RESOURCE ALLOCATION FOR RELAY ASSISTED TRANSMISSION IN MILLIMETRE WAVE WIRELESS SYSTEMS

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STATEMENT OF CANDIDATE

I, (Md Shirajul Islam Sagar), declare that this report, submitted as part of the requirement for the award of Masters of Research (Engineering) in the Department of Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment at any academic institution.

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ABSTRACT

Conventional microwave bands below a frequency of 10 GHz are on the verge of saturation point. Thus, the global bandwidth shortage facing wireless carriers has motivated the exploration of the underutilized millimeter wave (mmWave) frequency spectrum for future broadband cellular communication networks. The mmWave frequency spectrum brings the possibility of developing the science for gigabit wireless networks. However, mmWave communication suffers from significant attenuation and shortage of multipath in NLOS transmissions and so mmWave wireless systems need to rely on LOS-propagation to achieve high data rates. In NLOS environments, relay techniques can compensate for severe path loss to improve the system throughput. This thesis investigates the use of directional antennas both at the transmitter and receiver and relays to compensate for severe path loss in NLOS environments. This thesis derives closed-form equations for the optimal allocation of antennas for beamforming to maximize capacity between a given source and destination in order to achieve high energy efficiency. The use of Lagrange Multipliers is also introduced to study the optimal transmit power at the source along with the optimal number of transmit antennas to obtain maximum capacity between a source-destination pair.

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Chapter 1

Introduction and Motivation

The global bandwidth shortage facing wireless carriers has motivated the exploration of the underutilized millimeter wave (mmWave) frequency spectrum for future broadband cellular communication networks. Communications at 60 GHz band is referred to as millimeter-wave (mmWave) communications because the wavelength at this band is in the order of millimetres [3]. Demand for cellular data has been growing at an astonishing pace; with conservative estimates ranging from 40% to 70% year upon year increase in traffic [4] [5] [6]. Long Term Evolution (LTE), 3GPP and 4G cellular technology rollouts are limited by spectrum availability. LTE uses lots of bandwidth, and carriers only have so much spectrum. The cost of buying new spectrum is high, and the amount of spectrum is limited. Since conventional microwave bands below a frequency of 10 GHz are likely to reach saturation point within just a few years, it warrants the need for radio system designers to push towards ever- higher segments of the frequency spectrum in an attempt to increase capacity. Over the past decade, the wireless communication community has become increasingly interested in the worldwide 60 GHz radio frequency band for its potential to offer gigabit wireless networks [7] [8].

One fundamental distinguishing feature of mmWave communications is the high propagation loss. As the free space propagation loss increases proportionally as the square of the carrier frequency, the propagation loss at mmWave band is much higher than that at lower frequency bands, e.g., 28 dB higher than at 2.4 GHz [3]. The path loss becomes more serious since oxygen absorption peaks at 60 GHz [3]. Since NLOS transmissions in 60 GHz channels suffer from significant attenuation and shortage of multipath, mmWave wireless systems need to rely on LOS propagation to achieve high data rate. In the event of moving obstacles blocking the LOS propagation between the source and the destination, relaying can be used for data transmission. As mmWave signals attenuate significantly over distance, it is beneficial to employ relaying to transmit the signal from the source to the destination to reduce signal loss due to attenuation. Relay techniques will be discussed in more depth in sections to follow.

The capabilities of wireless communications continue to drive human productivity and innovation in many areas. Communication at mmWave operating frequencies represents the most recent game-changing development for wireless systems. Interest in mmWave is in its infancy and will be driven by consumers who continue to desire higher data rates for the consumption of media while demanding lower delays and constant connectivity on wireless devices. mmWave wireless communication is an enabling technology that has myriad applications to existing and emerging wireless networking deployments. New 60 GHz wireless products are exciting, not only because of their ability to satisfy consumer demand for high-speed wireless access, but also because 60 GHz products may be deployed worldwide, thanks to harmonious global spectrum regulations.

In the early days of 60 GHz wireless communication, many viewed fixed wireless broadband (e.g., fiber backhaul replacement) as the most suitable 60 GHz application, due to the requirements for highly directional antennas to achieve acceptable link budgets [3]. Today, however, the propagation characteristics that were once seen as limitations are now either surmountable or seen as advantages. For example, 60 GHz oxygen absorption loss of up to 20 dB/km is almost negligible for networks that operate within 100 meters [3]. The shift away from long-range communications actually benefits close-range communications because it permits aggressive frequency reuse with simultaneously operating networks that do not interfere with each other. Furthermore, the highly directional antennas required for path loss mitigation can actually work to promote security as long as network protocols enable antenna directions to be flexibly steered. Thus, many networks are now finding a home at 60 GHz for communication at distances less than 100 m. Also, the 20 dB/km oxygen attenuation at 60 GHz disappears at other mmWave bands, such as 28, 38, or 72 GHz, making them nearly as good as todays cellular bands for longer-range outdoor mobile communications. Recent work has found that urban environments provide rich multipath, especially reflected and scattered energy at or above 28 GHz. When smart antennas, beamforming, and spatial processing are used, this rich multipath can be exploited to increase received signal power in NLOS propagation environments. Recent results by Samsung show that over 1 Gbps can be carried over mmWave cellular at ranges exceeding 2 km; thus demonstrating that mmWave bands are useful for cellular networks [3].

1.1 Challenges

Despite the potential of mmWave cellular systems, there are a number of key challenges to realizing the vision of cellular networks in these bands.

Shadowing: A more significant concern for range is that mmWave signals are extremely susceptible to shadowing. For example, materials such as brick can attenuate signals by as much as 40-80 dB [9] and the human body itself can result in a 20-35 dB loss [10]. On the other hand, humidity and rain fades are common problems for long-range mmWave backhaul links.

Rapid channel fluctuations and intermittent connectivity: For a given mobile velocity, channel coherence time is linear in the carrier frequency [3], meaning that it will be very small in the mmWave range.

Processing power consumption: A significant challenge in leveraging the gains of multi-antenna, wide-bandwidth mmWave systems is the power consumption in the analog-to-digital (A/D) conversion. Power consumption generally scales linearly in the sampling rate and exponentially in the number of bits per samples [11] [12].

1.2 Scope and Aims

The benefits of high data rates and improved reliability via wireless communication are limited by its inherent drawbacks, including path loss, fading and interference. One promising strategy for overcoming these problems is to deploy nodes in the region between a transmitter and its intended receiver. These intermediate nodes can improve communication for this transmitter-receiver pair by receiving a transmitted message, processing it and relaying the processed output to the receiver. This transmission strategy, known as relay-assisted communication, can be especially beneficial when the transmitter-receiver pair are either separated by a large distance or when a large obstruction blocks the path between them. In non-line-of-sight (NLOS) environments, relay techniques can compensate for severe path loss to improve the system throughput.

mmWave uses antenna arrays and beamforming to extend the range of communication. We want to make use of directional antennas both at the transmitter and receiver and relays to compensate for severe path loss in non-line-of-sight (NLOS) environment. We also want to study the optimal allocation of antennas for beamforming to maximize capacity between a given source and destination in order to achieve high energy efficiency. We also want to investigate techniques for determining the optimal number of antennas needed, how to allocate power for a single link and also for the total power allocation for the path from source to destination via relay. In NLOS scenarios, the throughput performance improves using two relay paths. The interference from nearby mmWave nodes can be small due to shorter transmission distance of mmWave signal as well as the directional beamforming technique used at both transmitters and receivers [13].

Our proposed topology of the network is depicted in Figure 3.1, where the users communicates to base-station via another user acting as a relay. We assume half-duplex communication with both the users and base-station equipped with antenna arrays.

We are going to use relays with fixed power allocation to find out optimal antenna allocation. We are also going to study this problem of optimal antenna allocation for relays using water filling power allocation method. However, we are going to study optimal power and antenna allocation using relays with automatic gain control. We also envisage to study the effect of angle error in angle of departure for signal beams has on ergodic capacity.

1.3 Contributions

In this section, we are going to briefly talk about research outcomes without much technical details. The section will also discuss short and long-term impact of the research undertaken. The primary motive of this thesis was to formulate a comprehensive research problem that we could work on for a Masters of Research degree.

- We devised methods for optimally allocating antennas and power in network with one base station (BS), two relays and one user node, where two-hop relay topology is used. We considered Amplify & Forward relaying strategy that can operate in one of the three modes.
  - Fixed gain relay with fixed power allocation: Antenna allocation
  - Fixed gain relay using water filling power allocation: optimal power and antenna allocation
  - Fast AGC (Automatic Gain Control) relay using grid method: optimal power and antenna allocation
- We constructed a system model that includes the following
  - We developed a single relationship between angle of arrival and angle of departure irrespective of their quadrant positions. (i.e 1st, 2nd, 3rd or 4th)
  - Derived formula for array factor
  - We used the Matlab simulation tool to compute Noise Figure at the relay and destination.
  - Path loss models
  - Fading models
- We introduced the idea of angle error in angle of departure to change the direction beam and studied how that affect the ergodic capacity.
- Finally, we explored the idea of Lagrange Multipliers in constrained optimisation problems and derived optimal power allocation scheme for our Amplify & Forward relaying method.
- This thesis also provides the foundation and direction for future research problems on the topic.

1.4 Applications/scenarios

Video signals demand the greatest bandwidth and, accordingly, a higher data rate. Speeds of many gigabits per second are needed to transmit 1080p high definition (HD) video. That data rate can be reduced if video compression techniques are used prior to transmission. Then, data rates of several hundred meagbits per second can get the job done, but usually at the expense of the video quality.

Compression techniques invariably diminish the quality to allow available wireless standards like Wi-Fi 802.11n to be used. Standards like 802.11ac that use greater bandwidth in the 5-GHz band are now available to achieve gigabit data rates [14]. Millimeter-wave technologies make gigabit rates commonplace and relatively easy to achieve, making uncompressed video a reality.

Common applications include video transmission from a set-top box (STB) to an HDTV set or transmission between a DVD player and the TV set or from a game player to the TV set. Video also can be sent wirelessly from a PC or laptop to a video monitor or docking station. Transmitting signals from a laptop or tablet directly to the HDTV screen is popular as well. Other applications include wireless HD projectors and wireless video cameras. Millimeter-wave technologies allow the wireless transmission of popular video interfaces such as HDMI 1.3 or DisplayPort 1.2. A wireless version of PCI Express is also available.

There is now considerable interest in implementing a wireless version of USB 3.0. It is becoming the interface of choice not only on PCs and tablets but also TV sets and other consumer gear. USB 3.0 specifies a maximum rate of 5 Gbits/s with about 80% of that rate being achieved in a real application. A 10-Gbit/s USB version could be in the works as well. Wouldn't it be nice to have a millimeter-wave dongle that could achieve those rates?

The 60-GHz unlicensed industrial-scientific-medical (ISM) band from 57 to 64 GHz is getting lots of attention. It is already being used for wireless backhaul, and greater use is expected. Two short-range wireless technologies are also addressing this bands potential: IEEE 802.11ad and WirelessHD.

Device to device (D2D) communications are expected to be an essential feature of mmWave 5G cellular networks, to improve network capacity and build connections between two wireless devices. Due to the directional antenna and high propagation loss, mmWave communication has relatively low multi-user interference (MUI), which can support simultaneous communications. By allowing multiple concurrent D2D links, the network capacity can be further improved [15].

1.4.1 IEEE 802.11ad and WiGig

The designation 802.11ad is an extension of the IEEEs popular 802.11 family of wireless local-area network (LAN) standards generally known as Wi-Fi. The 11ad version is designed for the 60-GHz band [16]. It is backward compatible with all previous versions including 11a/b/g/n/ac, as the media access control (MAC) layers of the protocol are similar. The 11ad version is also known by its trade name WiGig. The Wireless Gigabit (WiGig) Alliance supports and promotes 11ad, and it recently announced plans to consolidate with the Wi-Fi Alliance under the Wi-Fi Alliance banner.

WiGig uses the unlicensed ISM 60-GHz band from 57 to 64 GHz, divided into four 2.16-GHz bands. The primary modulation scheme, orthogonal frequency division multiplexing (OFDM), can support a data rate up to 7 Gbits/s, making it one of the fastest wireless technologies available. The standard also defines a single carrier mode that uses less power and is a better fit for some portable handheld devices. The single carrier mode can deliver a data rate up to 4.6 Gbits/s. Both speeds permit the transmission of uncompressed video. The WiGig specification also provides security in the form of the Advanced Encryption Standard (AES).

Because of the small antenna size at 60 GHz, gain antennas are normally used to boost signal power and range. The maximum typical range is 10 meters. WiGig products use antenna arrays that can provide beamforming. This adaptive beamforming permits beam tracking between the transmitter and receiver to avoid obstacles and maximize speed even under changing environmental conditions.

1.5 Thesis Overview

The remainder of the thesis is organized as follows. Chapter 2 gives background information and discusses related work. Topics discussed include mmWave Communications, relay networks, relaying in mmWave, energy efficiency in wireless networks, Line-of-sight Transmission, Rician fading Model, Channel Capacity Model. The chapter also includes sections on antenna arrays and beamforming techniques. Finally, the chapter concludes with applications of mmWave wireless systems.

Chapter 3 discusses the primary issue this thesis intends to solve. It starts with explaining the system model. The chapter breaks down our desired network topology into smaller blocks of problem and solves them. In most cases, the solution to the problem is either deriving mathematical equations or writing matlab functions. Matlab functions are provided along with explanation where-ever deemed necessary. The chapter also thoroughly defines all the system parameters.

Chapter 4 includes the formulation of different optimisation problems and it is the most important chapter of all. The chapter also includes mathematical analysis of the solution to the optimisation problems. This chapter also discusses in detail the simulation results obtained using Matlab to reinforce the mathematical analysis.

Chapter 5 includes the conclusion that summarizes the thesis and looks at its contribution followed by the formulation of possible future research problems.

Chapter 2

Background and Related Work

This chapter gives an essential background on some of the topics related to the thesis and explores other researchers work which can be linked to the problem considered. Giving a comprehensive literature review is impractical; instead, focus is on studies which have a strong connection to the thesis. Other important studies are also referenced.

2.1 mmWave Communications

Communications at 60 GHz band is referred to as millimeter-wave (mmWave) communications because the wavelength at this band is in the order of millimetres.Over the past decade, the wireless communication community has become increasingly interested in the worldwide 60 GHz radio frequency band for its potential to offer gigabit wireless networks [7] [8]. Most of the cellular networks work below 3 GHz which has been fully occupied already. Bandwidth shortage has motivated the exploration of the rich millimeter wave (mmWave) frequency spectrum which ranges from 3 to 300 GHz. There are potential dozens of GHz available frequency resources at 28, 38, 45, and 60 GHz. It is expected that the gains of network capacity up to 10 times can be obtained from mmWave frequency spectrum [17], which is quite attractive for 5G systems. There are already ongoing academic and industrial efforts to study the feasibility of mmWave communications. Samsung has demonstrated over 1 Gbps download rate at 28 GHz frequency band [18]. Although some progress in mmWave communications has been made, there is still a long way before realizing practical 5G mmWave communications. The main technical obstacles include the following aspects:

1. Propagation characteristics and measurements: Since the radio waves of different frequency bands have different propagation characteristics, the channel models of traditional cellular wireless communication cannot be directly applied to mmWave communications [19]. The first task of mmWave communications is to understand the propagation characteristics. Several measurements campaigns have been conducted [20] [21] [22]. The atmospheric attenuation is 0.0140 dB/km at mmWave frequency, which is much higher than 0.00140 dB/km of frequency bands used by

traditional cellular networks. The rain attenuation up to 0.00140 dB/km varies with frequency and rain rate at mmWave frequency, which is much higher than 00.001 dB/km level of traditional used frequency bands; the reflection coefficients are up to 0.896 outdoor and 0.74 indoor separately, which are still higher than traditional used frequency bands. The path loss exponent is slightly higher than 2 for LOS channels and 4 for NLOS but in some specific environments, such as in vehicles, the path loss exponent can be up to 7 [23]. mmWave communications suffer from severe outage when distance is beyond 200 m. From the above discussion, mmWave communications suffer from severe path loss for NLOS, rapid channel fluctuations and intermittent connectivity, and is extremely sensitive to shadowing. Thus, it seems that the effective communication distance of mmWave signals is within 200 m [20]. However, the gain realized through antenna beamforming can compensate for the excessive path and penetration losses at millimeter wave frequencies [24].

2. Antenna arrays: Despite the unfavorable mmWave propagation characteristics, it can be used for short range communication in 5G systems if steerable directional antennas are employed. Antenna arrays are considered as a key technique to achieve mmWave communications. Large antenna arrays with beamforming [25] [26] [27] can provide sufficient gains to overcome the severe propagation loss. However, the narrow beams increase sensitivity to movement caused by pole sway and other environmental concerns. Besides, it also needs to adapt promptly when beams are blocked, which increases the processing complexity. Hence, high efficiency low complexity adaptive antenna array processing algorithms need to be further studied.

2.2 Relays in wireless communication

Relay networks are mainly justified due to the need to increase the coverage area and the system throughput, while having an acceptable transmit power. Moreover, deploying multiple relays makes it possible to send the information through several independent wireless links, thereby increasing the system reliability.

To facilitate the demand for a higher spectrum and power efficiency arising from the next generation mobile communication system, the introduction of relay-aided communication into the existing cellular infrastructure is considered as the most practical improvement under high rate and coverage [3]. In comparison with the legacy cellular network, relay-aided communication network enjoys relative advantages over coverage efficiency, operation cost and transmission capacity. Transmission in relay-aided system falls into three types: the three-terminal transmission model, two-hop multi-relay parallel transmission model, and multi-hop multi-relay transmission model.

Relays that receive and retransmit the signals between base stations and mobiles can be used to increase throughput extend coverage of cellular networks [28] [29]. Relays do not need wired connection to network thereby offering savings in operators backhaul costs. Mobile relays can be used to build local area networks between mobile users under the umbrella of the wide area cellular networks [28].

AF relay amplifies the received signal from the source and transmits it to the destination without doing any decoding [3]. Therefore, it is also called non-regenerative relaying. On the other hand, DF relay decodes, re-modulates and retransmit the received signal whereas in CF relaying scheme, the relay quantizes the received signal in one block and transmits the encoded version of the quantized received signal in the following block. AF introduces lower delays when compared to DF and CF. Also, AF requires much less computing power as no decoding or quantizing operation is performed at the relay side.

From signal processing point of view AF relays offer interesting challenges, especially when the AF relay operates in full-duplex mode: Adaptive algorithms are required for loop-back interference cancellation [3]. Furthermore, the effect of interference must be incorporated into analytical performance studies in future. Half-duplex communication is considered in this research. However, full-duplex communication will be considered in future.

2.2.1 Three-Terminal Transmission Model

The three-terminal transmission model was first proposed by Van der Meulen Cover and El Gamal gave its detailed theoretical derivation and performance analysis [1]. Several researchers have made detailed analysis of three-terminal communications system under different channel fading environments in recent years [30]. In the three-terminal transmission model as shown in Figure 2.1, specific channel fading characteristics influences system performance; the working mode of relays also plays a very important role.

According to signal receiving and transmitting, relaying has two basic modes: analogue and digital. The analogue relaying is also called non-regenerative relaying, in which signals are not required to be digitalized before sent by relays. AF is a kind of analogue relaying. Conversely, a relay, using digital relaying model, decodes and encodes signals before sending them out. Therefore, digital relaying is also called regenerative relaying, which DF and CC belong to.

The relay location should be used to select a proper relaying model to improve communications quality. For example, if a relay is near to user, it may select AF and use strong processing capability of BS or RS to make accurate detection and decoding; if a relay is near to BS, DF may be used to improve diversity for anti-fading [31].

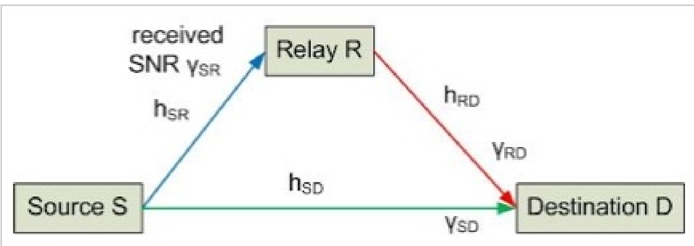

Figure 2.1: Three-terminal transmission model [1]

2.2.2 Two-Hop Multi-Relay Parallel Transmission Model

In this model as depicted in Figure 2.2, BS communicates with multiple users through multiple parallel relays [1]. The relays can be either user terminals or special relay stations. The user relays have their own demands on communications when they cooperate to transfer other users messages; the relay stations just receive and send a minimum of control signaling for channel synchronizing and channel message transferring, besides transferring users data. This is the biggest difference between user relays and RSs.

The relay-station-based two-hop multi-relay parallel transmission network can use the inter-relay space diversity to provide multiple users with multiple data links. The network may be regarded as a distributed multi-antenna system. Different from legacy distributed multi-antenna systems in which wired fiber networks are used for communications, RSs in the network use radio links to communicate with BS. Highly effective receiving/transmitting mechanism that guarantees the transmission performance of the first hop is important to the overall system transmission capability.

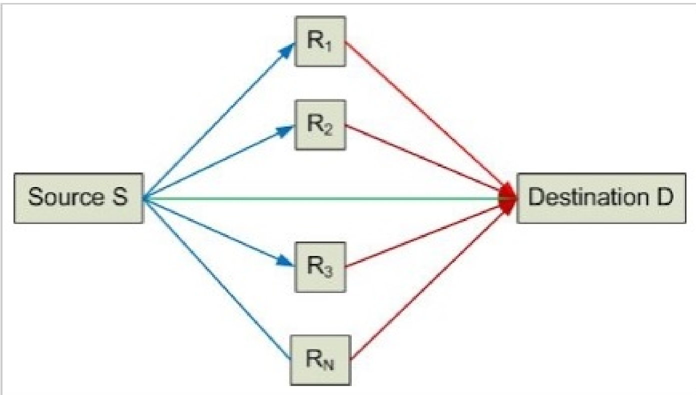

Figure 2.2: Two-hop multi-relay parallel transmission model [1]

2.3 Relay Selection

It is well known that relay technology is an effective way to combat severe fading caused by NLoS transmission environments. As the key of relay technology, the relay selection is consequently the core of improving the performance of 60 GHz mmWave radio. Extensive researches for relay selection have been proposed already. The following sections discusses few of the relay selections already in use. The opportunistic relay selection strategy [32] switches to the channel with the maximum signal-to-noise ratio (SNR) but without considering the reliable channel state information (CSI) acquiring. Similarly, the max-min relay selection in [33], selects a relay-capable node in the event that the worse one of source-relay (S-R) and relay-destination (R-D) channel conditions is the best among all the potential relays without the acquirement of CSI. While, the nearest neighbor selection policy [34] extracts the relays only based on the geography distances between S-R and

R-D without instantaneous CSI. Several relay selection techniques have been proposed in literature for relay aided transmission, namely random relay, best relay and optimal relay [35].

2.4 mmWave Communications and Relaying

In mmWave indoor communications, signals are exposed to heavy attenuation and cannot penetrate through walls and many obstacles like human bodies. The LOS propagation path between two 60 GHz nodes may completely be blocked by surrounding obstacles and humans [36] [37].

A 60 GHz system has to deal with 22 dB greater free-space path loss than an equivalent 5 GHz system since the propagation loss increases with the square of the carrier frequency [38]. Diffracted, scattered signals do not contribute to received power and the penetration loss in the 60 GHz band is also very high [39]. As diffracted, scattered and second order reflection components are ineffective for 60 GHz channel AWGN channel model is sufficiently accurate for Line of Sight (LOS) link [40]. Influence of human activity on 60 GHz wireless links in a real indoor environment is studied in [45] and it is observed that links are blocked for 1%-2 % of overall time in a regularly crowded scenario. This is due to high attenuation in direct links in the presence of human bodies on the path [41]. The future indoor wireless networks planned to utilize 60 GHz technology will especially be prone to link obstructions by mobility of the residents. To mitigate the link obstructions in 60 GHz networks, use of additional access units may be a solution [37] . Such architectures require additional costs and have overhead in terms of complexity and interference. Other than increasing the number of deployed access units, using dedicated relay stations is another method. In this scheme, relay stations are used to relay packets when there is no line-of-sight between the source and the destination.

Use of non regenerative relays for ad hoc networks is addressed in [42]; the contribution of relaying on power saving and multiple access interference reduction is illustrated in [42]. Covering longer distances while maintaining a certain channel quality without a relay device requires transmit power increase which is not preferred in most of the cases. Regenerative or non regenerative relays can be deployed according to complexity requirements and available resources for specific applications. The authors address the use of non regenerative relays for ad hoc networks and illustrate the contribution on power saving and multiple access interference reduction in [42]. Using relay also provides opportunity to trade capacity, processing power for connectivity [42]. An indoor WPAN is examined and a multi-hop MAC architecture is proposed in [43] for 60 GHz communication.

Using relay nodes provides advantages on amount of path loss due to nonlinear relation between distance and path loss. Despite extra required processing capacity and imposed delay; using a relay device in the network is evaluated for the sake of connectivity in the network. Delay imposed by relaying degrades network throughput by a factor of two where throughput degradation due to an obstacle causing 10 dB attenuation is a factor of ten [40]. It is possible to bypass an obstacle and keep connectivity of network via relay.

Considering the spread of network nodes in a home network two hop communication is satisfactory for majority of cases [44]. One relay can enhance connectivity of home networks sufficiently which also enables simplification in multi-hop routing algorithms.

In conventional communication systems, relay aided transmission has been regarded as an effective way to increase the coverage probability, throughput and transmission reliability of wireless networks [35].

2.5 Antennas

2.5.1 Multi-Antenna Configurations

Multi-antenna techniques can be seen as a joint name for a set of techniques with the common theme that they rely on the use of multiple antennas at the receiver and/or the transmitter, in combination with more or less advanced signal processing. Multi-antenna techniques can be used to achieve improved system performance, including improved system capacity (more users per cell) and improved coverage (possibility for larger cells), as well as improved service provisioning for example, higher per-user data rates.

An important characteristic of any multi-antenna configuration is the distance between the different antenna elements, to a large extent due to the relation between the antenna distance and the mutual correlation between the radio-channel fading experienced by the signals at the different antennas.

Multiple antennas at the transmitter and/or the receiver can be used to shape the overall antenna beam (transmit beam and receive beam respectively) in a certain way for example, to maximize the overall antenna gain in the direction of the target receiver/transmitter or to suppress specific dominant interfering signals. Such beamforming can be based either on high or low fading correlation between the antennas, as is further discussed in later sections of this thesis.

Multiple Receive Antennas

Perhaps the most straightforward and historically the most commonly used multi-antenna configuration is the use of multiple antennas at the receiver side. This is often referred to as receive diversity or R_X diversity even if the aim of the multiple receive antennas is not always to achieve additional diversity against radio-channel fading.

Multiple Transmit Antennas

As an alternative, or complement, to multiple receive antennas, diversity and beamforming can also be achieved by applying multiple antennas at the transmitter side. The use of multiple transmit antennas is primarily of interest for the downlink that is, at the base station. In this case, the use of multiple transmit antennas provides an opportunity for diversity and beamforming without the need for additional receive antennas and corresponding additional receiver chains at the terminal. On the other hand, due to complexity the use of multiple transmit antennas for the uplink that is, at the terminal is less attractive. In this case, it is typically preferred to apply additional receive antennas and corresponding receiver chains at the base station.

2.6 Beamforming Techniques

Beamforming or spatial filtering is a signal processing technique used in sensor arrays for directional signal transmission or reception [45].

To change the directionality of the array when transmitting, a beamformer controls the phase and relative amplitude of the signal at each transmitter, in order to create a pattern of constructive and destructive interference in the wavefront. The simple type of beam former utilizes power dividers, power combiners and phase shifters as shown in Figure 2.3.

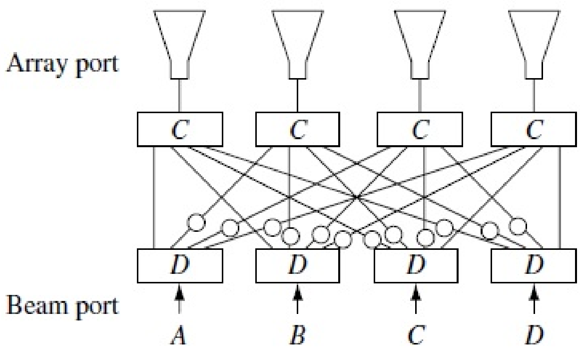

Figure 2.3: Simple Beamforming Network

Beamforming techniques can be broadly divided into two categories:

1. Conventional (fixed or switched beam) beamformers
2. Adaptive beamformers or phased array
    - Desired signal maximization mode
    - Interference signal minimization or cancellation mode

Conventional beamformers use a fixed set of weightings and time-delays (or phasings) to combine the signals from the sensors in the array, primarily using only information about the location of the sensors in space and the wave directions of interest. In contrast, adaptive beamforming techniques generally combine this information with properties of the signals actually received by the array, typically to improve rejection of unwanted signals from other directions. This process may be carried out in either the time or the frequency domain.

2.6.1 Phased Array

In antenna theory, a phased array is an array of antennas in which the relative phases of the respective signals feeding the antennas are varied in such a way that the effective radiation pattern of the array is reinforced in a desired direction and suppressed in undesired directions.

2.6.2 Transmitter-Side Beamforming

If some knowledge of the downlink channels of the different transmit antennas (more specifically, some knowledge of the relative channel phases) is available at the transmitter side, multiple transmit antennas can, in addition to diversity, also provide beamforming that is, the shaping of the overall antenna beam in the direction of a target receiver. In general, such beamforming can increase the signal strength at the receiver with up to a factor N_T - that is, in proportion to the number of transmit antennas. When discussing transmission schemes relying on multiple transmit antennas to provide beamforming one can distinguish between the cases of high and low mutual antenna correlation respectively.

High mutual antenna correlation typically implies an antenna configuration with a small inter-antenna distance, as illustrated in Figure 2.4(a). In this case, the channels between the different antennas and a specific receiver are essentially the same, including the same radio-channel fading, except for a direction-dependent phase difference. The overall transmission beam can then be steered in different directions by applying different phase shifts to the signals to be transmitted on the different antennas, as illustrated in Figure 2.4(b).

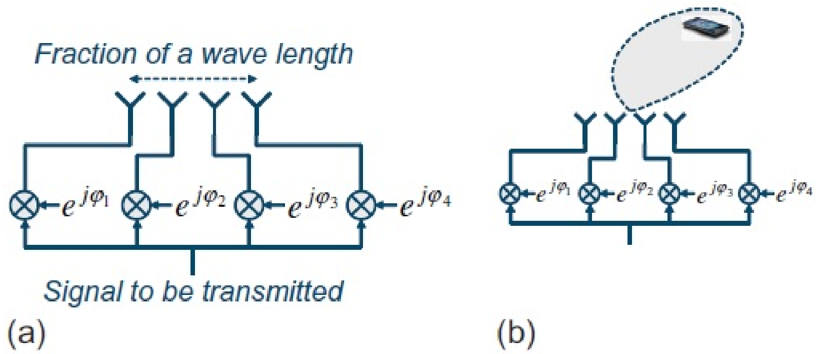

Figure 2.4: Classical beamforming with high mutual antennas correlation: (a) antenna configuration (b) beam-structure [2]

This approach to transmitter-side beamforming, with different phase shifts applied to highly correlated antennas, is sometimes referred to as ‘classical’ beamforming. Due to the small antenna distance, the overall transmission beam will be relatively wide and any adjustments of the beam direction in practice, adjustments of the antenna phase shifts will typically be carried out on a relatively slow basis. The adjustments could, for example, be based on estimates of the direction to the target terminal derived from uplink measurements. Furthermore, due to the assumption of high correlation between the different transmit antennas, classical beamforming cannot provide any diversity against radio-channel fading but only an increase of the received signal strength.

Low mutual antenna correlation typically implies either a sufficiently large antenna distance, as illustrated in Figure 2.5 or different antenna polarization directions. With low mutual antenna correlation, the basic beamforming principle is similar to that of Figure 2.4 that is, the signals to be transmitted on the different antennas are multiplied by different complex weights. However, in contrast to classical beamforming, the antenna weights should now take general complex values and both the phase and the amplitude of the signals to be transmitted on the different antennas can be adjusted. This reflects the fact that, due to the low mutual antenna correlation, both the phase and the instantaneous gain of the channels of each antenna may differ.

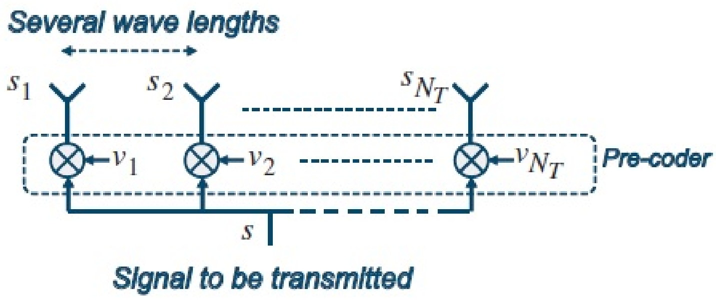

Figure 2.5: Pre-coder-based beamforming in the case of low mutual antenna correlation [2]

2.7 Energy Efficiency (EE) in Wireless Networks

The thesis investigates optimal transmit power allocation in relay networks. This help reduce energy needs and improves energy efficiency. Also, we do not study specific energy efficiency techniques. A short review of how relay networks can be used to improve energy efficiency is provided.

Given the worldwide growth in the number of mobile subscribers, the move to higher-data-rate mobile broadband, and the increasing contribution of information technology to the overall energy consumption of the world, there is a need on environmental grounds to reduce the energy requirements of radio access networks [46]. Nowadays, energy saving has attracted increasing attention from both the government and network operators. It is well known that relaying plays an important role to improve the link reliability, increase the throughput and enhance the energy efficiency in future communication networks [47] [48].

Large network coverage and high spectral efficiency are two central features of wireless networks, and the deployment of relay nodes [49] together with the concept of cooperation [50] have been identified as the principal mean to achieve both these goals.

Relay-assisted networks have also been considered in the standardization process for the next-generation mobile broadband communication systems [51]. Recently, driven by the explosive growth of wireless data traffic and the ever increasing economic and environmental costs associated with network operation, energy efficiency has become an important wireless network design consideration. In sensor networks, relaying and cooperation are known to improve the energy efficiency of the network. For example, diversity based node cooperation is analyzed in [38] and shown to provide a significant reduction in total energy consumption. Energy aware routing and cooperation is shown to prolong the lifetime of sensor networks in [52].

Relay selection will affect the energy efficiency of the network when multiple relays are deployed. Energy efficient relay selection has been widely studied in one-way relay networks including single relay [48] and multiple relays selection [53]. Due to low implementation complexity and excellent energy saving capability, single relay selection has become popular in contrast to multiple relays selection [48]. The best relay was selected in Amplify-and-Forward [54] and Decode-and-Forward (DF) [55] relay networks to transmit the signals from the source to the destination. Additionally, relay selection is always investigated with power allocation according to the channel state information (CSI). Energy efficient power allocation strategies were also developed in [48] and [55].

Although the one-way relaying can increase spectral efficiency, the half-duplex transmission reversely leads to spectral loss in practical systems. The two-way relaying was introduced recently to compensate for the deficiency of the one-way relaying through network coding technique. A lot of studies have addressed the issue of relay selection and power allocation in two-way relay networks for various goals [56] [57] [58].

Bidirectional asymmetric traffic and development of a cross-layer relay selection and power allocation scheme to optimize the energy efficiency of AF relay networks is discussed in [59].

The first and most widely used metric to mathematically express the Energy Efficiency (EE) of a given terminal has been the ratio between the throughput and the consumed power [60] [61] [62] [63], and references therein. Another proposed metric uses the outage probability in place of the throughput [64]. In all of the above works, as far as the computation of the consumed power is concerned, only the transmit power is considered, whereas the power that is dissipated in the electronic circuitry of each terminal in order to keep the terminal active is neglected. More recently, this assumption has been relaxed, and several papers have begun to address this issue [65] [66] by defining the consumed power as the sum of the transmit power plus a constant term independent of the transmit power, which models the circuit power needed for operating the terminal.

Chapter 3

System Model, Methodology and Techniques

In this chapter, we are going to define the topology of our network including relay positions. We derived the formula for array factor and antenna gain. We also formulated a single relationship between angle of arrival and angle of departure regardless of the transmitter and receiver orientation. Furthermore, the chapter includes path loss model for mmWave, rician fading channel and model assumptions. We would also write Matlab functions and try to include them. However, due to the page limit for the thesis, providing all Matlab Codes won't be possible.

3.1 Network Topology

The network consists of k-users and a base station in a square area as shown in Figure 3.1. The "*" represents each user and the $\triangledown$ represents the base station (BS).

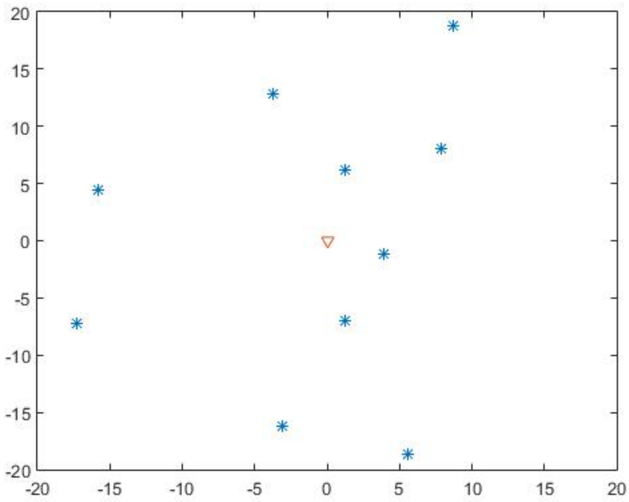

Figure 3.1: Topology of the network

Simplified Topology

The topology of typical conversation between a user (destination) and the base station (BS) via two relays (two different users) is depicted in Figure 3.2.

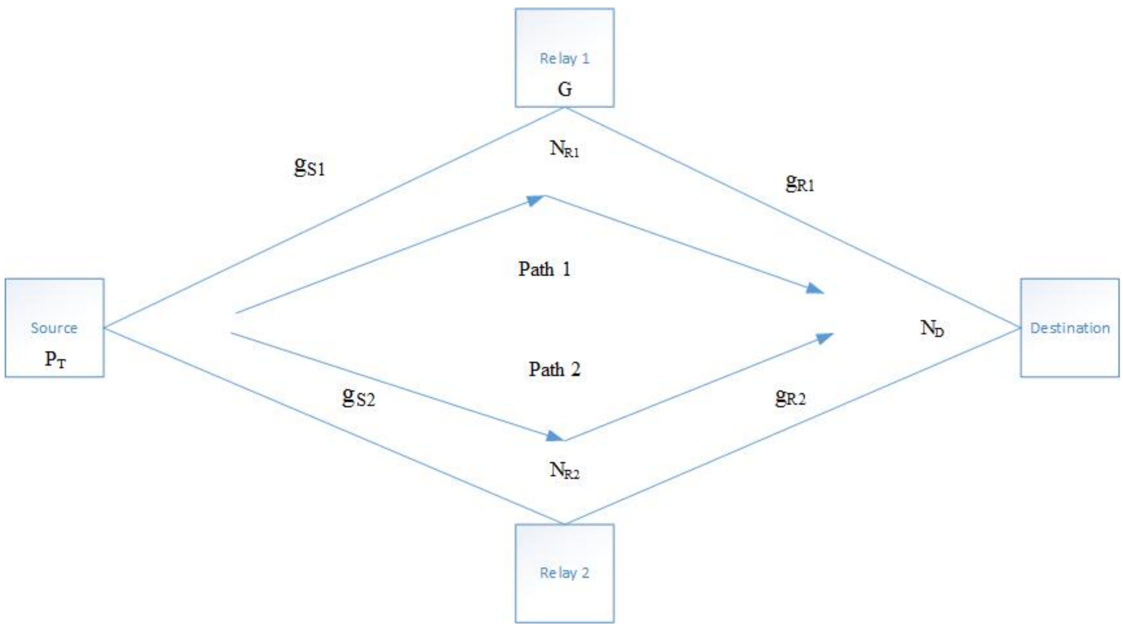

Figure 3.2: Simplified topology where two users act as relays to transmit to a third user (destination)

.

Assuming gain of single antenna be G_{ant}. In Figure 3.2, P_T represents the transmit power of the source and g_{S1} and g_{R1} are gains for the S-R1 and R1-D links respectively. h_{SR1}, h_{SR2}, h_{RD1} and h_{RD2} include both path loss and fading gains. The amplification gain for the relay be G. The noise added at the relay and destination are N_{R1} and N_D respectively. The transmit power (P_T) is used to transmit into two separate links, i.e S-R1-D and S-R2-D. Therefore, power available for S-R1-D path at the source is P_{T1} and the overall gains in the link including the array factor for the S-R1 and R1-D are as follows:

$$g_{S1} = AF_{SR1} \times G_{ant1} \times h_{SR1} \times AF_{R1} \times G_{ant1} \tag{3.1}$$

$$g_{R1} = AF_{RD1} \times G_{ant1} \times h_{RD1} \times AF_{UE} \times G_{ant1} \tag{3.2}$$

Similarly for path 2:

$$g_{S2} = AF_{SR2} \times G_{ant1} \times h_{SR2} \times AF_{R2} \times G_{ant1} \tag{3.3}$$

$$g_{R2} = AF_{RD2} \times G_{ant1} \times h_{RD2} \times AF_{UE} \times G_{ant1} \tag{3.4}$$

3.2 Euclidean Distance

We are using the topology as shown in Figure 3.1, where we have only 3 users and the base station. In other words, the communication between the nodes reduces to topology as shown in Figure 3.2. Every other communication would be of the same topology as long as only the base station and three other users are considered.

The base station is currently located at the center. However, it can be put anywhere in the region covered. We already have assigned the geographic location to all the users and the base station. Therefore, the distance between the base station and a single user can be calculated using Pythagoras Theorem. The following section consists all the information for the source (in this case the base station), the destination (one of the users) and the relays (two of the remaining user nodes) for two different scenarios.

```
% Fairly Balanced Scenario
point(1,1) = 0;            % BS
point(1,2) = 0;

point(2,1) = 2;            % UE
point(2,2) = 1.6;
```

```
point(3,1) = 2;            % Relay 1
point(3,2) = -1.6;

point(4,1) = 1;            % Relay 2
point(4,2) = 0.5;

%Fairly Unbalanced Scenario
point(1,1) = 0;            % BS
point(1,2) = 0;

point(2,1) = 2;            % UE
point(2,2) = 1.6;

point(3,1) = 2;            % Relay 1
point(3,2) = -1.6;

point(4,1) = 8;            % Relay 2 (placed further away)
point(4,2) = 0.5;
```

3.3 Array Factor and Antenna Gain

As mentioned earlier in literature review, the mmWave communication suffers from greater path loss. Therefore, to combat the the loss we need to use array of antennas to increase the gain. Arrays in mmWave can have 10's of antennas [67].The simplest and one of the most practical arrays is formed by placing the antenna-elements along a line. To simplify the presentation and give a better physical interpretation of the techniques, a two-element array will first be considered. The analysis of an N-element array will then follow.

3.3.1 Two-element array

Let us assume that the antenna under investigation is an array of two infinitesimal horizontal dipoles positioned along the z-axis, as shown in the Figure 3.3.

The total field of the array is equal to the field of a single element positioned at the origin multiplied by a factor which is widely referred to as the array factor (AF). Thus for the two-element array of constant amplitude, the array factor is given by

$$AF = 2\cos[\frac{1}{2}(kdcos\theta + \beta)] \tag{3.5}$$

where β is the difference in phase excitation between the elements, 'k' is the wave-number and 'd' is the distance between two successive elements in the array. The above equation in normalized form can be written as

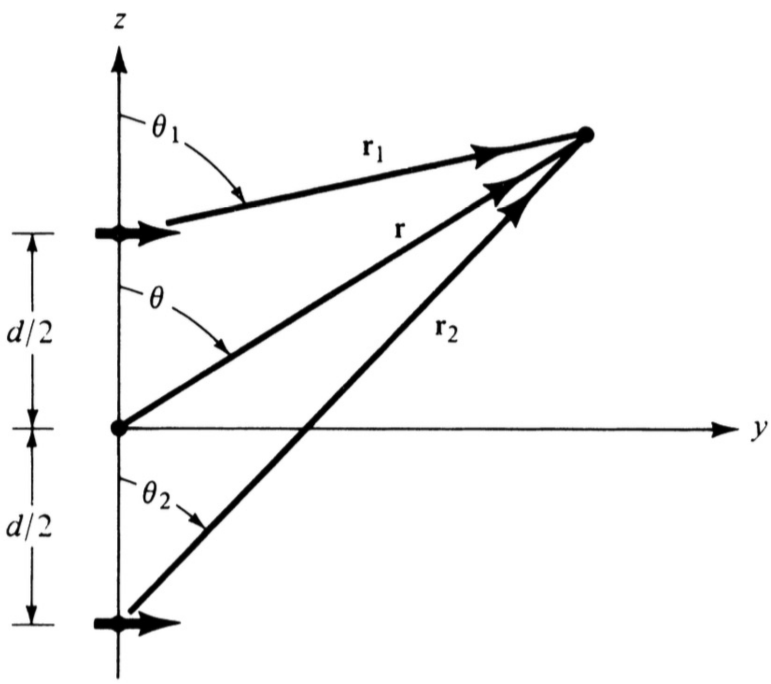

Figure 3.3: Geometry of a two-element array positioned along the z-axis: Two infinitesimal dipoles

$$AF = \cos[\frac{1}{2}(kdcos\theta + \beta)] \tag{3.6}$$

The array factor is a function of the geometry of the array and the excitation phase. By varying the separation d and/or the phase β between the elements, the characteristics of the array factor and of the total field of the array can be controlled.

3.3.2 N-Element Linear Array

Now that the arraying of elements has been introduced and it was illustrated by the two-element array, let us generalize the method to include N elements. Referring to the geometry of Figure 3.3, let us assume that all the elements have identical amplitudes but each succeeding element has a β progressive phase lead relative to the preceding one (β represents the difference in phase between the elements) [67]. The array factor can be obtained by considering the elements to be point sources. If the actual elements are not isotropic sources, the total field can be formed by multiplying the array factor of the isotropic sources by the field of a single element. The array factor is given by

$$AF = 1 + e^{+j(kdcos\theta+\beta)} + e^{+j2(kdcos\theta+\beta)} + ... + e^{+j(N-1)(kdcos\theta+\beta)} \tag{3.7}$$

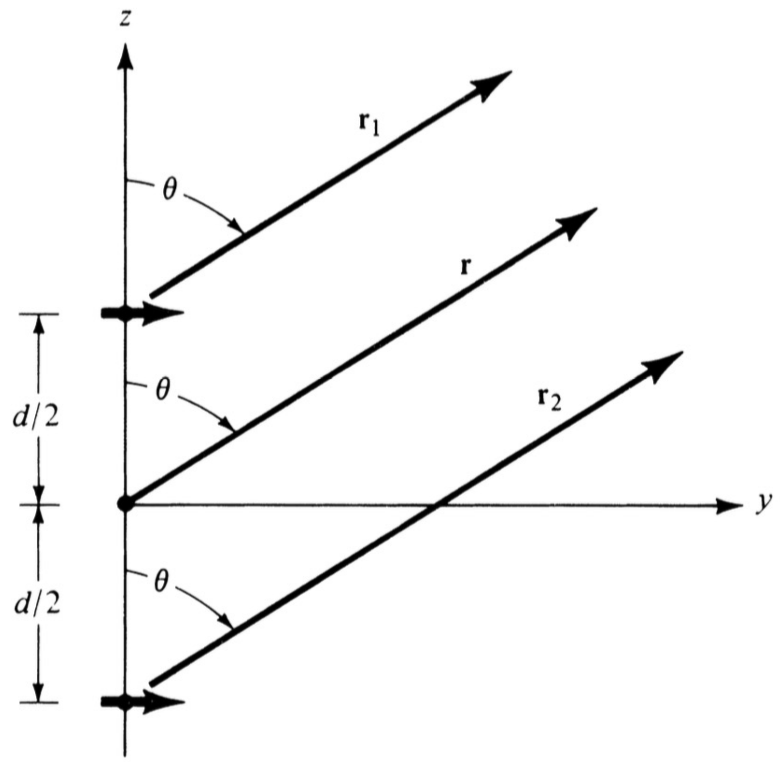

Figure 3.4: Geometry of a two-element array positioned along the z-axis: Far-field observations

$$AF = \sum_{n=1}^{N} e^{+j(n-1)(kdcos\theta+\beta)} \tag{3.8}$$

which can be written as

$$AF = \sum_{n=1}^{N} e^{j(n-1)\psi} \tag{3.9}$$

where $\psi = (kdcos\theta + \beta)$

Since the total array factor for the uniform array is a summation of exponentials, it can be represented by the vector sum of N phasors each of unit amplitude and progressive phase ψ relative to the previous one. Ignoring all the derivations, If the reference point is the physical center of the array, the array factor reduces to

$$AF = \frac{\sin\frac{N\psi}{2}}{\sin\frac{\psi}{2}} \tag{3.10}$$

The maximum array gain is N (the number of elements in the array and the assumption is single antenna gain is 1). We used this formula and wrote a Matlab function to calculate the array factor. The Matlab function is provided below.

```
function AF = ArrayFactor(theta,Nelements,dspacing,freq,beta)

c = 3*(1e8);
lam = c/freq;
k = 2*pi/lam;

psi = k*dspacing*cos(theta) + beta;

if psi == 0
    AF = Nelements;
else
    AF = (sin(Nelements*psi/2))/(sin(psi/2));
end
AF;
```

We have previously derived an equation for array factor (AF). Now, we use that to calculate antenna gain. Antenna gain is simply the multiplication of array factor and gain of a single antenna. Therefore, we wrote another Matlab function to calculate antenna gain and is provided below.

```
function Gain = AntennaGain(psin,nantennas,angleerror)

global frequency

f = frequency;
c = 3*(1e8);
lam = c/f;
beta = pi/2;
d = lam/4;
k = 2*pi/lam;


Nelements = nantennas;
psin;
dspacing = d;
freq = frequency;

if 0 <= psin && psin <= pi
    THETA = pi/2 - psin;
else
    THETA = -3*pi/2 + psin;
end
THETA;
beta = -k*d*cos(THETA+angleerror);


AF = ArrayFactor(THETA,Nelements,dspacing,freq,beta);

singleAntennaGain = 1;

Gain = abs(AF) * singleAntennaGain;
```

The next section explains the geometry on how to calculate angle of arrival and angle of departure.

3.4 Angle of Arrival and Angle of Departure

We have calculated the respective distances of the users from the base station. Now, we need to find out angle of departure (AOD) and the angle of arrival (AOA) of the signals from the base station to the users. The following section will explain the technique used to calculate AOA and AOD.

The following notation will be used throughout the thesis for angle to the normal, angle of departure relative to the positive-x-direction and the angle of departure relative to the Normal respectively. Subscript 1 and 2 mean transmitter and receiver side respectively.

1. θ_i: is the angle to the Normal relative to the positive-x-direction as shown in Figure 3.5
2. ϕ_i: is the angle of departure / angle of arrival relative to the positive-x-direction as shown in Figure 3.5
3. ψ_i: is the angle of departure / angle of arrival relative to the normal as shown in Figure 3.5

Receiver Side R_x

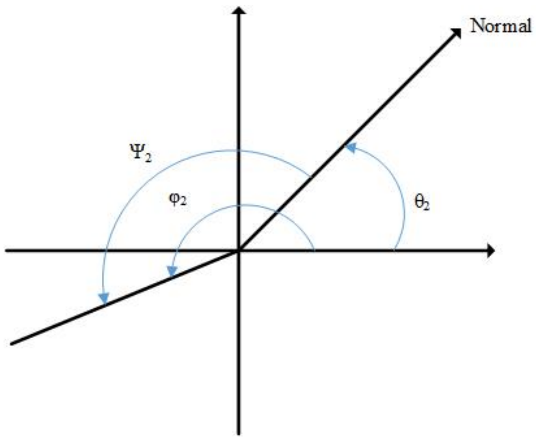

Figure 3.5: Scenario 1

We can observe the following relationship between the angle to the Normal relative to the positive-x-direction, the angle of arrival relative to the positive-x-direction and the angle arrival relative to the normal from the above figure.

$$\phi_2 = \psi_2 + \theta_2 \tag{3.11}$$

Therefore, rearranging we have,

$$\psi_2 = \phi_2 - \theta_2 \tag{3.12}$$

Transmitter Side, T_x

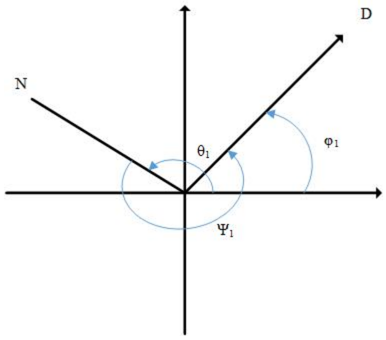

Figure 3.6: Scenario 2

We can observe the following relationship between the angle to the Normal relative to the positive-x-direction, the angle of departure relative to the positive-x-direction and the angle departure relative to the normal from the above figure.

$$\psi_1 + (\theta_2 - \phi_1) = 2\pi \tag{3.13}$$

Rearranging, we have

$$\psi_1 = 2\pi - (\theta_2 - \phi_1) \tag{3.14}$$

3.4.1 Relating AOD and AOA

The relationship between angle of departure and angle of arrival both relative to the positive-x-direction is given by,

$$\phi_2 = \pi + \phi_1 \tag{3.15}$$

1st and 2nd quadrant Scenario

$$(2\pi - \phi_2) = (\pi - \phi_1) \tag{3.16}$$
$$\phi_1 = \phi_2 - \pi \tag{3.17}$$
$$\phi_2 = \phi_1 + \pi \tag{3.18}$$

when $\phi_1 : \pi/2 \Rightarrow \pi$ then $\phi_2 : 3\pi/2 \Rightarrow 2\pi$

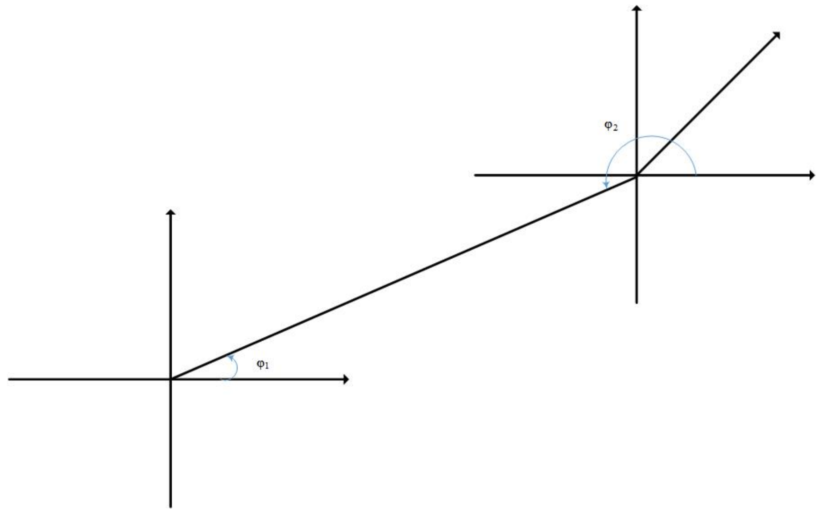

Figure 3.7: Scenario 3

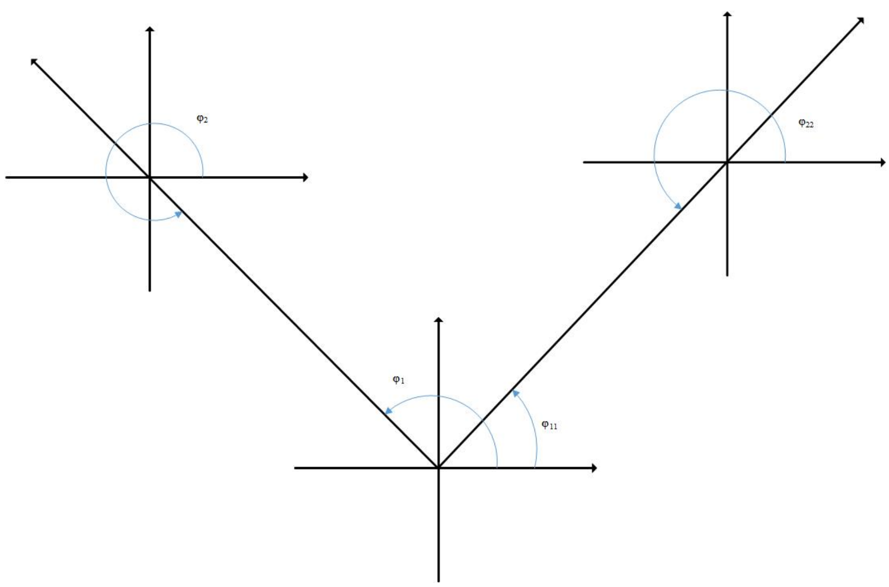

Figure 3.8: Scenario 4

$$\phi_{11} = \phi_{22} - \pi \tag{3.19}$$
$$\phi_{22} = \phi_{11} + \pi \tag{3.20}$$
$$\tag{3.21}$$

when $\phi_1 : 0 \Rightarrow \pi/2$ then $\phi_2 : \pi \Rightarrow 3\pi/2$

3rd and 4th quadrant Scenario

$$\phi_1 - \pi = \phi_2 \tag{3.22}$$

when $\phi_1 : \pi \Rightarrow 3\pi/2$ then $\phi_2 : 0 \Rightarrow \pi/2$

$$(2\pi - \phi_{11}) = (\pi - \phi_{22}) \tag{3.23}$$
$$\phi_{22} = \phi_{11} - \pi \tag{3.24}$$

when $\phi_1 : 3\pi/2 \Rightarrow 2\pi/$ then $\phi_2 : \pi/2 \Rightarrow \pi$

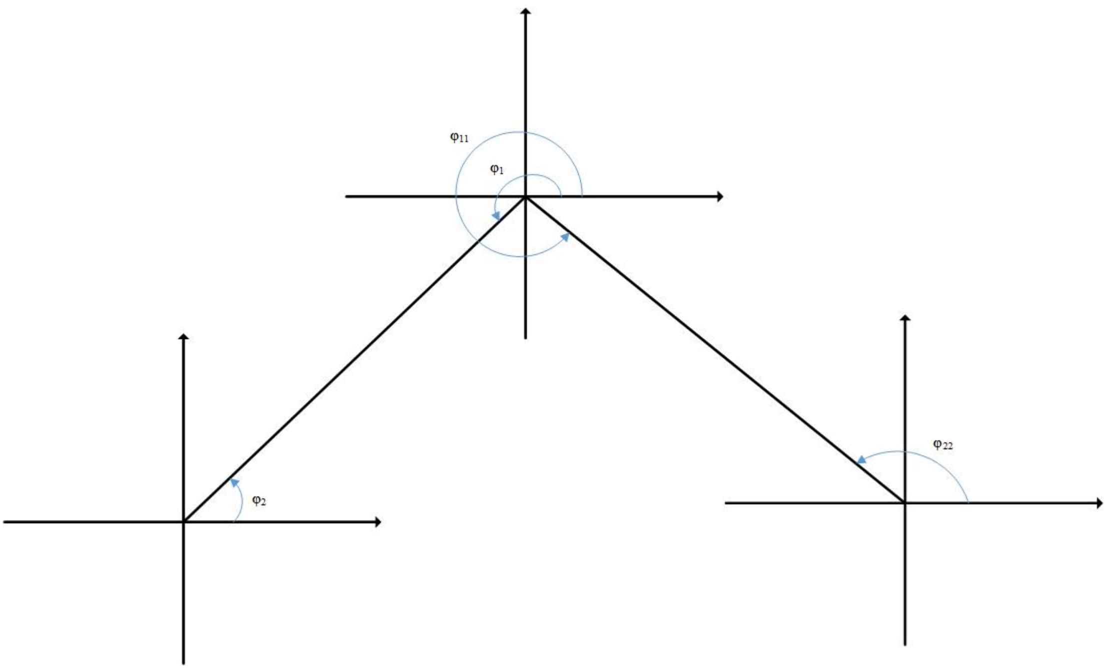

Figure 3.9: Scenario 5

From the above analysis, we finally derived a single relationship between ϕ_2 and ϕ_1. The relationship as follows:

$$\phi_2 = (\phi_1 + \pi) \mod 2\pi \tag{3.25}$$

3.5 Path Loss Model

The large-scale characteristics of the 60 GHz models are based on long-distance dependence of path loss with log-normal shadowing [68]. Log-normal shadowing indicates that measured values of path loss will fit a normal distribution with the values represented in a decibel scale. Due to the very wide absolute bandwidth of channels dedicated to 60 GHz communication, the frequency-dependence of the path loss is also sometimes taken into account [3].

$$PL(d, f) = PL_0 + 10k \log_{10}\left(\frac{f}{f_0}\right) + 10n \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{3.26}$$

where PL_0 is the reference path loss at carrier frequency f_0 and transmitter-receiver separation distance d_0. k is the frequency-loss factor (and is usually equal to 2); though further testing is needed to accurately determine the frequency-dependence of path loss [68]. Note that n is the path loss exponent, which describes how the path loss increases as the transmitter-receiver separation distance increases above d_0. X_σ is the log-normally distributed random variable that describes the shadowing characteristics of the channel. [68] states that most indoor LOS channel have a path loss exponent from 0.4 to 2.1 (a value less than 2 indicates that the environment prevents the energy spreading out spherically, but rather guides some of the radiated energy from the transmitter to the receiver). NLOS indoor 60 GHz channels have a path loss of 1.97 - 5.40 [68]. Higher antenna positions relative to the floor result in lower path loss exponents for most indoor environments [68].

3.5.1 Path Loss Matlab function

The following is the matlab function to calculate path loss provided the distance and frequency. All the values are taken from [3].

```
function PL = PathLossdB(d,f)

PL0 = 75.1;
d0 = 1;
f0 = 60*10^9;
k = 2;
n = 1.53;
Xsigma = 1.5;

PL = PL0 + 10*k*log10(f/f0) + 10*n*log10(d/d0) + Xsigma;
```

3.6 Rician Fading Model

mmWave communication mainly depends on line-of-sight propagation. Therefore, rician fading channel model is best suited for mmWave channel models. However, extensive research is being carried out to create the channel model for mmWave communication. Unfortunately, the work is still on progress [3].

Rician fading is a stochastic model for radio propagation anomaly caused by partial cancellation of a radio signal by itself the signal arrives at the receiver by several different paths (hence exhibiting multipath interference), and at least one of the paths is changing (lengthening or shortening). Rician fading occurs when one of the paths, typically a line of sight signal, is much stronger than the others [69]. In Rician fading, the amplitude gain is characterized by a Rician distribution.

Rician fading best characterizes a situation where there is a direct LOS path in addition to a number of indirect multipath signals. The Rician model is often applicable in an indoor environment whereas the Rayleigh model characterizes outdoor settings. The Rician model also becomes more applicable in smaller cells or in more open outdoor environments. The channels can be characterized by a parameter k, defined as follows:

$$k = \frac{\text{power in the dominant path}}{\text{power in the scattered paths}} \tag{3.27}$$

The Rayleigh-fading model assumes that all the paths are relatively equal - that is, that there is no dominant path. Despite the fact that Rayleigh fading is the most popular model, occasionally there is direct line-of-sight path in mobile radio channels and indoor wireless environments. In mmWave communication the channels are modelled to be rician fading channels since successful communication is only possible only if the signals are in strong line-of-sight [70]. The presence of direct path is usually required when communicating in very high frequency (i.e E-bands). In this case, the reflected paths are much weaker than the direct path, and we can model the complex envelope as

$$\tilde{E} = E_0 + \sum_{n=1}^{N} E_n e^{j\theta_n} \tag{3.28}$$

where the constant term represents the direct path and the summation represents the collection of reflected paths. This model is referred to as a Rician fading model. This analysis proceeds in a manner similar to that of the Rayleigh fading case, but with the addition of a constant term. A key factor in the analysis is the ratio of the power in the direct path to the power in the reflected paths. This ratio is referred to as the the Rician k-factor, defined as

$$k = \frac{s^2}{\left(\sum_{n=1}^{N} |E_n|^2\right)} \tag{3.29}$$

where $s^2 = |E_0|^2$. The Rician K-factor is often expressed in dB.
The amplitude density function of the Rician fading is

$$f_R(r) = \frac{r}{\sigma^2} e^{-(r^2+s^2)/2\sigma^2} I_0\left(\frac{rs}{\sigma^2}\right) \quad r \geq 0 \tag{3.30}$$

where $I_0(.)$ is the the modified Bessel function of zero'th order [70].

Deep fades are clearly less probable than with Rayleigh channel, and the probability of their occurrence decreases as the k factor increases.

A Rician fading channel can be described by two parameters: k and Ω [69]. The fading parameter K is the ratio between the power in the direct path and the power in the other, scattered, paths. Ω is the total power from both paths.

$$\Omega = V^2 + 2\sigma^2 \tag{3.31}$$

$$k = \frac{V^2}{2\sigma^2} \tag{3.32}$$

According to equation 3.32:

$$k = \infty \Rightarrow V^2 \gg 2\sigma^2 \tag{3.33}$$

When $k = 0$ the channel is Rayleigh (i.e., numerator is zero) and when $k = \infty$, the channel is AWGN (i.e., denominator is zero).

Here bit error rate is plotted as a function of the ratio Eb/No. Of course, as this ratio increases, the bit error rate drops. With a reasonably strong signal, relative to noise, an AWGN provides fairly good performance, as do Rician channels with larger values of k, roughly corresponding to microcells or an open country environment. The performance would be adequate for a digitized voice application, but for digital data transfer, efforts to compensate would be needed. The Rayleigh channel provides relatively poor performance; this is likely to be seen for flat fading and for slow fading. In these cases, error compensation mechanisms therefore become more desirable. Finally, some environments produce fading effects worse than the so called worst case of Rayleigh. Examples are fast fading in an urban environment and the fading within the affected band of a selective fading channel. In these cases, no level of Eb/No will help achieve the desired performance, and compensation mechanisms are mandatory.

3.6.1 Channel Gain Estimation: Ricean Channel

We have implemented a Matlab function that takes ricean factor, k as an input to estimate the channel gain.

```
function gain = riceangain (k)

P = 1;              % P = LOS + NLOS

NLOS = P/(k+1);      % NLOS
LOS = P*k/(k+1);     % LOS
m = sqrt(2*LOS);
sig = sqrt(NLOS);

gain = ((m + normrnd(0,sig))^2 + normrnd(0,sig)^2)/2;
```

3.7 Computing Noise at the relay and destination

Noise figure (NF) and noise factor (F) are measures of degradation of the signal-to-noise ratio (SNR), caused by components in a radio frequency (RF) signal chain. It is a number by which the performance of an amplifier or a radio receiver can be specified, with lower values indicating better performance.

The noise factor is defined as the ratio of the output noise power of a device to the portion thereof attributable to thermal noise in the input termination at standard noise temperature T0 (usually 290 K). The noise factor is thus the ratio of actual output noise to that which would remain if the device itself did not introduce noise, or the ratio of input SNR to output SNR. The noise figure is simply the noise factor expressed in decibels (dB).

The equivalent temperature is given by

$$T_e = (F - 1)T_o \tag{3.34}$$

We have written a function on Matlab to compute the Noise Power at the receiver (NoiseUE).

$$\text{NosieUE} = (F_R - 1)T_o kB + T_{A_R} kB \tag{3.35}$$
$$\tag{3.36}$$

where F_R is the noise factor of the relay, k is Boltzmann's constant, T_{A_R} is temperature of the relay and B is the bandwidth.

```
function [NoiseRel,NoiseUE] = computeNoiseAF2(FReldB,FUEdB,TARel,TAUE,BW)
k = 1.38e-23; %joule/K
T0 = 290;

F = 10^(FReldB/10);
TA = TARel;
Te = (F-1)*T0;
NA = k*BW*TA;
Ne = k*BW*Te;
NoiseRel = Ne + NA;

F = 10^(FUEdB/10);;
TA = TAUE;
Te = (F-1)*T0;
NA = k*BW*TA;
Ne = k*BW*Te;
NoiseUE = Ne + NA;
```

3.8 Energy Efficiency (EE) in Wireless Networks

Given the worldwide growth in the number of mobile subscribers, the move to higher-data-rate mobile broadband, and the increasing contribution of information technology to the overall energy consumption of the world, there is a need on environmental grounds to reduce the energy requirements of radio access networks [46]. Nowadays, energy saving has attracted increasing attention from both the government and network operators. It is well known that relaying plays an important role to improve the link reliability, increase the throughput and enhance the energy efficiency in future communication networks [47] [48].

Large network coverage and high spectral efficiency are two central features of wireless networks, and the deployment of relay nodes [49] together with the concept of co-operation [50] have been identified as the principal mean to achieve both these goals. Relay-assisted networks have also been considered in the standardization process for the next-generation mobile broadband communication systems [51]. Recently, driven by the explosive growth of wireless data traffic and the ever increasing economic and environmental costs associated with network operation, energy efficiency has become an important wireless network design consideration. In sensor networks, relaying and cooperation are known to improve the energy efficiency of the network. For example, diversity based node cooperation is analyzed in [38] and shown to provide a significant reduction in total energy consumption. Energy aware routing and cooperation is shown to prolong the lifetime of sensor networks in [52].

Relay selection will affect the energy efficiency of the network when multiple relays are deployed. Energy efficient relay selection has been widely studied in one-way relay networks including single relay [48] and multiple relays selection [53]. Due to low implementation complexity and excellent energy saving capability, single relay selection has become popular in contrast to multiple relays selection [48]. The best relay was selected in Amplify-and-Forward [54] and Decode-and-Forward (DF) [55] relay networks to transmit the signals from the source to the destination. Additionally, relay selection is always investigated with power allocation according to the channel state information (CSI). Energy efficient power allocation strategies were also developed in [48] and [55].

Although the one-way relaying can increase spectral efficiency, the half-duplex transmission reversely leads to spectral loss in practical systems. The two-way relaying was introduced recently to compensate for the deficiency of the one-way relaying through network coding technique. A lot of studies have addressed the issue of relay selection and power allocation in two-way relay networks for various goals [56] [57] [58].

Bidirectional asymmetric traffic and development of a cross-layer relay selection and power allocation scheme to optimize the energy efficiency of AF relay networks is discussed in [59].

The first and most widely used metric to mathematically express the Energy Efficiency (EE) of a given terminal has been the ratio between the throughput and the consumed power [60] [61] [62] [63], and references therein. Another proposed metric uses the outage probability in place of the throughput [64]. In all of the above works, as far as the computation of the consumed power is concerned, only the transmit power is considered, whereas the power that is dissipated in the electronic circuitry of each terminal in order to keep the terminal active is neglected. More recently, this assumption has been relaxed, and several papers have begun to address this issue [65] [66] by defining the consumed power as the sum of the transmit power plus a constant term independent of the transmit power, which models the circuit power needed for operating the terminal.

Chapter 4

Optimal Antenna and Power Allocation

In this chapter, we are going to formulate the problem of resource optimisation in our desired relay network. The chapter includes the different types of relay we have used. We considered AF relaying strategy that can operate in one of the three modes. The formulation of water-filling method for power allocation is also outlined. The chapter also includes the power allocation methods for the relay i.e fixed power allocation and water-filling method. We used ergodic capacity to compare between different scenarios of relay positions, i.e fairly balanced (relays are positioned nearly same distance away from the source) and fairly unbalanced (one relay is placed far away from source compared to the other relay). We also studied how ergodic capacity vary with noise figures. We explored the idea of Lagrange Multipliers in constrained optimisation problems and derived optimal power allocation scheme for our AF relaying method. Furthermore, the chapter includes formulation of optimisation problems and their mathematical analysis & solutions. We have included the Matlab simulation results including thorough discussion and analysis. We also have included the implication of our findings in sections deemed important.

4.1 Types of Relay

We looked at two different relays. The first one with a fixed gain and the other one with Fast Automatic Gain Control (Fast AGC). We used Amplify & Forward relaying strategy for both the cases.

4.1.1 Fixed Gain and Fast AGC

In case of Fixed Gain relay, the gain at the relay (G) is fixed regardless of the level of received power whereas for Fast AGC, the gain at the relay depends on the power received. In other words, the output power of the relay is going to be the same regardless of variation of the input power.

4.2 Optimal Number of Transmit Antennas (T_x) to maximise capacity

Let's denote the transmit power at the source be P_T, since the source needs to transmit in two different path, therefore, the power needs to be shared between the paths. Lets assume, P_{T1} and P_{T2} are the power available for path 1 and path 2 respectively. Channel gains are g_{S1} and g_{R1} for the S-R1 and R1-D links respectively. The amplification gain for the relay be G_1. The noise added at the relay and destination are N_{R_1} and N_{D_1} respectively.

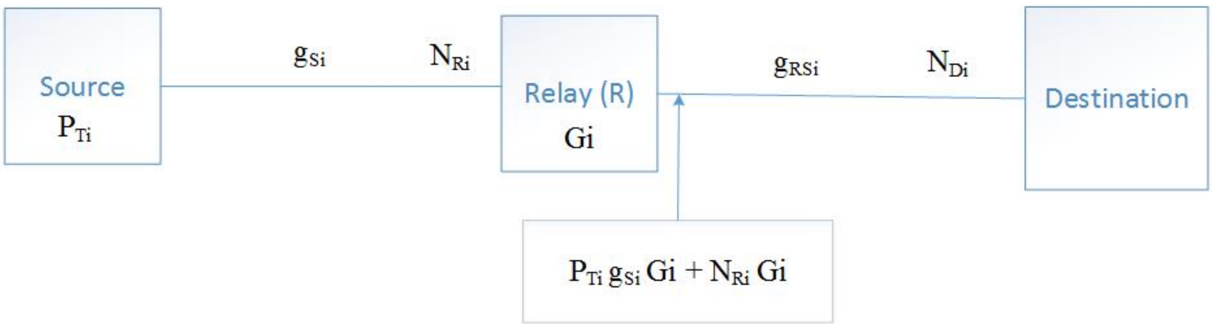

Figure 4.1: Topology for a single path used for deriving the SNR at the destination

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According to Figure 4.1, the subscript 'i' represents ith link. Now, if we consider only path 1 (in other words $i = 1$), the transmitting power available is P_{T1}, channel gain is g_{S1}, amplification gain of the relay is G_1 and the noise added at the relay 1 is N_{R1}. Then, the signal received at the relay 1 is $g_{S1}P_{T1} + N_{R1}$. Therefore, the signal transmitted from the relay would be amplified by the amplification gain, G_1. Note, total number of antennas is N. x number of antennas are assigned for path 1 and $(N - x)$ are assigned for path 2. Assuming gain of a single antenna is G_{ant1}.

$$\text{signal transmitted at the relay} = P_{T1} \times g_{S1} \times G_1 + N_{R1} \times G_1 \tag{4.1}$$

where g_{S1} is given by the the formula in equation 4.2. In equation 4.2, AF_{SR1} is the array factor for S-R link, G_{ant1} is the gain of the single antenna in the array, h_{SR1} is the channel gain of S-R link and AF_{R1} is the array factor of the antenna array of the relay. Similarly, we have g_{R1} given by the equation 4.3.

$$g_{S1} = AF_{SR1} \times G_{ant1} \times h_{SR1} \times AF_{R1} \times G_{ant1} \tag{4.2}$$

$$g_{R1} = AF_{RD1} \times G_{ant1} \times h_{RD1} \times AF_{UE} \times G_{ant1} \tag{4.3}$$

N_{D1} gets added when the signal is received at the destination. Therefore, the overall signal to noise ratio (SNR) at the destination is given by the following equation.

$$\gamma_1 = \frac{P_{T1} g_{S1} G_1 g_{R1}}{N_{R1} G_1 g_{R1} + N_{D1}} \tag{4.4}$$

Combining equations 4.2 and 4.4

$$\gamma_1 = P_{T1} x \tilde{A}_1 \tag{4.5}$$

where x is AF_{SR1}, we could replace array factor with number of antennas in the array as discussed earlier. h_{SR1} and h_{RD1} includes both path loss and fading gain. We assume SingleAntennaGain to be 1 and $\tilde{A}_1$ as follows

$$\tilde{A}_1 = \frac{h_{SR1} \times AF_{R1} G_1 g_{R1}}{N_{R1} G_1 g_{R1} + N_{D1}} \tag{4.6}$$

Similarly,

$$\gamma_2 = P_{T2}(N - x)\tilde{A}_2 \tag{4.7}$$

where $\tilde{A}_2$

$$\tilde{A}_2 = \frac{h_{SR2} \times AF_{R2} G_2 g_{R2}}{N_{R2} G_2 g_{R2} + N_{D2}} \tag{4.8}$$

4.2.1 Problem Formulation: Fixed Gain at the relay

Let, path 1 and path 2 are different routes from base station (BS) to destination (User). Using equation 4.5 and 4.7, the SNR at the destination for path 1 and path 2 are given by

$$\gamma_1 = A_1 x \tag{4.9}$$

$$\gamma_2 = A_2(N - x) \tag{4.10}$$

where $A_1 = P_{T1}\tilde{A}_1$ and $A_2 = P_{T2}\tilde{A}_2$

Finally, we use the above expressions for SNR at the destination to calculate the overall capacity from the source to the destination. Our aim is to find out the optimal allocation of the number of antennas (x, $N - x$) for which the capacity is maximised.

$$\text{capacity} = w \log_2(1 + A_1 x) + w \log_2(1 + A_2(N - x)) \tag{4.11}$$
$$= w \log_2\left((1 + A_1 x)(1 + A_2(N - x))\right) \tag{4.12}$$

$\log_2(x)$ is an increasing function of x. Thus, in order to find the the maximum capacity, we need to find the value of x for which the following expression takes maximum value.

$$1 + A_1 x + A_2(N - x) + A_1 A_2 x(N - x) \tag{4.13}$$

4.2.2 Mathematical Analysis

According to the discussion above, we need to find out the value of x for which $(1 + A_1 x)(1 + A_2(N - x))$ takes maximum value.

$$f(x) = (1 + A_1 x)(1 + A_2(N - x)) \tag{4.14}$$

Expanding we have,

$$f(x) = 1 + A_1 x + A_2(N - x) + A_1 A_2 x(N - x) \tag{4.15}$$

Upon further expansion,

$$f(x) = 1 + A_2 N + x(A_1 - A_2 + A_1 A_2 N) - x^2 A_1 A_2 \tag{4.16}$$

Even though, the number of antennas can only be integer, we are treating x as a continuous value so that we can apply calculus. Therefore in the final analysis, x needs to be rounded off to the nearest integer.

Now, we can use calculus to find out what is the value for x for the capacity to be maximum; in other words, the optimal number of transmit antennas in order to achieve maximum capacity. After differentiating with respect to x, we have the following equation.

$$f'(x) = A_1 - A_2 + A_1 A_2 N - 2x A_1 A_2 \tag{4.17}$$

For stationery points,

$$f'(x) = 0 \tag{4.18}$$

Solving the above two equations, we have the following expression for the optimal number of transmit antennas.

$$x = \frac{A_1 - A_2 + A_1 A_2 N}{2 A_1 A_2} \tag{4.19}$$

The method of calculus determines the optimal value of x if it is in the open interval $(0, N)$. Therefore, the extreme cases like $x = 0$ or $x = N$ needs to be separately handled. This issue has been addressed in Matlab coding.

4.2.3 Simulation Result: Optimal antenna allocation

We have previously found that optimal number of antennas to achieve the maximum capacity is given by

$$x = \frac{A_1 - A_2 + A_1 A_2 N}{2 A_1 A_2} \tag{4.20}$$

where N is the total number of transmit antennas and A_1 & A_2 are defined earlier.

We implemented the allocation method in Matlab and tested it for the two scenarios described in section 3.3. The Matlab output is provided below and the source code is provided in the appendix section of this thesis.

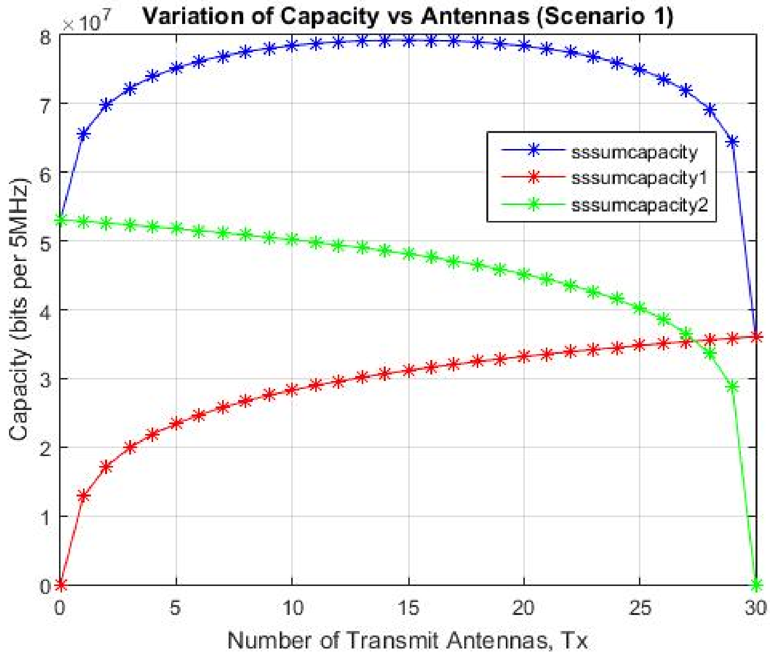

Figure 4.2: Optimal Number of antennas allocation to maximise capacity Scenario 1 (No Fading)

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In the second scenario, the second relay is placed further apart. Analyzing the data from the graphs, capacity reduces greatly when the second relay is placed further apart.

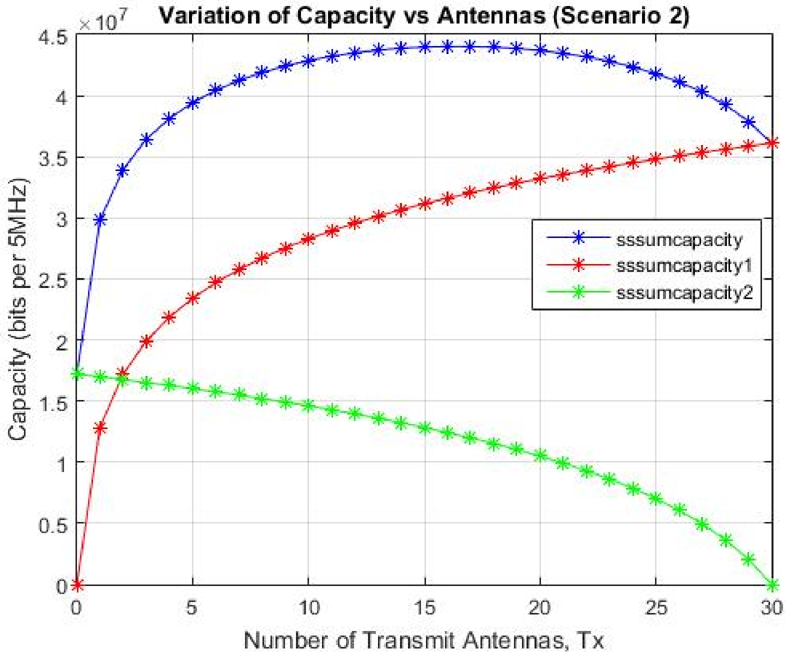

Figure 4.3: Optimal Number of antennas allocation to maximise capacity Scenario 2 (No Fading)

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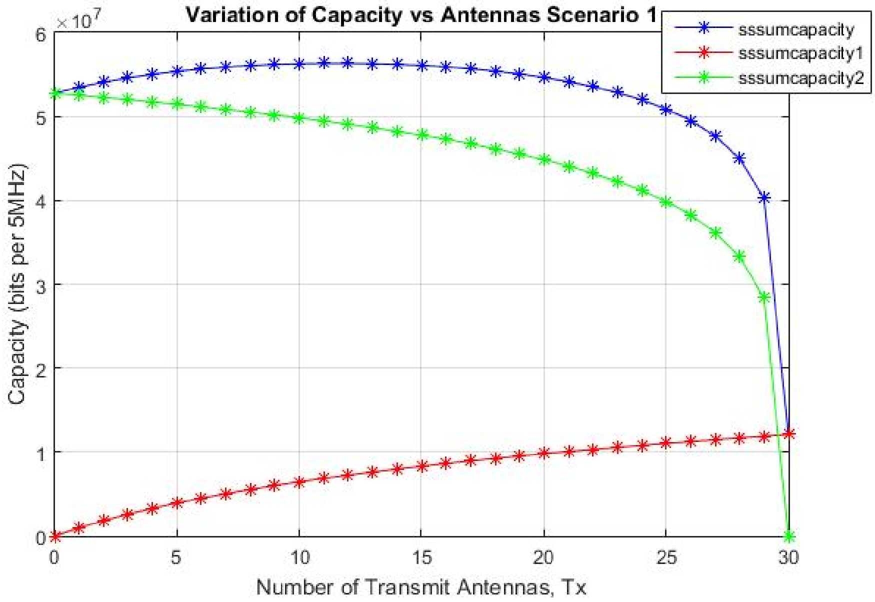

Figure 4.4: Optimal Number of antennas allocation to maximise capacity Scenario 1 (includes Fading Gain)

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4.3 Antenna and Power Allocation

We used three different power allocation methods. In previous section, we have used 50:50 power allocation method. In this section, we are going to use the other two power allocation methods. Firstly, we are going to explain the power allocation methodology and implement them on Matlab and then, we would use them in solving our optimisation problems.

1. Power Allocation with Fixed Gain using Water Filling Algorithm
2. Power Allocation with AGC using grid method

4.3.1 Water Filling Method: WFM

Let's assume, the total power available is P. The power is then shared in two different paths. Power for path 1 and path 2 are P_1 and P_2 respectively. Channel gain and noise at the receiver for path 1 and path 2 be g_1, g_2 and n_1, n_2 respectively.

Thus, the SNR for path 1 and path 2 are given by the following equations,

$$\gamma_1 = \frac{g_1 P_1}{n_1} \tag{4.21}$$

$$\gamma_2 = \frac{g_2 P_2}{n_2} \tag{4.22}$$

$$\max \sum_{i=1}^{2} w \log_2(1 + \gamma_i) \tag{4.23}$$

$$\text{subject to} \tag{4.24}$$
$$P_1 + P_2 \leq P$$
$$P_1, P_2 \geq 0 \tag{4.25}$$

The maximisation problem in 4.23 is the same as minimisation problem in 4.26.

$$\min - \sum_{i=1}^{2} w \log_2(1 + a_i P_i) \tag{4.26}$$

$$\text{subject to} \tag{4.27}$$
$$-P_i \leq 0$$
$$P_1 + P_2 - P = 0 \tag{4.28}$$

where a_i is

$$a_i = \frac{g_i}{n_i} \tag{4.29}$$

Using the Lagrangian Multipliers,

$$L(P, \lambda, \mu) = -\sum_{i=1}^{2} w \log_2(1 + a_i P_i) + \lambda(P_1 + P_2 - P) + \sum_{i=1}^{2} \mu_i(-P_i) \tag{4.30}$$

General solutions to the Lagrangian equation are as follows,

$$P_i = \max\left(\frac{1}{\lambda} - \frac{1}{a_i}\right) \tag{4.31}$$

$$P_1 + P_2 = P \tag{4.32}$$

if $a_1 \geq a_2$, then

$$\frac{1}{a_1} \leq \frac{1}{a_2} \tag{4.33}$$

Case 1

If $P \leq \left(\frac{1}{a_2} - \frac{1}{a_1}\right)$

$$P_1 = P \tag{4.34}$$

$$P_2 = 0 \tag{4.35}$$

Case 2

If $P > \left(\frac{1}{a_2} - \frac{1}{a_1}\right)$

$$P_1 = \left(\frac{1}{a_2} - \frac{1}{a_1}\right) + \frac{1}{2}\left(P - \left(\frac{1}{a_2} - \frac{1}{a_1}\right)\right) \tag{4.36}$$

$$P_2 = \frac{1}{2}\left(P - \left(\frac{1}{a_2} - \frac{1}{a_1}\right)\right) \tag{4.37}$$

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % Watter Filling Algorithm #1

    Given N1 antennas for path 1 and (N-N2) antennas for path 2

    Calculate path 1 gain
    Calculate path 2 gain

    Use water filling algorithm to find optimal power allocation
    for each possible N1 = 0,1,2 ...............N

    Use the best (i.e the allocation that gives the highest capacity)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

4.3.2 Grid Method

In this method of power allocation, for each set of power ratio the optimal number of antennas allocation is found out. Then, using an exhaustive search method, the best power allocation ratio and the optimal number of antennas allocation is found out on the basis of throughput. One such example of search method is depicted in Figure 4.5. Please refer to the source code for the implementation details in the Appendix section of this thesis.

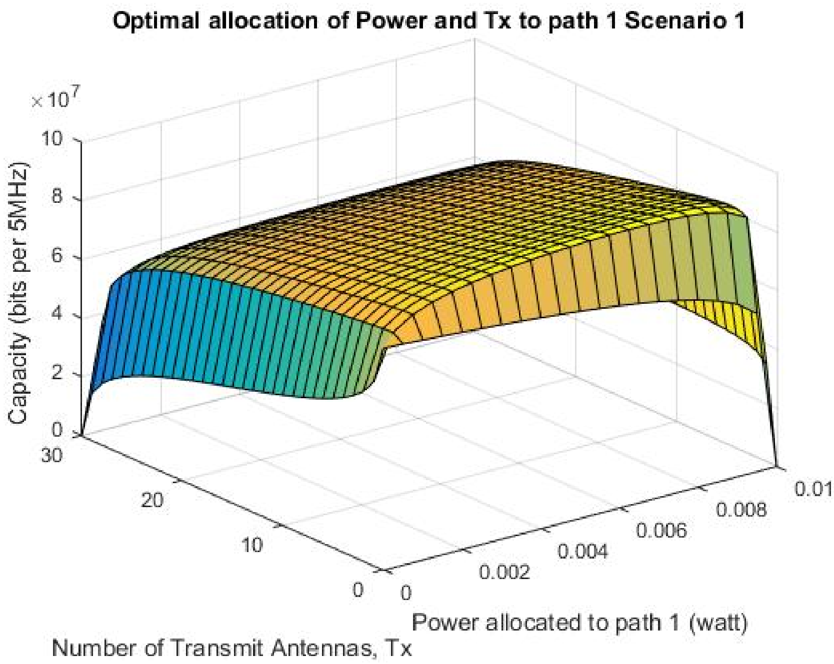

Figure 4.5: Optimal Allocation of antennas and power using Search Method

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4.4 Ergodic Capacity

Due to random nature of wireless channels, we can not compare results of a single realisation. Therefore, we used ergodic capacity to compare our results. Ergodic capacity for a certain method would remain the same even though the capacity for single realisation of the channel may vary.

The normalized capacity of a channel is given by

$$C(\gamma) = \log_2[1 + \gamma] \tag{4.38}$$

and this capacity is derived under the assumption of codes with infinite codeword length. Since, the codewords are infinitely long, they extend over different realizations of the fading state. The *ergodic (Shannon) capacity* in a fading channel is therefore the expected value of the capacity, taken over all realizations of the channel [70].

4.4.1 Fixed Gain and AGC Methods

Comparing Scenario 1 with Scenario 2: equal power allocation

Comparing Figure 4.6 and Figure 4.7: as expected, ergodic sum capacity for scenario 1 is higher compared to ergodic sum capacity of scenario 2 when equal power allocation is used. In the second scenario, relay 2 is placed further apart, therefore, the capacity via that link reduces as observed in Figure 4.7

Comparing Scenario 1 with Scenario 2: water-filling method #1

Comparing Figure 4.8 and Figure 4.9: Ergodic sum capacity for Scenario 1 is higher than that of Scenario 2. Relay 2 was placed further apart resulting in lower SNR at the destination for path 2, thus, reduced capacity as shown in Figure 4.9 when compared with Figure 4.8.

Comparing Scenario 1 with Scenario 2: Fast AGC

Comparing Figure 4.10 and Figure 4.11: Fast AGC also performs better for Scenario 1 compared to Scenario 2. However, the difference in ergodic sum capacity for Scenario 1 and Scenario 2 is much less when compared with equal power and water-filling power allocation method.

Comparing Scenario 1 and 2 for different power allocation methods

When the relays are fairly balanced (Scenario 1), the simulation results show that the ergodic capacity is the same regardless of which power allocation method is used. However, when the relays are fairly unbalanced (Scenario 2), the Fast AGC power allocation method performs the best as shown in Figure 4.11.

In conclusion, there's no advantage of using either of the power allocation methods in fairly balanced scenarios. However, for fairly unbalanced scenario Fast AGC power allocation gives the best result.

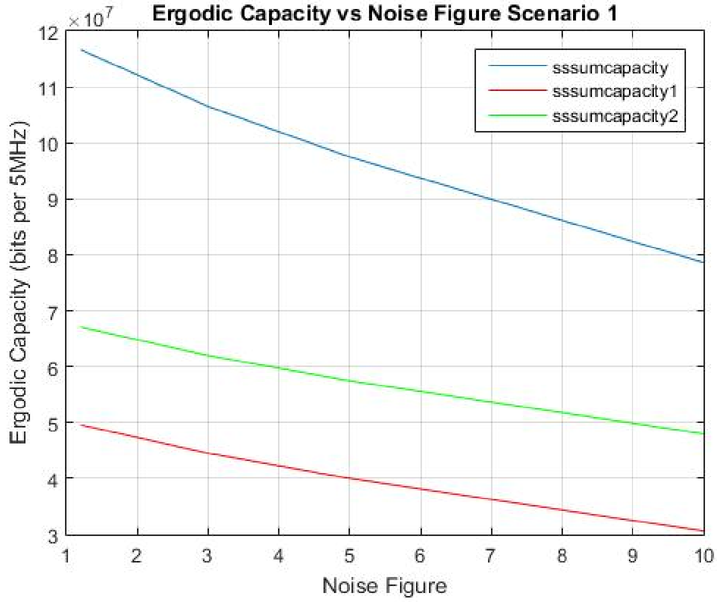

Figure 4.6: Ergodic Capacity vs Noise Figure using equal allocation of power

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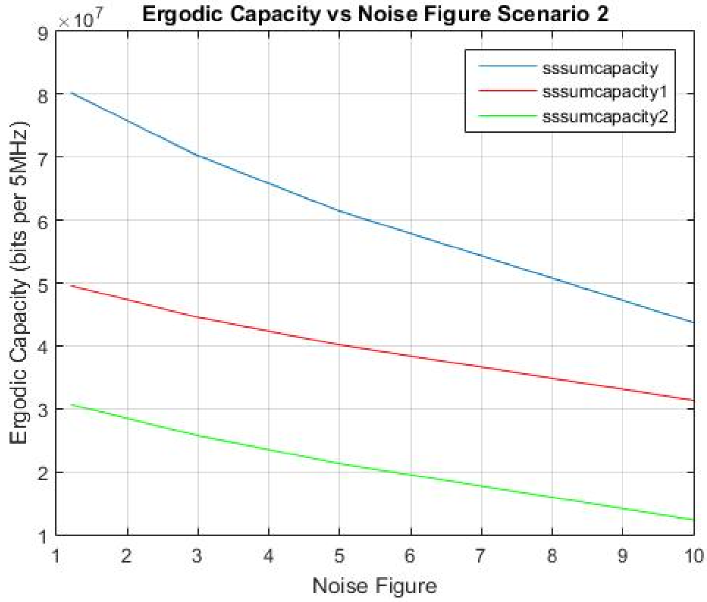

Figure 4.7: Ergodic Capacity vs Noise Figure using equal allocation of power

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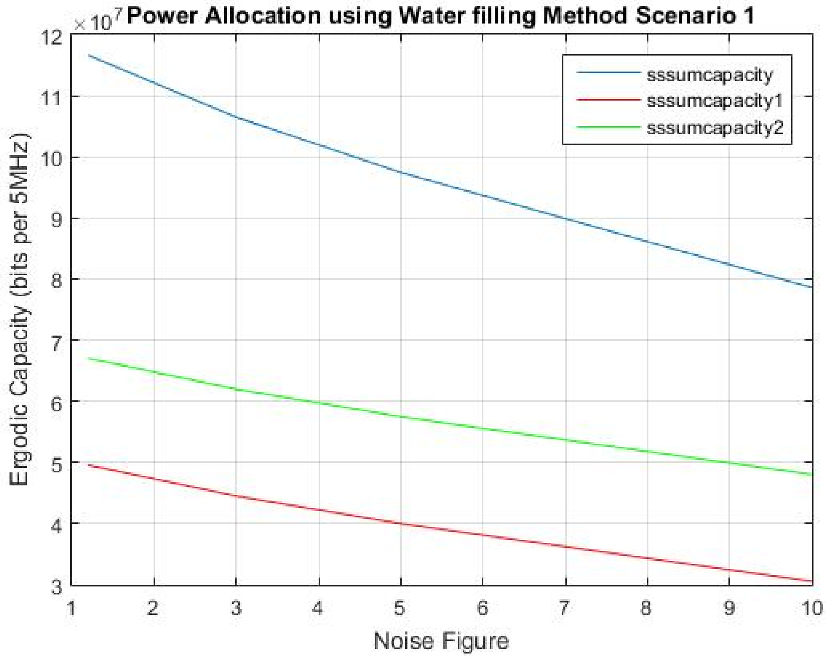

Figure 4.8: Ergodic Capacity vs Noise Figure using Water Filling Method

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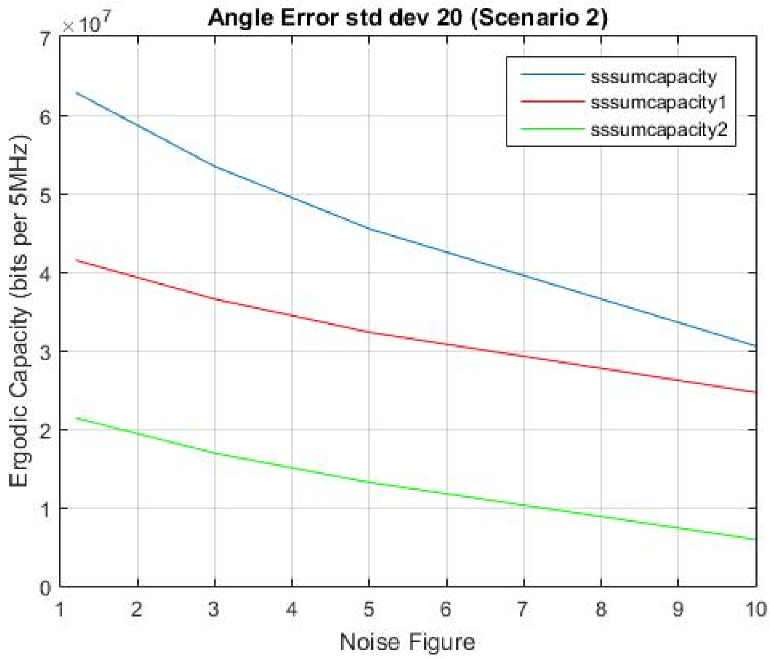

Figure 4.9: Ergodic Capacity vs Noise Figure using Water Filling Method

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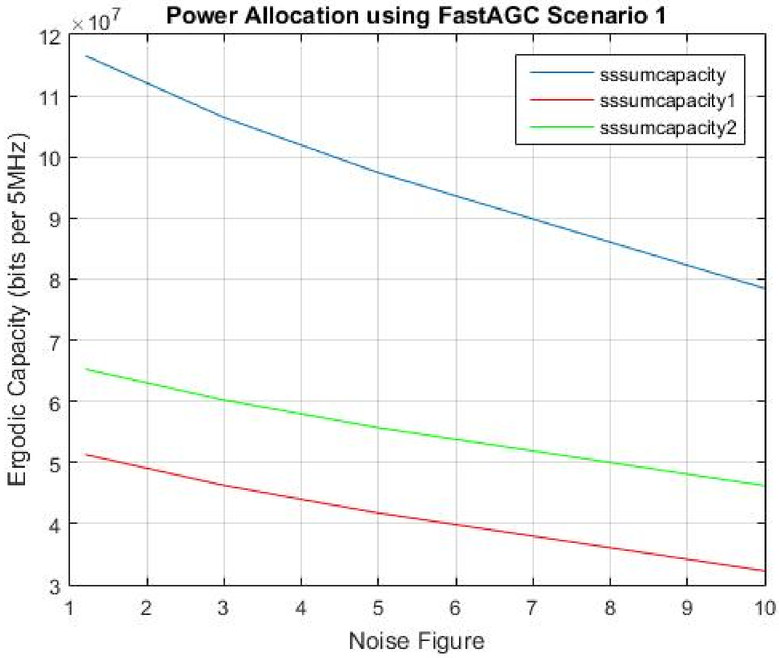

Figure 4.10: Ergodic Capacity vs Noise Figure using Fast AGC Method

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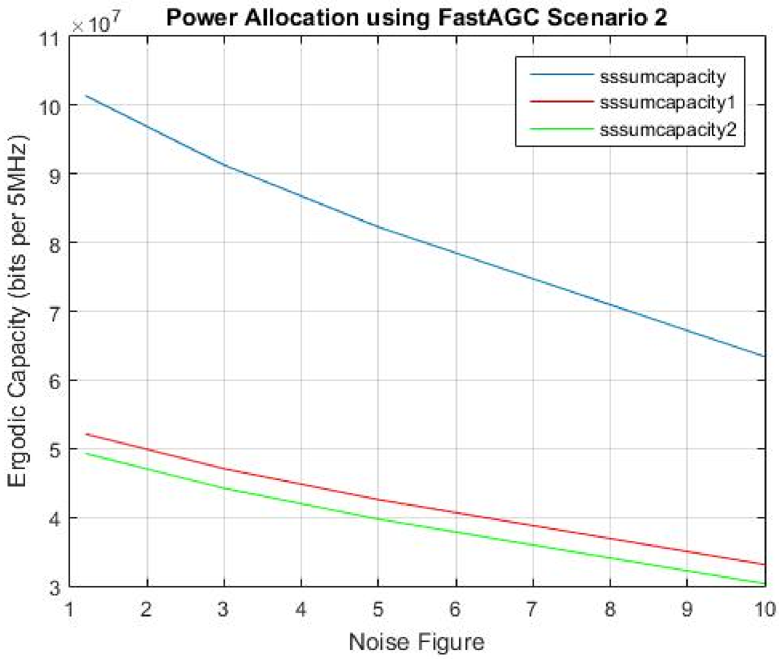

Figure 4.11: Ergodic Capacity vs Noise Figure using Fast AGC Method

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4.4.2 Optimal allocation of antennas and power: Grid method

The water-filling method is only applicable for fixed gain relay. In this section, we have introduced variable gain relay (Fast AGC). Therefore, we developed a method (Grid Method) to optimally allocate power and antenna when variable gain relay is used.

Grid method is implemented on Matlab. Please refer to source code in the Appendix section for details of the implementation. In grid method, power for different path is allocated in different ratios, i.e (0:0.1:1). For each set of power ratio the optimal number of antenna allocation is found out and recorded along with power ratio & capacity. Then, using exhaustive search method, the optimal power ratio and antenna allocation is found out on the basis of capacity. Grid method is not really an efficient way. Therefore, we would introduce Lagrange Multipliers in the next section of the thesis in order solve this power allocation method more efficiently.

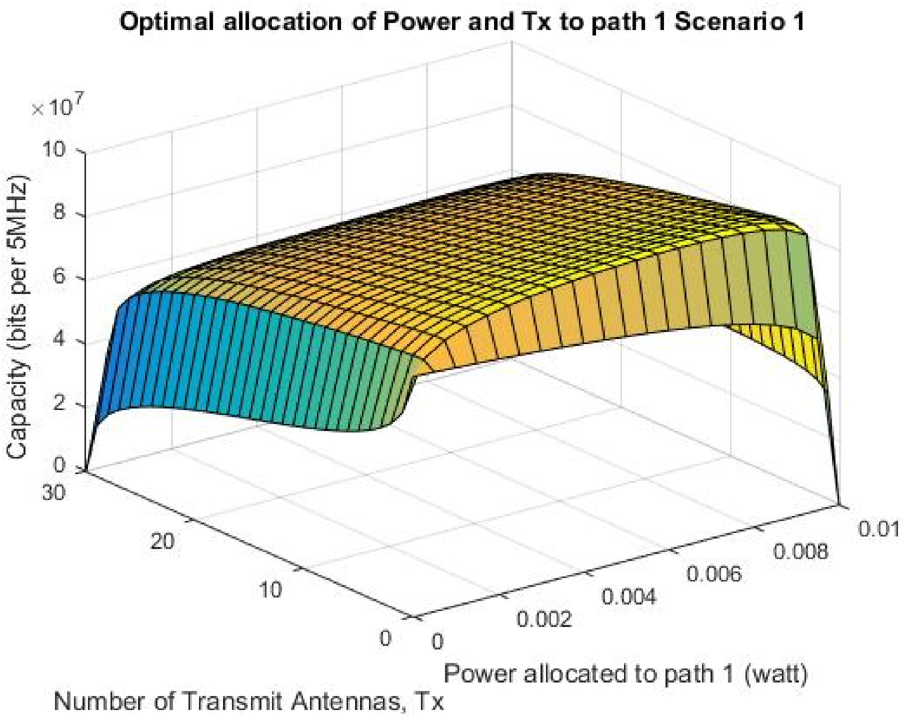

Figure 4.12: Optimal Allocation of antennas and power using fixed gain

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In Figure 4.12 , a power allocation of 0.65 is used for scenario 1 whereas power allocation of 0.60 is used in case of scenario 2 in Figure 4.13.

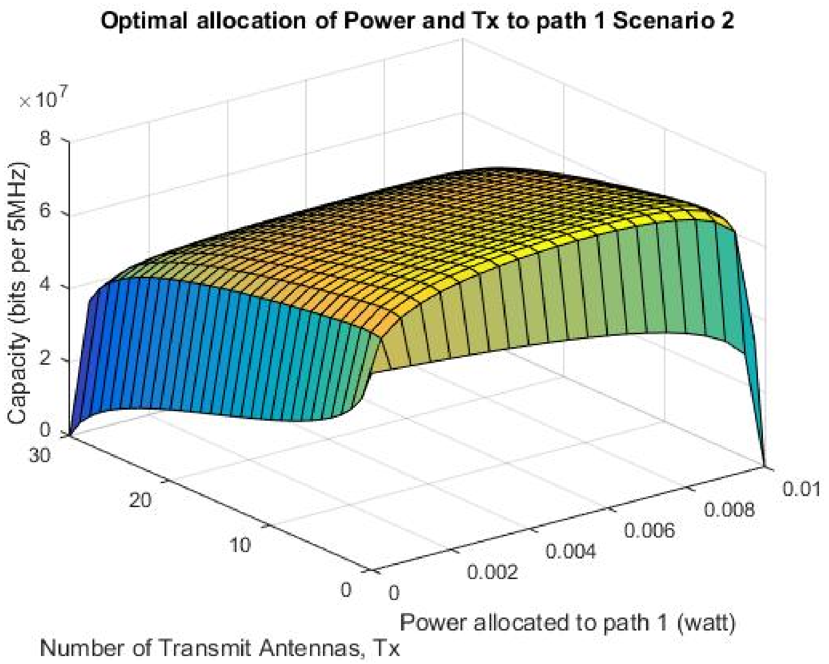

Figure 4.13: Optimal Allocation of antennas and power using fixed gain

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4.5 Angle Error

In this problem, we have introduced an angle error at the transmitter side by adjusting array-factor phase to point beam in different direction. If the angles from base-station to relay 1 and relay 2 are perfectly known then the array factor is the number of antennas allocated to that path. We intend to study what sort of effect the error has on the capacity.

Angle error could arise due to two main reasons. Firstly, due to movement which can happen due to sudden gust of wind [3]. Secondly, there could be error in measuring angle of arrival or angle of departure. The consequence of angle error is that the array factor will not be optimal (reduced). Therefore, the SNR at the destination would also reduce, thus, resulting in a lower throughput. We would now manually introduce error to study the effect on capacity.

4.5.1 WFM vs Fast AGC with angle error

Figure 4.14 and Figure 4.15 depicts the matlab simulation output for water filling method using fixed gain and grid method using Fast AGC method when angle error with 20 degrees standard deviation and zero mean is introduced for Scenario 1. Figure 4.16 and Figure 4.17 are the outputs of matlab simulation for Scenario 2.

In both scenarios, Fast AGC power allocation method performs better than water-filling method. However, in case of scenario 1, the difference in ergodic capacity between the methods is very small when compared with Scenario 2. On the other hand, between scenarios, the difference in ergodic capacity for water-filling method is much higher when compared with Fast AGC power allocation method.

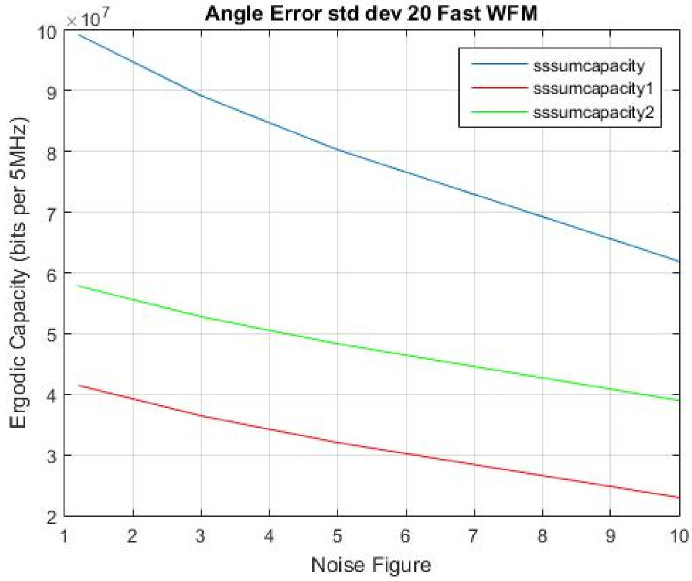

Figure 4.14: Ergodic Capacity vs Noise Figure with std dev 20 using WFM (Scenario 1)

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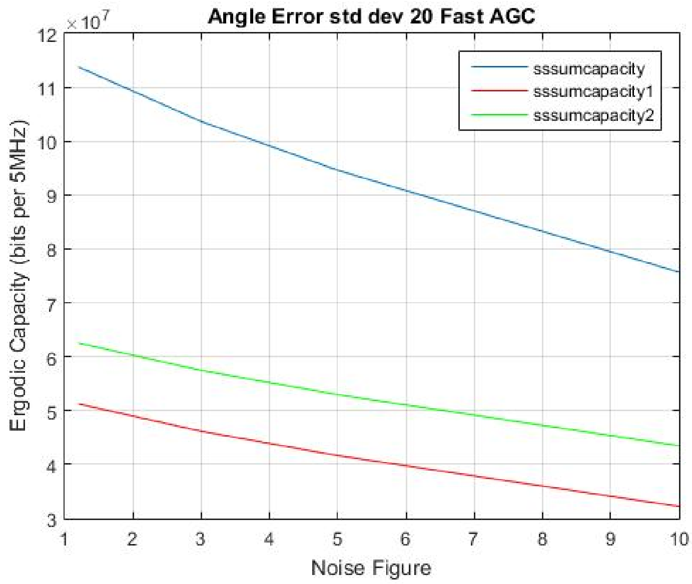

Figure 4.15: Ergodic Capacity vs Noise Figure with std dev 20 using Fast AGC method (Scenario 1)

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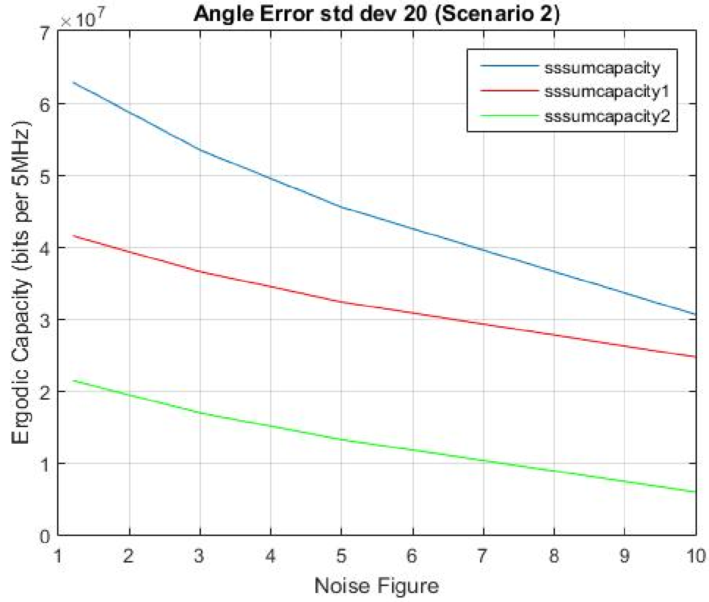

Figure 4.16: Ergodic Capacity vs Noise Figure with std dev 20 using WFM (Scenario 2)

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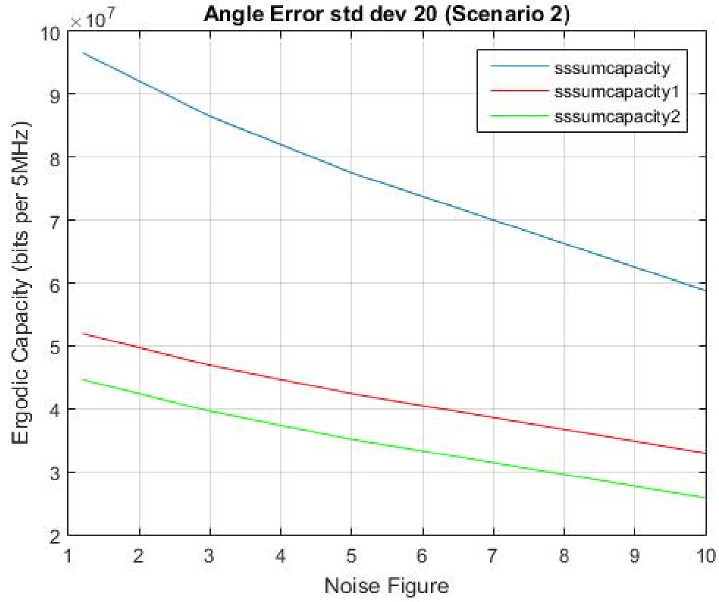

Figure 4.17: Ergodic Capacity vs Noise Figure with std dev 20 using Fast AGC method (Scenario 2)

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4.6 Varying both the Transmit Power and Number of Antennas

In this section, we are going to introduce Lagrange Multipliers. Lagrange Multipliers provide a better method of optimisation than the grid approach used earlier. This method is particularly useful when variable gain relays are used.

4.6.1 Lagrange Multipliers

In mathematical optimization, the method of Lagrange multipliers (named after Joseph Louis Lagrange is a strategy for finding the local maxima and minima of a function subject to equality constraints [71].

For instance (see figure 4.18), consider the optimization problem below:

$$\begin{aligned} \text{maximize} \quad & f(x, y) \\ \text{subject to} \quad & g(x, y) = c \end{aligned} \tag{4.39}$$

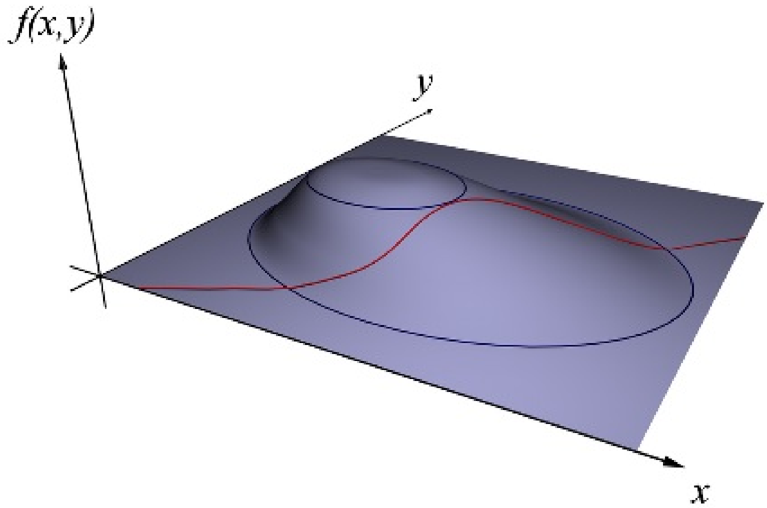

Figure 4.18: Find x and y to maximise f(x,y) subject to a constraint (shown in red) $g(x, y) = c$

We need both f and g to have continuous first partial derivatives. We introduce a new variable (λ) called a Lagrange multiplier and study the Lagrange function (or Lagrangian) defined by

$$\Lambda(x, y, \lambda) = f(x, y) + \lambda(g(x, y) - c) \tag{4.40}$$

where the λ term may be either added or subtracted. If $f(x_0, y_0)$ is a maximum of f(x, y) for the original constrained problem, then there exists λ_0 such that (x_0, y_0, λ_0) is a stationary point for the Lagrange function (stationary points are those points where the partial derivatives of Λ are zero). However, not all stationary points yield a solution of the original problem. Thus, the method of Lagrange multipliers yields a necessary condition for optimality in constrained problems [72] [73] [74] [75]. Sufficient conditions for a minimum or maximum also exist.

4.6.2 Problem formulation

This current problem (optimal transmit power and antenna allocation) is quite similar to the Optimal Antenna problem except we have two variables now. However, the structure of the problem remains the same. Now, we would formulate the problem, then use Lagrange Multipliers to solve the problem.

If transmit power available for S-R1 and S-R2 are P_1 and P_2 respectively, then, available power at the (base station) is P_T.

$$P_T = P_1 + P_2 \tag{4.41}$$

The SNR at the destination for the S-R1-D path is given by the following equation,

$$\gamma_1 = \frac{P_1 g_{S1} G_1 g_{RD1}}{N_{R1} G_1 g_{RD1} + N_{D1}} \tag{4.42}$$

$$= P_1 x B_1 \tag{4.43}$$

where x is AF_{SR1}, we could replace array factor with number of antennas in the array as discussed earlier. h_{SR1} and h_{RD1} includes both path loss and fading gain.

$$g_{S1} = AF_{SR1} \times \mathrm{SingleAntennaGain} \times \mathrm{h_{SR1}} \times \mathrm{AF_{R1}} \times \mathrm{SingleAntennaGain} \tag{4.44}$$

$$g_{RD1} = AF_{RD1} \times \mathrm{SingleAntennaGain} \times \mathrm{h_{RD1}} \times \mathrm{AF_{UE}} \times \mathrm{SingleAntennaGain} \tag{4.45}$$

where B_1 is

$$B_1 = \frac{h_{SR1} AF_{R1} G_1 g_{RD1}}{N_{R1} G_1 g_{RD1} + N_{D1}} \tag{4.46}$$

since g_{S1} and g_{RD1} are gains of the channel including array factor of the both the transmitter and receiver side antennas of the S-R1 and R1-D links respectively.

Similarly, the SNR at the destination for the S-R1-D path is given by equation 4.48, since g_{S2} and g_{RD2} are gains of the channel including array factor of the both the transmitter and receiver side antennas of the S-R2 and R2-D links respectively. Note, total number of antennas is N. x number of antennas are assigned for path 1 and $(N-x)$ are assigned for path 2.

$$\begin{aligned} \gamma_2 &= \frac{P_2 g_{S2} G_2 g_{RD2}}{N_{R2} G_2 g_{RD2} + N_{D2}} && (4.47) \\ &= P_2 (N-x) B_2 && (4.48) \end{aligned}$$

$$g_{S2} = AF_{SR2} \times \text{SingleAntennaGain} \times \text{h}_{\text{SR2}} \times \text{AF}_{\text{R2}} \times \text{SingleAntennaGain} \quad (4.49)$$

$$g_{RD2} = AF_{RD2} \times \text{SingleAntennaGain} \times \text{h}_{\text{RD2}} \times \text{AF}_{\text{UE}} \times \text{SingleAntennaGain} \quad (4.50)$$

where B_2 is

$$B_2 = \frac{h_{SR2} AF_{R2} G_2 g_{RD2}}{N_{R2} G_2 g_{RD2} + N_{D2}} \quad (4.51)$$

Finally, the SNR at the destination for path 1 and path 2 are

$$\gamma_1 = P_1 x B_1 \quad (4.52)$$

$$\gamma_2 = P_2 (N-x) B_2 \quad (4.53)$$

where B_1 & B_2 are constants, x is the number of transmit antennas allocated for path 1 & $(N-x)$ is the number of transmit antennas allocated for path 2 and assuming single antenna gain is 1 as explained in earlier sections.

Therefore, we can now deduce our capacity formula using the SNRs at the destination. The capacity equations thus becomes:

$$\begin{aligned} \text{capacity} &= w \log_2(1 + P_1 x B_1) + w \log_2(1 + P_2(N-x)B_2) && (4.54) \\ &= w \log_2\left((1 + P_1 x B_1)(1 + P_2(N-x)B_2)\right) && (4.55) \end{aligned}$$

4.6.3 Optimisation Problem

The maximum of logarithmic function of $\log(1 + f(x))$ depends on the maximum of f(x). Therefore, the optimisation problem can be formulated as follows.

$$\max\ (1 + P_1 x B_1)(1 + P_2(N - x)B_2) \tag{4.56}$$

subject to

$$0 \leq x \leq N \tag{4.57}$$
$$P_1 + P_2 \leq P_T \tag{4.58}$$
$$x, P_1, P_2 \geq 0 \tag{4.59}$$

The above problem can be re-written as follows:

$$\min\ -(1 + P_1 x B_1)(1 + P_2(N - x)B_2) \tag{4.60}$$

subject to

$$P_1 + P_2 - P_T \leq 0 \tag{4.61}$$
$$x - N \leq 0 \tag{4.62}$$
$$-x \leq 0 \tag{4.63}$$

We want to maximise the capacity of the links. The capacity equation is given by 4.55, where the capacity is a logarithmic function. As discussed above, the maximum of $\log(f(x))$ occurs at the same value of 'x' as the maximum of f(x) provided f(x) is greater than 0. Therefore, the function that we are going to maximise is given my equation 4.56. Maximising 4.56 mathematically is same as minimising 4.60.

4.6.4 Solution using Lagrange Multipliers

The typical Lagrangian equation is of the form as shown below, where u(x,y) is our function and v(x,y) are all the constraint functions.

$$L(x, y, \lambda) = x(x, y) - \lambda(v(x, y)) \tag{4.64}$$

Finally, our problem takes the following equation:

$$\begin{aligned} L(p, x, \lambda) = &-(1 + P_1 x B_1)(1 + P_2(N - x)B_2) \\ &+ \lambda_1(P_1 + P_2 - P_T) + \lambda_2(x - N) + \lambda_3 x \end{aligned} \tag{4.65}$$

(4.66)

Expanding we have:

$$\begin{aligned} L(p, x, \lambda) = & -(1 + P_2 B_2 (N - x) + P_1 B_1 x + P_1 B_1 P_2 B_2 x (N - x)) \\ & + \lambda_1 (P_1 + P_2 - P_T) + \lambda_2 (x - N) + \lambda_3 x \end{aligned} \tag{4.67}$$

Now, we take partial derivatives of our function with respect to x, P_1 and P_2. Taking partial derivative with respect to x we have:

$$\frac{\delta}{\delta x} = P_2 B_2 - P_1 B_1 - P_1 B_1 P_2 B_2 N + 2 P_1 B_1 P_2 B_2 x + \lambda_2 + \lambda_3 = 0 \tag{4.68}$$

Taking partial derivative with respect to P_1 we have:

$$\frac{\delta}{\delta P_1} = -B_1 x (1 + P_2 B_2 (N - x)) + \lambda_1 = 0 \tag{4.69}$$

Taking partial derivative with respect to P_2 we have:

$$\frac{\delta}{\delta P_2} = -(B_2 (N - x) + P_1 B_1 B_2 x (N - x)) + \lambda_1 = 0 \tag{4.70}$$

And, we have the constraint equations:

$$\lambda_1 (P_1 + P_2 - P_T) = 0 \tag{4.71}$$

$$\lambda_2 (x - N) = 0 \tag{4.72}$$

Now, we need to somehow solve these following set of equations. We have 6 variables and 6 equations.

$$\frac{\delta}{\delta x} = P_2 B_2 - P_1 B_1 - P_1 B_1 P_2 B_2 N + 2 P_1 B_1 P_2 B_2 x + \lambda_2 = 0 \tag{4.73}$$

$$\frac{\delta}{\delta P_1} = -B_1 x (1 + P_2 B_2 (N - x)) + \lambda_1 = 0 \tag{4.74}$$

$$\frac{\delta}{\delta P_2} = -(B_2 (N - x) + P_1 B_1 B_2 x (N - x)) + \lambda_1 = 0 \tag{4.75}$$

$$\lambda_1 (P_1 + P_2 - P_T) = 0 \tag{4.76}$$

$$\lambda_2 (x - N) = 0 \tag{4.77}$$

$$\lambda_3 (-x) = 0 \tag{4.78}$$

Case 1

Probably $\lambda_2 = 0 \because x \neq N$ and $\lambda_3 = 0$. Therefore, the set of equations reduces to the following set of equations.

$$P_2B_2 - P_1B_1 - P_1B_1P_2B_2N + 2P_1B_1P_2B_2x = 0 \tag{4.79}$$

$$-B_1x(1 + P_2B_2(N - x)) + \lambda_1 = 0 \tag{4.80}$$

$$-(B_2(N - x) + P_1B_1B_2x(N - x)) + \lambda_1 = 0 \tag{4.81}$$

$$P_1 + P_2 = P_T \tag{4.82}$$

Substituting $P_2 = P_T - P_1$ into Equation 4.79, we have

$$(P_T - P_1)B_2 - P_1B_1 - P_1B_1(P_T - P_1)B_2N + 2P_1B_1(P_T - P_1)B_2x = 0 \tag{4.83}$$

Equating λ_1 from Equation 4.80 and 4.81:

$$B_1x(1 + P_2B_2(N - x)) = (B_2(N - x) + P_1B_1B_2x(N - x)) \tag{4.84}$$

Simplifying Equation 4.84

$$P_1 = \frac{B_1x + P_TB_1B_2(N - x)x - B_2(N - x)}{2B_1B_2(N - x)x} \tag{4.85}$$

Simplifying Equation 4.83

$$x = \frac{-(P_T - P_1)B_2 + P_1B_1 + P_1(P_T - P_1)B_1B_2N}{2P_1(P_T - P_1)B_1B_2} \tag{4.86}$$

The above mathematical analysis of the solution of our optimal power and antennas allocation gave us two functions as shown in equation 4.85 and 4.86. We need to solve these two equations, in other words, we need need find values P_1 and x such that, they satisfy both the equations. The variables are inseparable, therefore, we would use Matlab to numerically solve the above set of equations.

Chapter 5

Conclusion and Future Work

5.1 Conclusion

The primary motive of this research was to cast more light on mmWave wireless systems for the next generation high speed mobile broadband networks. We derived closed-form equation for optimal antenna allocation in dual-hop relay network. We investigated how different power allocation methods have effect on ergodic capacity, i.e water filling method, Fast AGC method. We explored the idea of Lagrange Multipliers in constrained optimisation problems and derived optimal power allocation scheme for our Amplify & Forward relaying method in our two-hop relay network. The thesis made use of beamforming and different relay techniques in non-line-of-sight environments to compensate for severe path loss and improve system throughput. Benefits of 60 GHz directional communication are accompanied with new challenges specific for high frequency signals and directional communication. The major challenges for the future 60 GHz indoor wireless networks, high propagation and penetration losses, have been addressed analytically and through simulations in the context of relay communication.

5.2 Potential Problems to be investigated

This section briefly proposes possible further research on the topic. The suggestions discussed herein are beyond the scope of this project since we are allowed only nine months to undertake this research. Work presented in this thesis can be extended in several directions. The following section will briefly cover some research avenues which could be explored in the future.

5.2.1 Vary both the Transmit power and relay power

This problem is the extension of our first problem. However, varying the relay power makes it mathematically more challenging. The optimisation takes the following form.

$$\max C_1(x, P_{T1}, P_{R1}) * C_2(x, P_{T2}, P_{R2}) \tag{5.1}$$

subject to

$$0 \le x \le N \tag{5.2}$$
$$P_{T1} + P_{T2} \le P_T \tag{5.3}$$
$$P_{R1} + P_{R2} \le P_R \tag{5.4}$$

5.2.2 Vary transmit power in ratio of capacities

The other potential problem we can investigate in the future is to vary the transmit power according to ratio of capacities for the paths.

$$\frac{P_1}{P2} = \frac{C_1}{C_2} \tag{5.5}$$

5.2.3 Vary Number of Transmit antennas : 3 relays

This is once again extension of our first problem. However, the problem consists of 3 relays instead of 2. The capacity formula would therefore take the following form.

$$\text{capacity} = w \log_2(1 + A_1x_1) + w \log_2(1 + A_2x_2)) + w \log_2(1 + A_3(N - x_1 - x_2)) \tag{5.6}$$
$$= w \log_2 ((1 + A_1x_1)(1 + A_2x_2)(1 + A_3(N - x_1 - x_2))) \tag{5.7}$$

The optimisation would be to maximise $(1 + A_1x_1)(1 + A_2x_2)(1 + A_3(N - x_1 - x_2))$

5.2.4 *k*- relays

In this problem, we want to generalise our result for k - relays.

$$\text{capacity} = w \log_2(1 + A_1x_1) + ... + w \log_2(1 + A_k(N - x_1 - ..... - x_{k-1})) \tag{5.8}$$
$$= w \log_2 ((1 + A_1x_1) * .... * (1 + A_k(N - x_1 - .... - x_{k-1}))) \tag{5.9}$$

The optimisation for k-relays would be to maximise $((1 + A_1x_1) * (1 + A_1x_2) * .... * (1 + A_k(N - x_1 - x_2 - .... - x_{k-1})))$.

The solution to this would lead us to a very important conclusion. We could determine optimal number of relays that we could use before capacity decreases due to use of more relays.

5.2.5 Vary both the transmit power & transmit antennas for k-relays

This would be a very tedious problem to solve for because of the nature of the problem. It would require to solve $(k \times k)$ partial derivatives. Nonetheless, it is a potential future problem.

Chapter 6

Abbreviations

AF	Amplify and Forward
AGC	Automatic Gain Control
AOA	Angle of Arrival
AOD	Angle of Departure
AWGN	Additive White Gaussian Noise
BC	Broadcast Channel
BS	Base Station
CC	Coded Cooperation
CDMA	Code Division Multiple Access
CF	Compress and Forward
CRC	Cyclic Redundancy Check
CSI	Channel State Information
CSIR	Channel State Information at Receiver
CSIRO	Commonwealth Scientific Industrial Research Organisation
CSIT	Channel State Information at Transmitter
dB	Decibels
DF	Decode and Forward
EE	Energy Efficiency
ISM	Industrial Scientific and Medical
KKT	Karush Kuhn Tucker
LTE	Long Term Evolution
LOS	Line of Sight
MIMO	Multiple Input Multiple Output
MISO	Multiple Input Single Output
mmWave	Millimeter Wave
NF	Noise Figure
NLOS	Non Line of Sight
RF	Radio Frequency
QoS	Quality of Service
SE	Spectral Efficiency

SIMO	Single Input Multiple Output
SINR	Signal to Interference plus Noise Ratio
SISO	Single Input Single Output
SNR	Signal to Noise Ratio
SR	Selection Relaying
TDMA	Time Division Multiple Access
WFM	Water Filling Method
WLAN	Wireless Local Area Network

Appendix A

Matlab Coding

A.1 Overview

The project source code is provided below. However, due to strict page limit I could not include different Matlab functions I wrote. On a different note, few of the Matlab Coding lines are too big to fit in one line. Therefore, I have split the line into two and left a note there. Those lines need to be aligned first before the code could be run on Matlab. The Matlab functions could be provided upon request.

A.2 Source Code

```
clear all;
clc;
global frequency

sameseed = 1;
if sameseed
    param_seed = 3724333;
    stream = RandStream('mt19937ar','seed',param_seed);
    RandStream.setGlobalStream(stream);
end

frequency = 6.0e10;
f = frequency;
c = 3*(1e8);
lam = c/f;
k = 2*pi/lam;
d = lam/4;
KRicean = 5;
TARel1 = 100;
```

```
TARel2 = 100;
TAUE = 100;
anglestd = 0;   % degrees

BW = 5e6;
%%%%%%%%%%%%%%%%%%%%%   Device IDs   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
BS = 1;
UE = 2;
Relay(1) = 3;
Relay(2) = 4;

%%%%%%%%%%%%%%%%%%   Device parameters   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Antennas(BS) = 30;
Antennas(Relay(1)) = 1; % Assume one relay for transmitting and one for
                        % receiving for each relay, otherwise must divide
                        %capacity by 2
Antennas(Relay(2)) = 1;
Antennas(UE) = 2;

SingleAntennaGain(BS) = 1;    % Assume always this is 1. Need to include
                              %as parameter in Antenna Gain function
SingleAntennaGain(Relay(1)) = 1;
SingleAntennaGain(Relay(2)) = 1;
SingleAntennaGain(UE) = 1;

TxPower(BS) = 1.0e-2;
TxPower(Relay(1)) = 1.0e-2;
TxPower(Relay(2)) = 1.0e-2;

TxPowerdB = 10*log10(TxPower/1e-3);

RelayGain1 = 100*1e6;
RelayGain1 = 1e7;
RelayGain2 = 1e7;

FF = 10;
nerr = 1;
nruns = 1;
randomizerun = 0;
norandomizerun = 1;
randomizeclock = 0;

scenario = 2; % Pick scenario 1/2
```

```
doplot = 0;

if doplot == 1  % allocate 1
    FF = [1.2 3 5 10];
    allocate = 1;
    nerr = 1;
    nruns = 1;
    randomizerun = 0;
    norandomizerun = 1;
    randomizeclock = 0;
elseif doplot == 2  %allocate 1 ergodic capacity
    FF = [1.2 3 5 10];
    allocate = 1;
    nerr = 1;
    nruns = 10;
    randomizerun = 1;
    norandomizerun = 0;
    randomizeclock = 0;
elseif doplot == 3  %allocate 2 ergodic capacity
    FF = [1.2 3 5 10];
    allocate = 2;
    nerr = 1;
    nruns = 10;
    randomizerun = 1;
    norandomizerun = 0;
    randomizeclock = 0;
elseif doplot == 4  %allocate 3 ergodic capacity
    FF = [1.2 3 5 10];
    allocate = 3;
    nerr = 1;
    nruns = 10;
    randomizerun = 1;
    norandomizerun = 0;
    randomizeclock = 0;
elseif doplot == 5  %allocate 1/2/3 ergodic capacity with angle error
    FF = [1.2 3 5 10];
    allocate = 3;
    nerr = 50;
    nruns = 10;
    randomizerun = 1;
    norandomizerun = 0;
    randomizeclock = 0;
    anglestd = 20;   % degrees
```

```
elseif doplot == 0  % keep power ratio fixed and vary number of antennas
    FF = 10;
    allocate = 0;
    nerr = 1;
    nruns = 1;
    AAntennasTx = 0:1:Antennas(BS);
    TTxPowerRatio1 = 0.5;
elseif doplot == -1  % keep number of antennas fixed and vary power ratio
    FF = 10;
    allocate = 0;
    nerr = 1;
    nruns = 1;
    AAntennasTx = 20;


    TTxPowerRatio1 = 0:0.05:1.0;
end

FixedGainRelay1 = 1;
SlowAGCRelay1 = 0;
FastAGCRelay1 = 0;

FixedGainRelay2 = 1;
SlowAGCRelay2 = 0;
FastAGCRelay2 = 0;

if allocate == 1 || allocate == 2
    FixedGainRelay1 = 1;
    SlowAGCRelay1 = 0;
    FastAGCRelay1 = 0;
    FixedGainRelay2 = 1;
    SlowAGCRelay2 = 0;
    FastAGCRelay2 = 0;
end

if allocate == 3
    FixedGainRelay1 = 0;
    SlowAGCRelay1 = 0;
    FastAGCRelay1 = 1;
    FixedGainRelay2 = 0;
    SlowAGCRelay2 = 0;
```

```
    FastAGCRelay2 = 1;
end
%%%%%%%%%   Node positions and related angles   %%%%%%%%%%%%%%%%%%%%%%%

node_coord_x=[];
node_coord_y=[];
maxX =20;
maxY = 20;

npoints = 4;
selectrandompoints = 0;

if scenario == 1  % "fairly balanced"
    point(1,1) = 0;            % BS
    point(1,2) = 0;

    point(2,1) = 2;            % UE
    point(2,2) = 1.6;

    point(3,1) = 2;            % Relay 1
    point(3,2) = -1.6;

    point(4,1) = 1;            % Relay 2
    point(4,2) = 0.5;

    thetadeg(1) = 0;
    thetadeg(2) = 180;
    thetadeg(3) = 180;
    thetadeg(4) = 180;
elseif scenario == 2  % "fairly unbalanced"
    point(1,1) = 0;            % BS
    point(1,2) = 0;

    point(2,1) = 2;            % UE
    point(2,2) = 1.6;

   point(3,1) = 2;            % Relay 1
   point(3,2) = -1.6;

   point(4,1) = 8;            % Relay 2
   point(4,2) = 0.5;

    thetadeg(1) = 0;
```

```
    thetadeg(2) = 180;
    thetadeg(3) = 180;
    thetadeg(4) = 180;
end

if selectrandompoints
    for k = 1:npoints
        node_coord_x(k) = unifrnd(-maxX,maxX);
        node_coord_y(k) = unifrnd(-maxY,maxY);
        point(k,1) = node_coord_x(k);
        point(k,2) = node_coord_y(k);

        thetadeg(k) = unifrnd(0,360);
    end
end


theta = 2*pi*thetadeg/360;

for p1 = 1:npoints
    for p2 = 1:npoints
        if p1 ~= p2
            [phidepx(p1,p2),phiarrx(p1,p2),psidepn(p1,p2),psiarrn(p1,p2)]

% Upper line + the line below become 1 line
            = findangles(point(p1,:),point(p2,:),theta(p1),theta(p2));
        end
    end
end

phidepxdeg = phidepx*360/(2*pi);
phiarrxdeg = phiarrx*360/(2*pi);
psidepndeg = psidepn*360/(2*pi);
psiarrndeg = psiarrn*360/(2*pi);

%%%%%%%%%%%%   Path losses between nodes   %%%%%%%%%%%%%%%%%%%%%%%%%%%%

for p1 = 1:npoints
    for p2 = 1:npoints
        if p1 ~= p2
            deltax = point(p2,1) - point(p1,1);

            deltay = point(p2,2) - point(p1,2);
```

```
            distance(p1,p2) = sqrt(deltax^2 + deltay^2);
            PLdB(p1,p2) = PathLossdB(distance(p1,p2),frequency);
            meanPL(p1,p2) = 10^(PLdB(p1,p2)/10);
        end
    end
end

%%%%%%%%%%%   Random environments   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

FFadingGain = ones(npoints,npoints,nruns);
aangleerrordeg = zeros(nruns,nerr);

for irun = 1:nruns

    if randomizerun
        param_seed = 163573 + irun*5001;
        stream = RandStream('mt19937ar','seed',param_seed);
        RandStream.setGlobalStream(stream);
    end

    if norandomizerun
        param_seed = 77350;
        stream = RandStream('mt19937ar','seed',param_seed);
        RandStream.setGlobalStream(stream);
    end

    if randomizeclock
        cc = clock();
        param_seed = 163573 + irun*5001 + floor(cc(6)*7);
        stream = RandStream('mt19937ar','seed',param_seed);
        RandStream.setGlobalStream(stream);
    end


    for p1 = 1:npoints
        for p2 = 1:npoints
            if p1 ~= p2
                FFadingGain(p1,p2,irun) = riceangain2(KRicean);
            end
        end
    end
```

```
    for ierr = 1:nerr
        aangleerrordeg(irun,ierr) = normrnd(0,anglestd);
    end
end



for irun = 1:nruns

    fprintf('+++++++++++++++++++++++++++++++\n');
    fprintf('irun=%d\n',irun);
    FadingGain = FFadingGain(:,:,irun);
    angleerrordeg = aangleerrordeg(irun,:);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for iF = 1:length(FF)


        FReldB1 = FF(iF);
        FReldB2 = FF(iF);
        FUEdB = FF(iF);

 [NoiseRelay1,NoiseUE1] = computeNoiseAF2(FReldB1,FUEdB,TARel1,TAUE,BW);
 [NoiseRelay2,NoiseUE2] = computeNoiseAF2(FReldB2,FUEdB,TARel2,TAUE,BW);

        AntennasRx(BS,Relay(1)) = Antennas(Relay(1));
        AntennasRx(BS,Relay(2)) = Antennas(Relay(2));

        AntTx(Relay(1),UE) = Antennas(Relay(1));
        AntTx(Relay(2),UE) = Antennas(Relay(2));

        AntennasRx(Relay(1),UE) = 1;
        AntennasRx(Relay(2),UE) = Antennas(UE) - AntennasRx(Relay(1),UE);

GainRx(BS,Relay(1)) = AntennaGain(psiarrn(BS,Relay(1)),AntennasRx(BS,Relay(1)),0);
GainRx(BS,Relay(2)) = AntennaGain(psiarrn(BS,Relay(1)),AntennasRx(BS,Relay(2)),0);
GainTx(Relay(1),UE) = AntennaGain(psidepn(Relay(1),UE),AntTx(Relay(1),UE),0);
GainTx(Relay(2),UE) = AntennaGain(psidepn(Relay(2),UE),AntTx(Relay(2),UE),0);

GainRx(Relay(1),UE) = AntennaGain(psiarrn(Relay(1),UE),AntennasRx(Relay(1),UE),0);
GainRx(Relay(2),UE) = AntennaGain(psiarrn(Relay(2),UE),AntennasRx(Relay(2),UE),0);

 hSR1 = SingleAntennaGain(BS)*FadingGain(BS,Relay(1))/meanPL(BS,Relay(1));
```

```
 hSR2 = SingleAntennaGain(BS)*FadingGain(BS,Relay(2))/meanPL(BS,Relay(2));

        GRxR1 =  GainRx(BS,Relay(1));
        GRxR2 =  GainRx(BS,Relay(2));

        GTxR1 = GainTx(Relay(1),UE);
        GTxR2 = GainTx(Relay(2),UE);

        hRD1 = FadingGain(Relay(1),UE)/meanPL(Relay(1),UE);
        hRD2 = FadingGain(Relay(2),UE)/meanPL(Relay(2),UE);

        GRxUE1 = GainRx(Relay(1),UE);
        GRxUE2 = GainRx(Relay(2),UE);

        gRD1 = GTxR1*hRD1*GRxUE1;
        gRD2 = GTxR2*hRD2*GRxUE2;
%Allocate antennas only using equal power alloc, assuming fixed gain relay
        if allocate == 1
            TTxPowerRatio1 = 0.5;
            PT1 = TxPower(BS)*TTxPowerRatio1;
            PT2 = TxPower(BS) - PT1;

            N = Antennas(BS);
            G1 = RelayGain1;
            G2 = RelayGain2;
            nR1 = NoiseRelay1;
            nR2 = NoiseRelay2;
            nD1 = NoiseUE1;
            nD2 = NoiseUE2;

            AA1 = hSR1*G1*gRD1/(nR1*G1*gRD1 + nD1);
            AA2 = hSR2*G2*gRD2/(nR2*G2*gRD2 + nD2);

            A1 = PT1*AA1;
            A2 = PT2*AA2;

            xmax = (A1 - A2 + A1*A2*N)/(2*A1*A2)
            if xmax < 0; xmax = 0; end
            if xmax > N; xmax = N; end
            AAntennasTx = round(xmax);

        elseif allocate == 2  % Assume fix gain relay
            % Use waterfilling to determine the optimal power allocation
```

```
          N = Antennas(BS);

          nR1 = NoiseRelay1;
          nR2 = NoiseRelay2;
          nD1 = NoiseUE1;
          nD2 = NoiseUE2;
          w = BW;
          Amaxcap = 0;
          for NX=0:Antennas(BS)
              G1 = RelayGain1;
              G2 = RelayGain2;
              gs1 = NX*hSR1*G1*gRD1;
              gs2 = (N-NX)*hSR2*G2*gRD2;
    [PT1,PT2] = waterfillgainnoise(gs1,gs2,NoiseUE1,NoiseUE2,TxPower(BS));
              SNR1 = PT1*gs1/(nR1*G1*gRD1 + nD1);
              SNR2 = PT2*gs2/(nR2*G2*gRD2 + nD2);
              Acap1 = w*log(1+SNR1)/log(2);
              Acap2 = w*log(1+SNR2)/log(2);
              Acap = Acap1 + Acap2;
              if Acap > Amaxcap
                  Amaxcap = Acap;
                  APT1 = PT1;
                  APT2 = PT2;
                  ANX = NX;
              end
          end
           TTxPowerRatio1 = APT1/TxPower(BS);
           AAntennasTx =ANX;

% Assume fastAGC. Search over PT1,NX grid for max capacity
       elseif allocate == 3
           N = Antennas(BS);
          nR1 = NoiseRelay1;
          nR2 = NoiseRelay2;
          nD1 = NoiseUE1;
          nD2 = NoiseUE2;
          w = BW;

          Amaxcap = 0;
          nPower = 20;
          dPower = TxPower(BS)/nPower;
          NNX = 0:Antennas(BS);
          iiPower = 0:nPower;
```

```
            PPower = TxPower(BS)*iiPower/nPower;
            for NX=0:Antennas(BS)
              for iPower=0:nPower;
                PT1 = iPower*dPower;
                PT2 = TxPower(BS) - PT1;
                PR1 = TxPower(Relay(1));
                PR2 = TxPower(Relay(2));

                G1 = PR1/(NX*hSR1*PT1 + nR1);
                G2 = PR2/(NX*hSR2*PT2 + nR2);
                gs1 = NX*hSR1*G1*gRD1;
                gs2 = (N-NX)*hSR2*G2*gRD2;

                SNR1 = PT1*gs1/(nR1*G1*gRD1 + nD1);
                SNR2 = PT2*gs2/(nR2*G2*gRD2 + nD2);
                Acap1 = w*log(1+SNR1)/log(2);
                Acap2 = w*log(1+SNR2)/log(2);
                Acap = Acap1 + Acap2;
                grid3(NX+1,iPower+1) = Acap;
                if Acap > Amaxcap
                    Amaxcap = Acap;
                    APT1 = PT1;
                    APT2 = PT2;
                    ANX = NX;
                end
              end
            end
             TTxPowerRatio1 = APT1/TxPower(BS);
             AAntennasTx =ANX;
        else  % Default for manual allocation
        end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for ierr = 1:nerr
    Tmaxcap = 0;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for TT=1:length(TTxPowerRatio1)
TxPowerRatio1 = TTxPowerRatio1(TT);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    for iAnt = 1:length(AAntennasTx)
AntTx(BS,Relay(1)) = AAntennasTx(iAnt);
AntTx(BS,Relay(2)) = Antennas(BS) - AntTx(BS,Relay(1));

anglerr = angleerrordeg(ierr)*2*pi/360
```

```
GainTx(BS,Relay(1))=AntennaGain(psidepn(BS,Relay(1)),AntTx(BS,Relay(1)),anglerr);
GainTx(BS,Relay(2))=AntennaGain(psidepn(BS,Relay(2)),AntTx(BS,Relay(2)),anglerr);
Gain(BS,Relay(1)) = GainTx(BS,Relay(1)) * GainRx(BS,Relay(1)) /meanPL(BS,Relay(1));
Gain(BS,Relay(2)) = GainTx(BS,Relay(2)) * GainRx(BS,Relay(2)) /meanPL(BS,Relay(2));
Gain(Relay(1),UE) = GainTx(Relay(1),UE) * GainRx(Relay(1),UE) /meanPL(Relay(1),UE);
Gain(Relay(2),UE) = GainTx(Relay(2),UE) * GainRx(Relay(2),UE) /meanPL(Relay(2),UE);

Gainwithfading = Gain.*FadingGain;
GGainBSRel1(iAnt) = Gain(BS,Relay(1));
GaindB = 10*log10(Gain);
GainwithfadingdB = 10*log10(Gainwithfading);
TxPowerBSRelay1 = TxPowerRatio1*TxPower(BS);
TxPowerRelay1UE = TxPower(Relay(1));

PT1 =TxPowerBSRelay1;
PR1 = TxPowerRelay1UE;
nR1 = NoiseRelay1;

if FixedGainRelay1
    G1 = RelayGain1;
end
if SlowAGCRelay1
    G1 = PR1/(Gain(BS,Relay(1))*PT1 + nR1);
end
if FastAGCRelay1
   G1 = PR1/(Gainwithfading(BS,Relay(1))*PT1 + nR1);
end
PR1 = G1*(Gainwithfading(BS,Relay(1))*PT1+nR1);
gs1 = Gainwithfading(BS,Relay(1))*G1*Gainwithfading(Relay(1),UE);

[SNRRel1,SNRUE1] = computeSNRAF2(Gainwithfading(BS,Relay(1)),G1,Gainwithfading

% upper line + this line (Relay(1),UE),TxPowerBSRelay1,NoiseRelay1,NoiseUE1);
capBSR1UE = twohoprelaycapacityAF2(SNRRel1,SNRUE1);

TxPowerBSRelay2 = (1 -TxPowerRatio1)*TxPower(BS);
TxPowerRelay2UE = TxPower(Relay(2));


PT2 =TxPowerBSRelay2;
PR2 = TxPowerRelay2UE;
nR2 = NoiseRelay2;
```

```
if FixedGainRelay2
    G2 = RelayGain2;
end
if SlowAGCRelay2
    G2 = PR2/(Gain(BS,Relay(2))*PT2 + nR2);
end
if FastAGCRelay2
   G2 = PR2/(Gainwithfading(BS,Relay(2))*PT2 + nR2);
end
PR2 = G2*(Gainwithfading(BS,Relay(2))*PT2+nR2);

gs2 = Gainwithfading(BS,Relay(2))*G2*Gainwithfading(Relay(2),UE);

[SNRRel2,SNRUE2] = computeSNRAF2(Gainwithfading(BS,Relay(2)),G2,Gainwithfading

% Upper line + this line (Relay(2),UE),TxPowerBSRelay2,NoiseRelay2,NoiseUE2);
capBSR2UE = twohoprelaycapacityAF2(SNRRel2,SNRUE2);

GG1(iAnt) = gs1;
GSNR1(iAnt) = SNRUE1;
GCap1(iAnt) = capBSR1UE;

GG2(iAnt) = gs2;
GSNR2(iAnt) = SNRUE2;
GCap2(iAnt) = capBSR2UE;

sumcapacity1 = BW*(capBSR1UE);
sumcapacity2 = BW*(capBSR2UE);
sumcapacity = sumcapacity1 + sumcapacity2;

psumcapacity(iF,TT,irun) = sumcapacity;
psumcapacity1(iF,TT,irun) = sumcapacity1;
psumcapacity2(iF,TT,irun) = sumcapacity2;

sssumcapacity(iF,iAnt,irun) = sumcapacity;
sssumcapacity1(iF,iAnt,irun) = sumcapacity1;
sssumcapacity2(iF,iAnt,irun) = sumcapacity2;

SSNRRel1(iF,iAnt,irun) = SNRRel1;
SSNRRel2(iF,iAnt,irun) = SNRRel2;
SSNRUE1(iF,iAnt,irun) = SNRUE1;
SSNRUE2(iF,iAnt,irun) = SNRUE2;
```

```
esumcapacity(ierr) = sumcapacity;
esumcapacity1(ierr) = sumcapacity1;
esumcapacity2(ierr) = sumcapacity2;

        if sumcapacity > Tmaxcap
            Tmaxcap = sumcapacity;
            Tmaxcap1 = sumcapacity1;
            Tmaxcap2 = sumcapacity2;
            Tmaxant = AAntennasTx(iAnt);
            Tmaxpowerratio1 = TxPowerRatio1;
        end
    end
end  % iAnt
end % TTxPowerRatio1
end %ierr

NN = Antennas (BS);
w = BW;
xx = Tmaxant;

C1 = Tmaxcap1/w;
C2 = Tmaxcap2/w;

if xx ~= 0 && xx ~= NN
    AB1 = (2^C1 - 1)/xx;
    AB2 = (2^C2 - 1)/(NN-xx);

xBmax = (AB1 - AB2 + AB1*AB2*NN)/(2*AB1*AB2)
if xBmax < 0; xBmax = 0; end
if xBmax > NN; xBmax = NN; end

maxcap = (w*log10(1+AB1*xBmax) + w*log10(1 + AB2*(NN-xBmax)))/log10(2)
end
if doplot == 1
    doplotx(iF) = FF(iF);
    doploty(iF) = sumcapacity;
    doploty1(iF) = sumcapacity1;
    doploty2(iF) = sumcapacity2;
end
if doplot == 2 || doplot == 3 || doplot == 4
    doplotx(iF) = FF(iF);
    doploty(iF,irun) = sumcapacity;
```

```
    doploty1(iF,irun) = sumcapacity1;
    doploty2(iF,irun) = sumcapacity2;
end
if doplot == 5
    doplotx(iF) = FF(iF);
    doploty(iF,irun) = mean(esumcapacity);
    doploty1(iF,irun) = mean(esumcapacity1);
    doploty2(iF,irun) = mean(esumcapacity2);
end % iF
end % irun
```

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