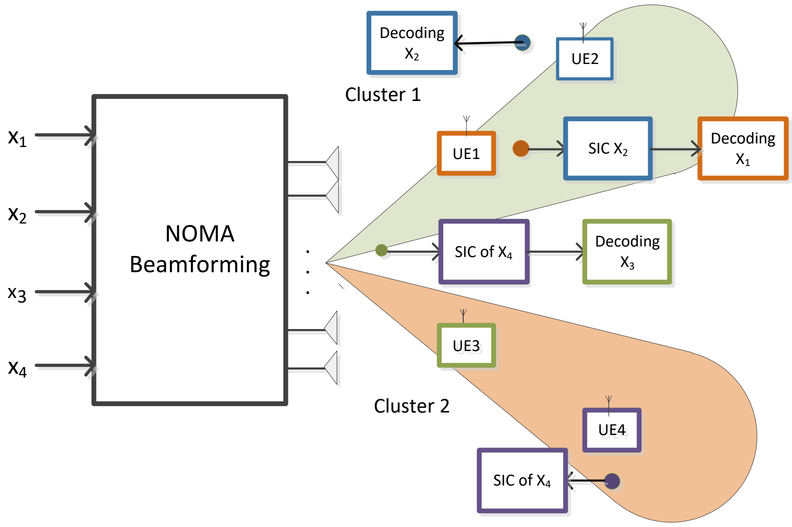


FIGURE 3.9: Non- Orthogonal Multiple Access with beamforming

power values and considering all possible values of α. Figure 3.8 shows a comparison of the achievable sum rate of users in the case Fixed power allocation, FTPA and a fair power allocation scheme adopted from [51].

3.1.5 NOMA with beamforming

Multiple input multiple output (MIMO) is a technique for increasing the spectral efficiency and increasing network capacity. Multi antenna systems open the door for Space division multiple access (SDMA), where multiple users can communicate at the same time and frequency but in different spaces. NOMA can be extended to a case of multiple antennae at the base station and at the users resulting in MIMO NOMA or MISO NOMA. For the downlink, the base station uses its multiple antennae for beamforming to increase received SNR or for spatial multiplexing to increase throughput. NOMA with beamforming exploits the power domain as well as the spatial domain by assigning each user with its own beamforming vector. This introduces design problems that include optimisation of the beamforming, power allocation, user clustering and SIC ordering. This can be done jointly or partially under some performance metric. MIMO NOMA paves the way for massive connectivity. An example of MIMO NOMA system with 2 clusters and 2 users is shown in Figure 3.9.

Figure 3.10 presents a comparison between a Semi-Definite Relaxation (SDR) beamforming solution of a MISO NOMA system and a conventional centralized system. A power minimisation problem is considered with the assumption that each user i has a $\texttt{SINR}$ target denoted by γ_i. The power minimisation problem subject to interference constraints is given by

$$\underset{\mathbf{w}_i}{\texttt{minimise}} \quad \sum_{i=1}^{N} \|\mathbf{w}_i\|^2 \tag{3.15}$$

$$\text{subject to} \quad \texttt{SINR}_i \geq \gamma_i, \quad \forall i \tag{3.16}$$

$$\|\mathbf{w}_i\|^2 \leq P_{\max}, \forall i \tag{3.17}$$

In the probelem defined above, equation (3.15) is the objective function which is the sum of the transmit power of all users in their allocated channels, constraint 3.10 depicts the $\texttt{SINR}$ constraints and constraint 3.11 ensures that the total transmit power is not greater than the maximum allowed transmit power at the basestation. The simulation considers the setting of one basestation and two users. In addition the noise power $\sigma^2 = 0.1$ and a $\texttt{SINR}$ target of the users is $2.5dB$. The plot depicts the number of antenna at the basestation versus the total transmission power with the number of antenna ranging between $N = 2$ and $N = 10$. Observed from this plot is that NOMA outperforms the conventional approach, with the NOMA system leading in lower power usage. In addition as the number of antenna increases the gap between the two plots decreases and results in a state of convergence. This is a result of an increase in the number of nulls in the direction of the user resulting in less interference and hence lower power usage.

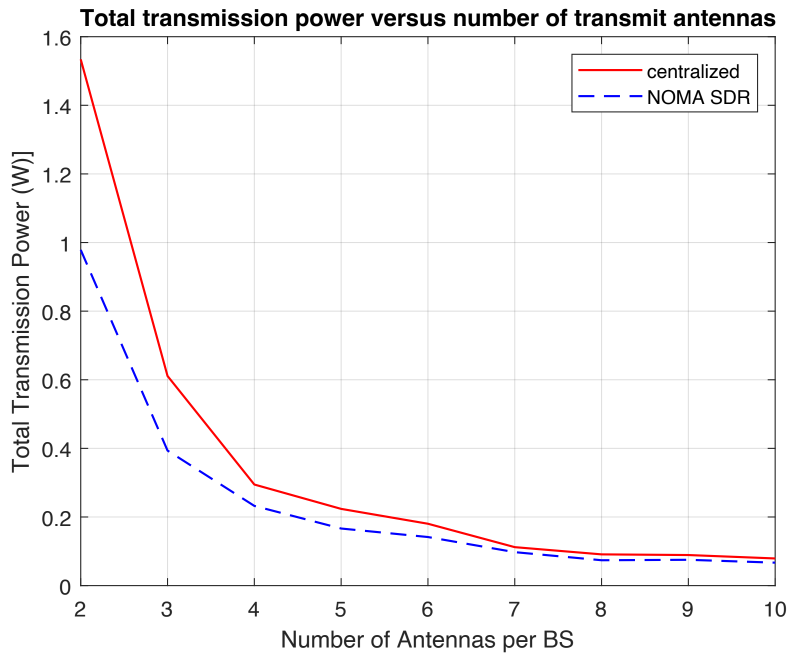


FIGURE 3.10: Total transmission power versus number of transmit antennas

3.2 Related Work

Numerous research has been conducted in a quest to identify the potential of NOMA in 5G and beyond. Presented in this section are relevant research studies on NOMA. The concept of NOMA was first explored in [39–42] for downlink transmission. The impact of user pairing was studied in [47] for a two user NOMA system. The authors explore the static allocation of transmission powers in a fixed and opportunistic user pairing schemes. The authors in [54] investigate the impact of power allocation on the fairness of downlink NOMA. They consider perfect channel state information (CSI) and average CSI. NOMA in MIMO systems has drawn significant attention and researchers have investigated the performance [55]. Previous research has been on the study of the comparison of MIMO NOMA over MIMO OMA , in terms of sum rate and ergodic sum rate, under differing conditions and constrictions [56–59]. The authors in [39] study the fundamentals of MIMO NOMA. The authors consider a 2 user NOMA cluster with single antenna users and 2 transmit antenna at the receiver. They use a fixed power allocation strategy at the transmitter and a two step interference cancellation method at the user receivers. The first step includes interference rejection combining technique (IRC) as a method for suppressing inter-cluster interference, while the second step includes SIC as a method for intra beamcluster interference cancellation. In [60], the authors consider a multi-user conventional MIMO NOMA model in which zero forcing beamforming was done. The authors propose a user clustering algorithm that takes into consideration the channel correlation and the gain differences among users.

Single cluster NOMA does not exploit the spatial degrees of freedom in MIMO NOMA and it increases the complexity of the beamforming design and SIC. Multi cluster MIMO NOMA has been explored in [57, 61, 62].In [63] the authors consider a downlink NOMA cellular system and further present a power allocation scheme that dynamically groups users. Their goal being to maximise the overall cell capacity subject to constraints on transmit power and data rate requirements and received power. Their simulations, similar to [64], present and put to light the advantages of NOMA in terms of spectrum efficiency. The authors in [65] apply NOMA to visible light communication and propose a user grouping scheme based on users locations. In [66] a low complexity multi-user grouping power allocation scheme is proposed as a way on enhancing the performance of users in the group. From their proposition they conclude that there is a trade off between user computational complexity and fairness. The authors in [67] propose a user pairing scheme for downlink NOMA is proposed by considering the channel correlation between users and the channel gain. The authors further optimise the pre-coding matrix in order to maximise the sum rate.

3.3 Conclusion

This chapter demonstrated the fundamentals of NOMA by exploring and defining the governing principles and strategies in both uplink and downlink NOMA. The chapter describes the power allocation strategies used in NOMA and further exhibits the superiority of NOMA over performance of conventional OFDMA. To begin with a comparison of the rate pairs, spectral efficiency and energy efficiency of NOMA over OFDMA is depicted in figure 3.3, 3.4 respectively. NOMA exhibits higher rate pairs and achieves higher spectral efficiency. In terms of sum capacity, a comparison on power allocation strategies for fixed, fair and fractional power allocation strategies is depicted in figure 3.8. Fractional transmit power allocation achieves a higher sum rate than it's other counterparts. The plot in Figure 3.10 depicts the number of antenna at the basestation versus the total transmission power. Observed from this plot is that NOMA outperforms the conventional approach, with the NOMA system leading in lower power usage. An increase in the number of antenna results in the gap between the two plots decreasing and thus a state of convergence occurs. This can be attributed to the increase in the number of nulls in the direction of the user resulting in less interference and hence lower power usage.

Chapter 4

Multi-auctioneer auction for downlink resource allocation

This chapter presents an auction mechanism which allows for multi-auctioneers, multi-bidders, and multi-item network environments. The mechanism is a user-centric solution this means that it accommodates heterogeneity in wireless networks in terms of topology, participants, items or services being offered. The mechanism is seen to improve cell edge user admission with reduced average transmitted power. Ultimately, the revenue of the service provider is equally improved.

4.1 System Model

The network considered is shown in Figure 4.1. The small cell access points (APs) are deployed to service their host users (HUs), especially at macro cell edge regions where coverage is an issue. It is assumed that the APs are operating in non-overlapping frequency bands, therefore; there is no intercell interference. It is further envisaged that there are open users (OUs) in the vicinity of the APs. The OUs have the privilege to connect to any of the APs of their choice by conducting concurrent auctions.

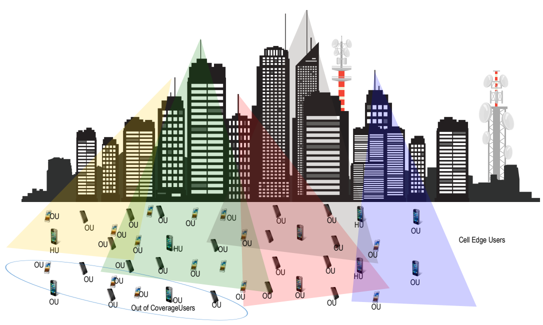


FIGURE 4.1: Distribution of users overa heterogeneous network under the assumption that OUs are cell edge users.

In this setting, there will be multiple-auctioneers and multiple-bidders, being the OUs and APs, respectively. Note that this model can have multiple items or a diverse class of items. In addition, a configuration of this sort offers a user-centric model which gives the OUs the autonomy to choose their preferred service providers at an agreed price. In this work, an auction environment is modeled wherein the OUs are auctioneers, the APs are the bidders, and the transmission power is the commodity on sale.

In order to provide seamless connections to the users, and a less complex system, it is assumed that the auction is held over one common frequency with error free communication. Thus, an assumption that the APs have antenna(s) reserved for auction activities and multiple antennas for data transfer is made. Similarly, each OU is equipped with two antennas, one for auction communication and the other for data transfer.

This work does not focus on the performance of the auction links since they are are assumed to be be error free. It is worth noting that an extension of this work may look at the impact of errors in the auction links on the overall performance of the system. An introduction to errors will ultimately introduce errors in the preference list and affect the ranking of the ask price. This may result in the user paying more. It should also be noted that the auction antennas can be used for data transfer whenever the user is not participating in any auction. This configuration will switch the multiple-input, single-output (MISO) system to a multiple-input, multiple-output (MIMO) system. Future work will address this configuration.

The APs are selling their transmission powers to the OUs by granting them access through NOMA. It is assumed that all OUs and HUs are equipped with successive interference cancellation (SIC) capabilities. Note that before admitting a OU, an AP will have already allocated some power to its HUs, which may include already admitted OUs. The APs can therefore admit new OUs with the provision that the performance of their HUs will not be degraded. All users are assumed to have a specific quality of service (QoS) requirement that needs to be met, otherwise they will not be admitted. The main objective is to design an auction mechanism which will let the APs admit the OUs with the aim to increase the number of admitted users at the cell-edges. Under this objective, the APs have to solve a surplus maximisation problem. Future work will look into scenarios wherein the APs solve a profit maximisation problem.

4.2 User-Centric Auction Environment

The proposed user-centric auction environment consists of OUs as auctioneers, APs as bidders, and transmission power as the traded item. Since the bidders are the ones who are selling the transmission power to the OUs, the auction setting is regarded as a reverse auction. Therefore; the proposals from the APs to the users will be termed as the asks. An ask from the s-th bidder to the g-th user is denoted as a_{sg}. Upon reception of the broadcasted invitations from the OUs, the APs compute the transmission powers required to serve each user falling under their coverage area using NOMA. The transmission power required by the s-th AP to serve g-th OU is denoted as p_{sg}. An ask a_{sg} will be determined with inference from the computed p_{sg}. Note that if each AP submits their asks a_{sg} such that $a_{sg} = p_{sg}$ for all the $s \in \mathcal{S}$ and $g \in \mathcal{G}$, where $\mathcal{S}$ is a set of all APs and $\mathcal{G}$ is a set of all OUs, then the network may achieve maximum surplus from the perspective of auction theory. But this will not manifest in real systems where in bidders may be very selfish and opt to shadow their ask values in order to win more OUs. At this juncture, it is assumed that the APs are rational and truthful. Hence, the assumption that the APs will submit truthful asks to OUs such that $a_{sg} = p_{sg}$.

Note that this configuration may not generate any margin on the APs side if the ask captures the exact cost for serving the users. But since the asks are computed with the hope that all users under the coverage of a particular AP will be admitted, those asks will form the maximum possible prices the users should pay in the presence of all other potential users. Note that when an AP loses one or moreOUs, it will require less power to serve its admitted users. This means that a difference between the asks prior to OUs admission and the transmission powers post admission will generate margins for the APs. Other mechanisms to improve the margins for the APs without affecting their faithfulness are discussed in the next section.

When an OU receives an ask values from its potential bidders in a set $S_g \subseteq \mathcal{S}$, it constructs a vector $\mathbf{a}_g = [a_{1g}, a_{2g}, \ldots, a_{S_g g}]$. Once all the asks have been received, the user sorts the elements in ascending order, to get a new vector $\mathbf{a}'_g = [a'_{sg}, a'_{2g}, \ldots, a'_{S_g g}]$ such that $a'_{ag} < a'_{bg}$ for $a < b$. The aim for each OU is to acquire services at the lowest which will maximize its utility u_g given as

$$u_g = v_g - a_{g\mathtt{min}} \tag{4.1}$$

where v_g is the value of the service requested by the OU and $a_{g\mathtt{min}} = \mathtt{argmin}\{\mathbf{a}'_g\}$. Since v_g and a_g are on different bases, v_g is converted to a currency base. This is done by multiplying v_g by k, where k is currency per unit of data rate. According to (4.1), the allocation rule is such that the OU will allocate (or associate) itself to the AP with the lowest ask value. Consequently, the proposed payment rule dictates that the OU must make a payment of $\texttt{pay} = a_{\texttt{gmin}}$ to the appointed AP. Thus far, all the system parameters of the proposed auction have been discussed, with the exception of the problem solved by AP which should lead to the mathematical approach for deriving the asks. The following section will address this gap.

4.3 NOMA Based Solution

The user-centric auction proposed above is integrated with a power domain multiplexing NOMA problem which will be solved at the APs sides. The derivation of the solution benchmarks on the solution proposed in [68] which proposed a novel bid-wait auction (BWA) mechanism. In particular, we will only refer to the BWA with adaptive preference profile (APP) since it was concluded to give better user admission. Let us consider a network with $S = |\mathcal{S}|$ APs deployed at the cell-edge of the macrocell. Each AP is equipped with $M + 1$ antennas where one antenna is reserved for transmission and reception in the auction link. The auction takes place over a common link which uses time-division multiple access scheme. This means there are timeslots for sending invitations to APs and for receiving ask values, respectively. Each auction participant gets to send and receive auction information over this auction link. The APs use NOMA for simultaneous downlink transmission of data using the remaining M antennas. Each AP is assumed to be serving one single antenna HU at any instance. Similarly, each OU has an extra antenna which is used for auction link transactions. A set of OUs, $G = |\mathcal{G}|$, uniformly distributed around the cell-edge of the macrocell is envisaged. The set of all OUs under the coverage of the s-th is denoted by $\mathcal{G}_s \subseteq \mathcal{G}$

Further the random channel vector from the s-th AP to the l-th user is denoted as $\mathbf{h}_{sl}$ where $l \in \{h, g\}$ with $g \in \mathcal{G}_s$. Therefore, the beamformer vector for the l-th user is denoted $\mathbf{w}_l \in \mathbb{C}^M$. The signal received at the l-th user from s-th AP is given by

$$y_l = \sum_{k=1}^{G_s+1} \mathbf{h}_{sl}^{\mathsf{H}} \mathbf{w}_k s_k + n_l \tag{4.2}$$

where n_l, is the zero-mean circularly symmetric additive white Gaussian noise at the end users represented as $n_l \sim \mathcal{CN}(0, \sigma^2)$. The σ^2 gives us the receiver noise power. It is assumed that s_k, which is the information symbol to the k-th user, is normalised such that $\mathbb{E}\{|s_k|\} = 1$. In NOMA setting, users at each AP are ordered such that i.e., $\|\mathbf{h}_{s1}\|_2 \leq \|\mathbf{h}_{s2}\|_2 \leq \ldots \|\mathbf{h}_{sG_s+1}\|_2$. The users with good channel condition detect and remove signals of other users with poorer channel conditions using successive interference cancellation (SIC). This implies that the l-th user should be able to successively detect and subtract l-1 users' signals and treat $l+1$ to G_s+1 users' signals as noise or interference. After cancellation of $l-1$ users' signals the residual signal which remains at the l-th user is

$$y_l = \mathbf{h}_{sl}^{\mathsf{H}} \mathbf{w}_l s_l + \sum_{r=l+1}^{G_s+1} \mathbf{h}_{sl}^{\mathsf{H}} \mathbf{w}_r s_r + n_l \tag{4.3}$$

The SINR of the l-th user at the s-th AP is therefore given

$$\mathsf{SINR}_l^s = \frac{|\mathbf{h}_{sl}^{\mathsf{H}} \mathbf{w}_l|^2}{\sum_{r=l+1}^{G_s+1} |\mathbf{h}_{sl}^{\mathsf{H}} \mathbf{w}_r|^2 + \sigma^2}. \tag{4.4}$$

In order for the AP to be able to compute the transmission power required to serve each OU under its coverage, the AP solves the power minimization problem given by

$$\begin{aligned} \underset{\{\mathbf{w}_l\}}{\texttt{minimize}} \quad & \sum_{l \in \mathcal{G}_s \cup h} \|\mathbf{w}_l\|_2^2 \\ \texttt{subject to} \quad & \mathsf{SINR}_l^s \geq \gamma_l^s, \ \ \forall l \in \mathcal{G}_s \cup h, \\ & \sum_{l \in \mathcal{G}_s \cup h} \|\mathbf{w}_l\|_2^2 \leq \varphi_s^{\max}, \end{aligned} \tag{4.5}$$

where $\varphi_s^{\max}$ is the maximum allowable or available transmission power at the s-th AP. This problem is not convex, mainly due to the SINR constraints. The whole problem can be made convex by rewriting the SINR constraints in second order (SOC) form as

$$\begin{aligned} \underset{\{\mathbf{w}_l\}}{\texttt{minimize}} \quad & \sum_{l \in \mathcal{G}_s \cup h} \|\mathbf{w}_l\|_2^2 \\ \texttt{subject to} \quad & \begin{bmatrix} \sqrt{1 + \frac{1}{\gamma_l^s}} \mathbf{h}_{sl}^{\mathsf{H}} \mathbf{w}_l \\ \mathbf{h}_{sl}^{\mathsf{H}} \mathbf{W}_s \\ \sigma \end{bmatrix} \succeq_{\mathrm{SOC}} 0, \ \ l \in \mathcal{G}_s \cup h, \\ & \Im(\mathbf{h}_{sl}^{\mathsf{H}} \mathbf{w}_l) = 0, \ \ \forall l, \\ & \sum_{l \in \mathcal{G}_s \cup h} \|\mathbf{w}_l\|_2^2 \leq \varphi_s^{\max}, \end{aligned} \tag{4.6}$$

where the notation $\succeq_{\mathrm{SOC}}$ is the generalized inequalities with respect to second-order cone, and $\Im(\cdot)$ is the imaginary part of the argument. Due to the resource constraints and competition, it is not always the case that an AP will be able to serve all users under its coverage. At this juncture note another difference between the proposed NOMA based solution with that which is presented in [68, 69]. In [68, 69], surplus maximization at the AP is claimed to be guaranteed first by solving the cardinality problem

$$\begin{aligned}
&\texttt{minimize} \; \|\mathbf{f}^s\|_1 \\
&\texttt{subject to} \begin{bmatrix} \sqrt{1+\frac{1}{\gamma_l^s}}\mathbf{h}_{sl}^{\mathsf{H}}\mathbf{w}_l + f_l^s \\ \mathbf{h}_{sl}^{\mathsf{H}}\mathbf{W}_s \\ \sigma \end{bmatrix} \succeq_{\mathrm{SOC}} 0, \;\; l \in \mathcal{G}_s \cup h, \\
&\qquad \mathbf{f}^s \geq 0 \;\; \forall l, \\
&\qquad \Im(\mathbf{h}_{sl}^{\mathsf{H}}\mathbf{w}_l) = 0, \;\; \forall l, \\
&\qquad \sum_{l\in\mathcal{G}_s\cup h} \|\mathbf{w}_l\|_2^2 \leq \varphi_s^{\max},
\end{aligned} \tag{4.7}$$

where $\mathbf{f}^s = [f_1^s, f_2^s, \ldots, f_{G+1}^s]$ is vector of slack variables, $\|\mathbf{f}^s\|_1$ is the ℓ_1-norm of $\mathbf{f}^s$. The vector is sorted in ascending order with the user having the smallest channel gain being the most preferred one. The users are then admitted sequentially by solving (4.6). Since the system should avoid disrupting the performance of the HU(s), their entries are set to zeros.The solution proposed here should be differentiated from the one proposed in [68, 69] since it; applies NOMA during admission, and does not go through cardinality problem in (7). Hence the solution avoids sequential admission of users which ultimately leads to multiple auction rounds. The solution proposed here, requires only one auction round. The proposed solution uses the sorted $\mathbf{f}^s$ as an ordering mechanism for SIC.

4.4 Numerical results

In this section the performance of the user-centric solution against the solution proposed in [68, 69] is demonstrated. We consider all the system values used in [68, 69]. For instance, the considered macrocell and APs have radii of 500m and 30m, respectively. The transmission power limit at each AP is 20 dBm. Figures 4.2 and 4.3 show that the proposed solution is comparable to that of the BWA-APP when the user SINR targets of the OUs is low or high in terms of user admission and revenue generation, respectively.

This is because at low SINR targets, the amount of interference cancelled through SIC is very minimal, hence leading to no or less significant change as compared to when there is no SIC. At higher SINR targets, the resources at the APs get depleted quickly under the admission of few OUs, consequently resulting to less admitted users. The $\mathbf{f}^s$ tends to sort the users in terms of the magnitude of orthogonality in the channels. This means the few admitted users already have less mutual interference

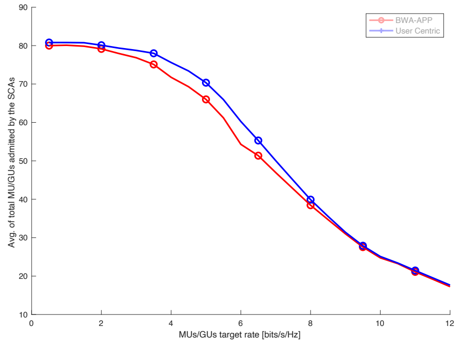


FIGURE 4.2: Median number of admitted HUs/OUsat APs.

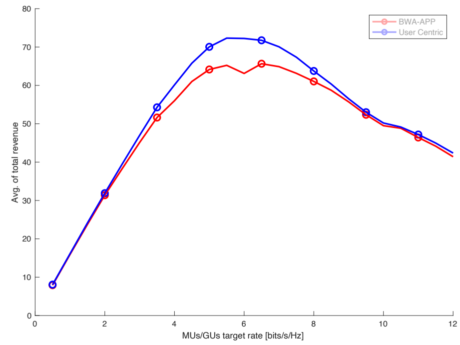


FIGURE 4.3: Average of the total revenue.

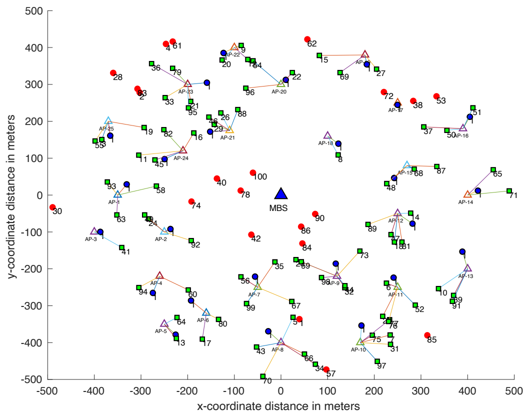


FIGURE 4.4: BWA-APP with NOMA Admission with target rate of 6 bits/s/Hz

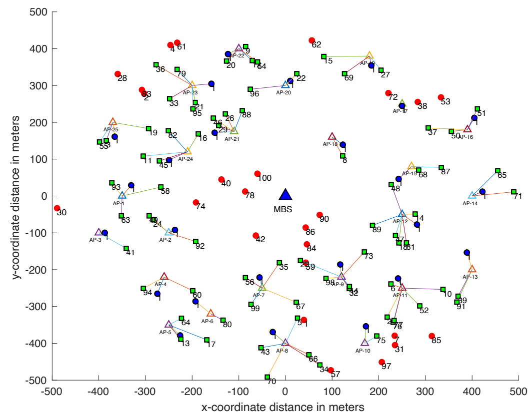


FIGURE 4.5: BWA-APP Admission with target rate of 6 bits/s/Hz

to each, making SIC less effective. In both Figures 4.2 and 4.3 the red line depicts the performance of the BWA-APP while the blue line depicts the performance of the BWA with NOMA. Figure 4.2 shows the average number of admitted HUs while the target data rate of the HUs/OUs is varied. The depiction shows that the BWA with NOMA admits more users than the BWA-APP. The particular reason for this circumstance is the ability of NOMA to accommodate more users as compared to the conventional orthogonal multiple access schemes. It can also be observed that as the target data rate increases the number of admitted HUs/OUs decreases. This is as a result of the relation between the HUs/OUs target data rate and the transmit power at the SCAs. As the target data rate of the HUs/OUs is increased, the total transmit power at the SCAs increases hence less admitted users. In contrast, Figure 4.3 shows the average generated revenue while the target data rate of the HUs/OUs is varied .As seen, in terms of revenue generation, the BWA with NOMA generates more revenue than the BWA-APP.

Figures 4.4 and 4.5 show user admission at a particular channel with the target rate of all the OUs set to 6 bits/s/Hz. At this target rate, it is expected that the proposed user-centric solution will outperform the BWA-APP as illustrated in the graph on Figure 4.2. For this particular channel realizations, note that admission of OUs is comparable at all APs except at following set of APs; $\{5, 6, 9, 10, 11, 12, 13, 20, 22\}$. In general, there is either more user admission or a different user admission set at any of the aforementioned APs. For instance, AP-10 managed to admit three (3) more OUs as compared to under BWA-APP. Above that, AP-10 managed to win OU number 77 from AP-11 when considering the proposed solution. The improved performance is owed to the application of NOMA and the proposed ordering scheme.

4.5 Conclusion

This work considered a multi-auctioneer, multi-item problem under NOMA settings. The problem is highly decomposed by considering mobile users as the auctioneers, who have the right to choose a network to connect to at any given time. This user-centric solution gives a decentralised system with better performance as compared to the baseline BWA-APP solution. The results demonstrate that at low and high SINR targets the proposed solution is comparable to BWA-APP. At lower SINR targets the amount of interference cancelled is minimal, hence leading to less significant change. At higher SINR targets there are more resources depleted at the APs hence admission of few OUs. This also means few admitted users already have less mutual interference making SIC less effective. The results continue on to demonstrate that at a particular channel the proposed user centric solution outperforms the BWA-APP as illustrated in Figure 4.3. At certain APs admission of OUs is comparable whilst at other not. At the APs listed, it is observed that in general there is either more user admission or a different user admission set. The proposed solution has some limitations or setbacks. Firstly, it relies on having a dedicated auction link, which may reduce the efficiency of the network. The effects of this limitation may be alleviated by using the auction link as a data link whenever there is no auction transactions. Secondly, the auction link may have errors which will result in poor user admission due to a inaccurate auction solution. Thirdly, in the solution the users need to be incentivised for performing SIC. A rewarding mechanism can be proposed to counter this challenge. Finally, NOMA scheme compromises physical layer security, and often, it over satisfies user's target rates. Our future works will consider closing the aforementioned gaps.

Chapter 5

Summary and future directions

5.1 Conclusion

The aim of this thesis was to design an auction mechanism which will let the APs admit the OUs with the aim to increase the number of admitted users at the cell edges. This is done by designing a power allocation mechanism that minimises the total transmit power at the base station and using an auction as the allocation mechanism. In the thesis the APs are selling their transmission powers to the OUs by granting them access through NOMA. The thesis contribution and findings are summarised as follows:

- Chapter 4 presents an auction environment wherein the OUs are auctioneers, the APs are the bidders, and the transmission power is the commodity on sale. The proposed network configuration deploys APs to service their HUs, especially at macro cell edge regions where coverage is an issue. There are open users OUs, in the vicinity of the APs, which have the privilege to connect to any of the APs of their choice by conducting concurrent auctions. In this setting, there is multiple-auctioneers and multiple-bidders, being the OUs and APs, respectively. The model can have multiple items or a diverse class of items. The configuration presents a user-centric model which gives the OUs the autonomy to choose their preferred service providers at an agreed price.

- The user-centric auction proposed is integrated with a power domain multiplexing NOMA problem which will be solved at the APs sides. The derivation of the solution benchmarks on the solution proposed in [68] which proposed a novel bid-wait auction (BWA) mechanism.

- This user-centric solution gives a decentralised system with better performance as compared to the baseline BWA-APP solution in [68]. However there are limitations due to the presence of errors in the auction link, lack of incentive for users performing SIC and the NOMA scheme compromising physical layer security,and often, over satisfying user's target rate.

5.2 Future work

- This work does not focus on the performance of the auction links since they are assumed to be error free. Extension of the work may look at the impact of errors in the auction link on the overall performance of the system. A introduction of errors may result in errors in the preference list and the ranking of the ask price. This could result in the user paying more or less.

- Incentives can be proposed for users to perform SIC so as to improve system performance. A incentive based system may present a system with increased capacity for self directed learning and autonomy. The authors in [70] provide a game theoretic framework for incentive based models while [7,71] have used auction based incentive mechanisms.

- Switching the configuration from MISO to MIMO by using auction antennas can be used for data transfer whenever the user is not participating in any auction. This may present further mathematical analysis and may improve system throughput and capacity.

- An important issue in current and future heterogeneous networks or environments is the seamless mobility. The scope of the thesis only considered static users therefor the handover scenario can be considered in future work.

- The thesis focused on downlink transmission. The formulation of uplink problems with application of similar solution methods may present further mathematical analysis.

References

[1] G. Shobha, R. R. Chittal, and K. Kumar, "Medical applications of wireless networks," *Second Int. Conf. Syst. Networks Commun. ICSNC 2007*, no. Icsnc, 2007.

[2] A. Vision, A. Elements, S. Issues, N. Mpstme, and J. Ram, "Internet of Things (IoT)," pp. 492–496, 2017.

[3] L. Zhou, J. J. P. C. Rodrigues, H. Wang, M. Martini, and V. C. M. Leung, "5g multimedia communications: Theory, technology, and application," *IEEE MultiMedia*, vol. 26, no. 1, pp. 8–9, 2019.

[4] U. B. Shukurillaevich, R. O. Sattorivich, and R. U. Amrillojonovich, "5g technology evolution," in *2019 International Conference on Information Science and Communications Technologies (ICISCT)*, Nov 2019, pp. 1–5.

[5] "A review on activities of fifth generation mobile communication system," *Alexandria Engineering Journal*, vol. 57, no. 2, pp. 1125–1135, 2018.

[6] M. Ghorbanzadeh, A. Abdelhadi, and C. Clancy, *Cellular communications systems in congested environments: Resource allocation and end-to-end quality of service solutions with MATLAB*, 2016.

[7] Y. Huang, C. Zhang, J. Wang, Y. Jing, L. Yang, and X. You, "Signal processing for mimo-noma: Present and future challenges," *IEEE Wireless Communications*, vol. 25, no. 2, pp. 32–38, 2018.

[8] T. Duong, X. Chu, and H. Suraweera, *Ultra-dense Networks for 5G and Beyond: Modelling, Analysis, and Applications*, 04 2019.

[9] M. Agiwal, A. Roy, and N. Saxena, "Next generation 5G wireless networks: A comprehensive survey," *IEEE Commun. Surv. Tutorials*, vol. 18, no. 3, pp. 1617–1655, 2016.

[10] *Design Principles for 5G Communications and Networks*. John Wiley Sons, Ltd, 2020, ch. 6, pp. 195–238.

[11] C. A. Gizelis and D. D. Vergados, "A survey of pricing schemes in wireless networks," *IEEE Commun. Surv. Tutorials*, vol. 13, no. 1, pp. 126–145, 2011.

[12] N. C. Luong, P. Wang, D. Niyato, Y. C. Liang, Z. Han, and F. Hou, "Applications of Economic and Pricing Models for Resource Management in 5G Wireless Networks: A Survey," *IEEE Commun. Surv. Tutorials*, vol. 21, no. 4, pp. 3298–3339, 2019.

[13] S. Parsons, J. A. Rodriguez-Aguilar, and M. Klein, "Auctions and bidding: A guide for computer scientists," *ACM Comput. Surv.*, vol. 43, no. 2, 2011.

[14] I. Koutsopoulos and G. Iosifidis, "Auction mechanisms for network resource allocation," *WiOpt 2010 - 8th Intl. Symp. Model. Optim. Mobile, Ad Hoc, Wirel. Networks*, pp. 554–563, 2010.

[15] D. E. Charilas and A. D. Panagopoulos, "A survey on game theory applications in wireless networks," *Comput. Networks*, vol. 54, no. 18, pp. 3421–3430, 2010.

[16] F. Vega-Redondo, "Economics and the theory of games," *Econ. Theory Games*, vol. 18, no. 2, pp. 1–512, 2003.

[17] J. Moura and D. Hutchison, "Cloud Computing @ Network core How GT could empower new styles of networking ? Fog Computing @ Network edge," *IEEE Commun. Surv. Tutorials*, vol. PP, no. c, p. 1, 2018.

[18] N. C. Luong, P. Wang, D. Niyato, Y. C. Liang, Z. Han, and F. Hou, "Applications of Economic and Pricing Models for Resource Management in 5G Wireless Networks: A Survey," *IEEE Commun. Surv. Tutorials*, vol. 21, no. 4, pp. 3298–3339, 2019.

[19] W. H. Kuo and W. Liao, "Utility-based optimal resource allocation in wireless networks," *GLOBECOM - IEEE Glob. Telecommun. Conf.*, vol. 6, no. January 2005, pp. 3508–3512, 2005.

[20] R. Ranji, E. Sitnikova, and F. d. Hartog, "How to define utility for use in practical wireless network resource trading platforms," in *2021 IEEE International Conference on Communications Workshops (ICC Workshops)*, 2021, pp. 1–6.

[21] A. Abdelhadi, A. Khawar, and T. C. Clancy, "Optimal downlink power allocation in cellular networks," *Phys. Commun.*, vol. 17, pp. 1–14, 2015.

[22] M. Xiao, N. B. Shroff, and E. K. Chong, "A utility-based power-control scheme in wireless cellular systems," *IEEE/ACM Trans. Netw.*, vol. 11, no. 2, pp. 210–221, 2003.

[23] N. Tadayon and S. Aïssa, "Radio resource allocation and pricing: Auction-based design and applications," *IEEE Transactions on Signal Processing*, vol. 66, no. 20, pp. 5240–5254, 2018.

[24] Y. Zhang, C. Lee, D. Niyato, and P. Wang, "Auction approaches for resource allocation in wireless systems: A survey," *Communications Surveys Tutorials, IEEE*, vol. 15, pp. 1020–1041, 01 2013.

[25] X. Zhou and H. Zheng, "TRUST : A General Framework for Truthful Double Spectrum Auctions," *IEEE INFOCOM 2009*, pp. 999–1007, 2009.

[26] X. Wang, L. Huang, H. Xu, and H. Huang, "Auction-based resource allocation for cooperative cognitive radio," *Comput. Commun.*, vol. 97, pp. 40–51, 2017.

[27] X. Zhang, D. Yang, G. Xue, R. Yu, and J. Tang, "Transmitting and Sharing : a Truthful Double Auction for Cognitive Radio Networks," *2018 IEEE Int. Conf. Commun.*, pp. 1–6, 2018.

[28] K. Elangovan and S. Subashini, "Double Auction Framework to Manage the Secondary Users in Cognitive Radio Networks (Crns)," vol. 7, pp. 935–940, 2018.

[29] Q. Shi, C. Comaniciu, and K. Jaffrès-Runser, "An Auction-based Mechanism for Cooperative Sensing in Cognitive Networks *," Tech. Rep.

[30] Q. Shi, C. Comaniciu, and K. Jaffres-Runser, "An auction-based mechanism for cooperative sensing in cognitive networks," *Wireless Communications, IEEE Transactions on*, vol. 12, pp. 3649 – 3661, 08 2013.

[31] S. G. Wang, P. Xu, X. H. Xu, S. J. Tang, X. Y. Li, and X. Liu, "TODA: Truthful online double auction for spectrum allocation in wireless networks," *2010 IEEE Symp. New Front. Dyn. Spectrum, DySPAN 2010*, no. May, 2010.

[32] Y. Zhu, J. Jiang, B. Li, and B. Li, "Rado: A randomized auction approach for data offloading via D2D communication," *Proc. - 2015 IEEE 12th Int. Conf. Mob. Ad Hoc Sens. Syst. MASS 2015*, pp. 1–9, 2015.

[33] C. Li, Q. Zhang, Q. Li, and J. Qin, "Price-Based Power Allocation for Non-Orthogonal Multiple Access Systems," *IEEE Wirel. Commun. Lett.*, vol. 5, no. 6, pp. 664–667, 2016.

[34] Z. Wang, C. Wen, Z. Fan, and X. Wan, "A Novel price-based power allocation algorithm in non-orthogonal multiple access networks," *IEEE Wirel. Commun. Lett.*, vol. 7, no. 2, pp. 230–233, 2018.

[35] R. Aldebes, K. Dimyati, and E. Hanafi, "Game-theoretic power allocation algorithm for downlink NOMA cellular system," *Electron. Lett.*, vol. 55, no. 25, pp. 1361–1364, 2019.

[36] G. Liu, R. Wang, H. Zhang, W. Kang, T. A. Tsiftsis, and V. C. Leung, "Super-Modular Game-Based User Scheduling and Power Allocation for Energy-Efficient NOMA Network," *IEEE Trans. Wirel. Commun.*, vol. 17, no. 6, pp. 3877–3888, 2018.

[37] A. Kilzi, J. Farah, C. Abdel Nour, and C. Douillard, "Mutual successive interference cancellation strategies in noma for enhancing the spectral efficiency of comp systems," *IEEE Transactions on Communications*, vol. 68, no. 2, pp. 1213–1226, 2020.

[38] A. Marzook, H. Mohammed, and H. Roomi, "Performance of non-orthogonal multiple access (noma) with successive interference cancellation (sic)," *Iraqi Journal for Electrical and Electronic Engineering*, vol. sceeer, pp. 152–156, 07 2020.

[39] A. Benjebbour, Y. Saito, Y. Kishiyama, A. Li, A. Harada, and T. Nakamura, "Concept and practical considerations of non-orthogonal multiple access (NOMA) for future radio access," *ISPACS 2013 - 2013 Int. Symp. Intell. Signal Process. Commun. Syst.*, pp. 770–774, 2013.

[40] R. Razavi, M. Dianati, and M. A. Imran, "Non-Orthogonal Multiple Access (NOMA) for future radio access," *5G Mob. Commun.*, pp. 135–163, 2016.

[41] A. Benjebbour, A. Li, Y. Kishiyama, H. Jiang, and T. Nakamura, "System-level performance of downlink NOMA combined with SU-MIMO for future LTE enhancements," *2014 IEEE Globecom Work. GC Wkshps 2014*, no. 1, pp. 706–710, 2014.

[42] A. Benjebbour, K. Saito, A. Li, Y. Kishiyama, and T. Nakamura, "Non-orthogonal multiple access (NOMA): Concept, performance evaluation and experimental trials," *Int. Conf. Wirel. Networks Mob. Commun. WINCOM 2015*, pp. 1–6, 2016.

[43] K. HIGUCHI and A. BENJEBBOUR, "Non-orthogonal multiple access (noma) with successive interference cancellation for future radio access," *IEICE Transactions on Communications*, vol. E98.B, no. 3, pp. 403–414, 2015.

[44] A. Benjebbour, A. Li, K. Saito, Y. Saito, Y. Kishiyama, and T. Nakamura, "Noma: From concept to standardization," in *2015 IEEE Conference on Standards for Communications and Networking (CSCN)*, 2015, pp. 18–23.

[45] L. Dai, B. Wang, Y. Yuan, S. Han, C. L. I, and Z. Wang, "Non-orthogonal multiple access for 5G: Solutions, challenges, opportunities, and future research trends," *IEEE Commun. Mag.*, vol. 53, no. 9, pp. 74–81, 2015.

[46] S. M. R. Islam, N. Avazov, O. A. Dobre, and K.-s. Kwak, "power NOMA," pp. 1–41.

[47] Z. Ding, P. Fan, and H. V. Poor, "Impact of User Pairing on 5G Nonorthogonal Multiple-Access Downlink Transmissions," *IEEE Trans. Veh. Technol.*, vol. 65, no. 8, pp. 6010–6023, 2016.

[48] Z. Q. Al-abbasi and D. K. C. So, "User-Pairing based Non-Orthogonal Multiple Access (NOMA) System," pp. 1–5, 2016.

[49] J. He and Z. Tang, "Low-complexity user pairing and power allocation algorithm for 5G cellular network non-orthogonal multiple access," *Electron. Lett.*, vol. 53, no. 9, pp. 626–627, 2017.

[50] Y. Saito, A. Benjebbour, Y. Kishiyama, and T. Nakamura, "System-level performance evaluation of downlink non-orthogonal multiple access (NOMA)," *IEEE Int. Symp. Pers. Indoor Mob. Radio Commun. PIMRC*, pp. 611–615, 2013.

[51] N. Otao, Y. Kishiyama, and K. Higuchi, "Performance of non-orthogonal multiple access with SIC in cellular downlink using proportional fair-based resource allocation," *IEICE Trans. Commun.*, vol. E98B, no. 2, pp. 344–351, 2015.

[52] T. Manglayev, R. Kizilirmak, and Y. H. Kho, "Optimum power allocation for non-orthogonal multiple access (noma)," 10 2016, pp. 1–4.

[53] S. Tao, H. Yu, Q. Li, X. Bai, and Y. Tang, "Power allocation of non-orthogonal multiple access based on dynamic user priority for indoor qos-guaranteed visible light communication networks," *Applied Sciences*, vol. 8, no. 8, 2018.

[54] S. Timotheou and I. Krikidis, "Fairness for Non-Orthogonal Multiple Access in 5G Systems," *IEEE Signal Process. Lett.*, vol. 22, no. 10, pp. 1647–1651, 2015.

[55] Z. Ding, F. Adachi, and H. V. Poor, "The Application of MIMO to Non-Orthogonal Multiple Access," *IEEE Trans. Wirel. Commun.*, vol. 15, no. 1, pp. 537–552, 2016.

[56] M. Zeng, A. Yadav, O. A. Dobre, G. I. Tsiropoulos, and H. V. Poor, "On the Sum Rate of MIMO-NOMA and MIMO-OMA Systems," *IEEE Wirel. Commun. Lett.*, vol. 6, no. 4, pp. 534–537, 2017.

[57] M. Zeng, A. Yadav, O. A. Dobre, G. I. Tsiropoulos, and H. V. Poor, "Capacity comparison between mimo-noma and mimo-oma with multiple users in a cluster," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 10, pp. 2413–2424, 2017.

[58] Y. Liu, G. Pan, H. Zhang, and M. Song, "On the capacity comparison between MIMO-NOMA and MIMO-OMA," *IEEE Access*, vol. 4, pp. 2123–2129, 2016.

[59] Q. Sun, S. Han, I. Chin-Lin, and Z. Pan, "On the Ergodic Capacity of MIMO NOMA Systems," *IEEE Wirel. Commun. Lett.*, vol. 4, no. 4, pp. 405–408, 2015.

[60] B. Kimy, S. Lim, H. Kim, S. Suh, J. Kwun, S. Choi, C. Lee, S. Lee, and D. Hong, "Non-orthogonal multiple access in a downlink multiuser beamforming system," *Proc. - IEEE Mil. Commun. Conf. MILCOM*, no. 2012, pp. 1278–1283, 2013.

[61] Z. Chen, Z. Ding, and X. Dai, "Beamforming for combating inter-cluster and intra-cluster interference in hybrid NOMA systems," *IEEE Access*, vol. 4, pp. 4452–4463, 2016.

[62] J. Choi, "Minimum power multicast beamforming with superposition coding for multiresolution broadcast and application to NOMA systems," *IEEE Trans. Commun.*, vol. 63, no. 3, pp. 791–800, 2015.

[63] M. S. Ali, E. Hossain, and D. I. Kim, "Non-Orthogonal Multiple Access (NOMA) for downlink multiuser MIMO systems: User clustering, beamforming, and power allocation," *IEEE Access*, vol. 5, pp. 565–577, 2017.

[64] M. S. Ali, H. Tabassum, and E. Hossain, "Dynamic User Clustering and Power Allocation for Uplink and Downlink Non-Orthogonal Multiple Access (NOMA) Systems," *IEEE Access*, vol. 4, pp. 6325–6343, 2016.

[65] X. Zhang, Q. Gao, C. Gong, and Z. Xu, "User grouping and power allocation for NOMA visible light communication multi-cell networks," *IEEE Commun. Lett.*, vol. 21, no. 4, pp. 777–780, 2017.

[66] L. Yao, J. Mei, H. Long, L. Zhao, and K. Zheng, "A novel multi-user grouping scheme for downlink non-orthogonal multiple access systems," *IEEE Wirel. Commun. Netw. Conf. WCNC*, vol. 2016-Septe, no. Wcnc, pp. 0–5, 2016.

[67] J. Kim, J. Koh, J. Kang, K. Lee, and J. Kang, "Design of user clustering and precoding for downlink non-orthogonal multiple access (NOMA)," *Proc. - IEEE Mil. Commun. Conf. MILCOM*, vol. 2015-Decem, pp. 1170–1175, 2015.

[68] B. Basutli and S. Lambotharan, "Auction based competition of hybrid small cells for dropped macrocell users," *IET Signal Processing*, vol. 11, 03 2017.

[69] B. Basutli, J. Chuma, and S. Lambotharan, "Network capacity enhancement in hetnets using incentivized offloading mechanism," *IEEE Access*, vol. PP, pp. 1–1, 07 2018.

[70] N. Shama and N. Saxena, "A review on game-theoretic incentive mechanisms for mobile data offloading in heterogeneous networks," *IETE Technical Review*, vol. 34, pp. 15–26, 12 2017.

[71] P. Li and S. Guo, "Incentive mechanisms for device-to-device communications," *IEEE Network*, vol. 29, pp. 75–79, 07 2015.