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MIMO CHANNEL MODEL

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Abstract

Multiple-input multiple-output is a system that allows the technology to meet the growing demand for high data rates in wireless communications systems. The aim of this thesis is to investigate the capacity capability of the geometric channel model by using the one-ring and two-ring channel model and attempting to explain the differences and similarities between these two models.

Simulations were performed on one-ring and two-ring channel models by using mat-lab code programming. These simulations indicate the ideal capacity results of one-ring and two-ring channel models. The simulation results show that capacity increased for both one-ring and two-ring channel model. However, in one-ring model, the mean capacity is more stable than the mean capacity of two-ring model, but the two-ring model has greater mean capacity than one-ring model.

There are two types of conditions that have been applied: the equal power allocation and the water-filling. Mean capacity of both equal power and water-filling increased as the signal to noise ratio (SNR) is increased. The difference between these two capacities is that the equal power method has no knowledge about the channel of the transmitter and the transmit signal power is divided equally over the transmitting antennas. Water-filling assumes perfect knowledge about the channel which allows the total power to be divided in the most efficient way over different transmitters. Therefore, the results show the equal power has less capacity than the water-filling. Another element that affects the mean capacity is mutual coupling. The results show that the mutual coupling can be increased or decreased based on the close space between antennas.

Acknowledgement

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This thesis is dedicated to my parents, my father Homoud Alhajri and my mother Haya Alshiek and all my brothers and sisters for all their support and encouragements. Special thanks to all my friends back home (Saudi Arabia), here (United Kingdom) and also my class mates for sharing their knowledge with me and having a good time together.

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Chapter one

Background and motivation

1.1 Background

Wireless communication can be considered as one of the fastest technology in the recent years. Each generations of wireless communication separated by only a few years time that brought important improvement in terms of link communication speed, device size, battery life, different application and so on. As the communication systems become part of human life, huge demand of high speed data rate for both business and private sectors enforce bandwidth on demand with high spectrum efficiencies and more reconfigurable system and adaptive so it can be applied multiple standards and multiple frequency bands which help accelerating the research and development for broadband access technologies without needs of new bandwidth. As the developing countries realized the principals for such technologies that improved quality of economic and daily life, broadband wireless access both in fixed and mobile type environment are increasing.

One of the challenges that face fixed broadband wireless system to achieve high data rates and high quality wireless access over fading channels at most wire-line quality since they are compared to cable modems and asynchronous DSL which operate over fixed wire-line channel. One of the most promising solutions of this problem is by using multiple antennas at both side of receiver (Rx) and transmitter (Tx) to reduce the fading that described. This method is known as multi-input multi-output (MIMO) antennas by using combination signal processing and coding that can provide to have a good implementation choice. However, fading is still causing a major problem for wireless system that can be caused by destructive addition of multi-path in the propagation medium and interference from other users. For MIMO system, the performance gained can be improved through four aspects array gain, diversity gain, interference suppression and multiplexing gain. In array gain, multiple antennas can coherently combine signals to increase the signal to noise ratio and hence improve the performance that can be applied at both the Tx and Rx to be exploited, one requires channels state information (CSI). CSI is difficult to find at the Tx, therefore array gain usually occur at the Rx. spatial diversity via multiple antenna can be used to reduce the fading and improve the link reliability.

According to Jakes (1974) the Rx can receive several identical transmitted singles which can be capable to reduce the fading and interference. Most common diversity are time diversity and frequency diversity, but in recent year spatial or antenna diversity started to appear and have more effective. Diversity gain can be found at both the Rx and Tx end. Space time code which is coding crosses space (antenna) and crosses time developed to allow the diversity gain to receive the signals without identify the channel at the Tx. The separating single transmission has been implemented in similar systems which use multiple antennas at the Rx and a single antenna at the Tx knowing as single-input multiple-output (SIMO). This system provide spatial/receive diversity and with maximum ratio combination to have higher capacities. Tanner (1999) says using multiple antennas in the MIMO system help out the multipath environment to be exploited through spatial multiplexing and to be capable to improve capacities. Paulraj (2001) claims that the separation of data stream occurs in spatial domain via several of different propagation path in the rich scattering environment, one of that is capable to transmit several data stream simultaneously at the same time and with the same frequency interval without changing the overall transmit power of the system. Moreover, the deep fade can be disappeared and single levels are higher and more stable over time.

Cioff (2005) believes another factor to improve the implementation of MIMO systems is interference suppression which is used to suppress co-channel interference and hence increasing capacity. Telatar (1995) says fixed line MIMO systems have different condition, since the channel changes are negligible and have prefect state information at the Tx. In the situation, it can use water-filling, yielding optimal performance of the MIMO system. If the CSI is not perfect, the Tx can rely on the average statistic from the Rx which can result in sub-optimal channels capacity.

1.2 Outline thesis

This chapter has shown an introduction of MIMO channel models which explained the motivation and aims of the thesis. The rest of thesis is organized as follows

In chapter two, literature review of MIMO channel model is presented. Literature review indicates different classification of MIMO channel models that depend on of the channel type such as narrowband or the modelling approach such as physical model. However, geometric channel models are the main purpose of this thesis, especially one-ring and two-ring channel models. Therefore, both models have been explained in more details.

In chapter three, MIMO capacity analysis is presented to understand the operation of MIMO system, since there are many elements present between the transmitter antennas and receiver antennas. Moreover, both capacities of one-ring and two-ring channel modes are explained in more details and the power allocation that implement on one-ring and two-ring channel model. Another aspect that affects the capacity is mutual coupling that has been explained in more details.

Chapters four and five shows the MIMO capacity results based on one-ring and two ring channel models respectively. The capacity results effect of number of scatteres, spacing antenna and different distance between the transmitter antennas and receiver antennas are discussed as function of signal noise ratio (SNR). The different capacity results based on different power allocation are explained.

Finally, chapter six provides a summary of the thesis and presents some suggestion of future work.

Chapter 2:

Literature review:

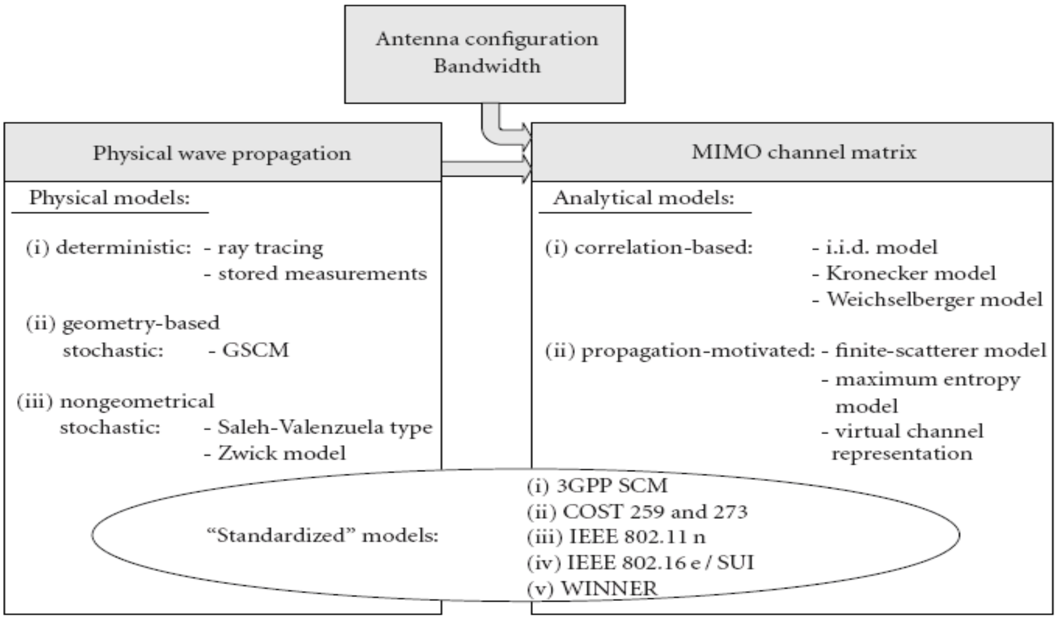
2.1 Introduction

Multiple-input multiple-output systems (MIMO) are a new evolution for future wireless communication. According to Kahn (2000), the last ten years MIMO technology has been developed from purely theoretical performance analyse that provide a huge capacity gain to reality products for the wireless communications market. However, MIMO techniques still have not reached the maximum realistic propagation condition and hence their integration into real applications can be considered to still be underdeveloped. Czink (2005) believes it is the radio propagation channel that determines the characteristics of all MIMO systems. Therefore, the accurate modelling of the MIMO system is very significant especially for MIMO system design, simulation and performance and it is also important for analytical MMO channel models that represent the impulse response of the channel between the receiver and transmitter at both link ends. Providing analytical expressions for the channel matrix are very important for improving MIMO algorithms in general. In order to determine the goodness of the MIMO performance, certain measures are required. Some applications of specific matrices can be effective to reduce the reality to some specific aspects, but a single matrix is not enough for capturing entire properties of MIMO channels. In this chapter, two types of stochastic channel models shall be reviewed. These include geometric models and correlation based models.

2.2 Classification of channel models

There are different categorizes of MIMO channel models that have different construct and analysis complexity. Rohila (2005) says that data rate of MIMO systems increases linearly with number of transmitter (TX) antennas. However, increasing the transmission data in a given bandwidth which can be exploited in MIMO system depends on a number of parameters observed at the receiver (RX), the average power of the desired signal, thermal, system related noise and co-channel interferences. According to Ozcelik (2006) a variety of channel models, many of them dependent on measurement, have been reported a few years ago. Therefore, it can be classified in many different ways. One of the ways to distinguish the individual modes is based on the types of the channel, since there are two baseband MIMO channels narrow band (flat fading) and wideband (frequency selective). For narrowband MIMO, channels can be completely characterized in order of their spatial structure. On the other hand, wideband channels need additional modelling of multipath characteristics.

Another method to classify channel models (Zwick, 2006) suggests that channel models can be classified based on the modelling approach taken. Therefore, there are two different classifications, physical models and analytics models as shown in figure 1. The basic distinction between these two is that physical channel models characterize an environment on the basis of electromagnetic wave propagation by indicating the double direction multipath propagation between the locations of the transmitter (Tx) and receiver (Rx). The parameters of this wave kind of model propagation can be like complex amplitude, direction of departure (DoD) and direction of arrival and delay of an multipath component (MPC). Moreover, more advantageous modes incorporate polarization and time variation. Physical models can be more accurate. Reproduction model propagation depends on the chosen complexity and it also has independent configuration and system bandwidth from antenna configuration and bandwidth. On the other hand, analytical channel models are characterized based on the impulse response of the channel between the individual receiver and transmitter antennas in analytical or mathematical method without clearly knowing the number of wave propagation. The individual impulse responses are part of MIMO channel matrix. Analytical models can be seen more in synthesizing MIMO matrices in the context of the system, verification and algorithm.



2.2.1 Physical models

Jensen (2001) believes that physical MIMO channel models can be subdivided to three main models: deterministic models, geometry-based stochastic models and non-geometric stochastic models. In deterministic models, propagation parameters are in a completely deterministic way. For geometry-based stochastic channel models (GSCM), it is easy to implement as the impulse response is characterized by the low wave propagation that applies to the transmitter (Tx), receiver (Rx) and scatterer geometries as they are chosen in a stochastic (random) way. On the other hand, the non-geometric stochastic model is the opposite of the previous as there are no references to the geometry applied to the transmitter (Tx), receiver (Rx) and scatterer geometries, for example the Saleh-Valenzuela model.

2.2.1.1 Deterministic physical models

Physical propagation models or deterministic models invloves reproducing the actual physical radio propagation process for a given environment. Paul (2008) shows that in an urban environment case, the geometry and electromagnetic characteristics of the environment can be easily stored in files and the corresponding propagation can be simulated through software. One of the most popular software is ray tracing for simulating the electromagnetic propagation between transmitter (Tx) and receiver (Rx). The advantage of these models is the accuracy and they can be used in campaigns when time is at premium. In ray tracing technique, the polygons shapes generally represent buildings. Ray tracing software is usually based in phenomena geometrics such as reflection, refraction and diffraction. In urban environments, the geometrical optics is very suitable since the wavelength of operation is much smaller than other environments which introduce many obstacles.

2.2.1.2Geometry-based stochastic models

Paul (2008) says geometry based channel models can be considered as a simplification of the deterministic models, as the deterministic model requires a huge database of the environment and its propagation condition. In geometry based channel models, the scatter locations are found randomly as they are controlled by probability distribution functions depending on the performance. This part will be further investigated later on.

2.2.1.3Non-geometrical based stochastic models

According to Valenzuela (1987), there are no references to the geometry of physical environments. It only describes the path from the transmitter (Tx) to the receiver (Rx). In non-geometrical model, there are two classes that are most popularly used: The extend

Saleh-Valenzuela model and Zwick model. The extend Saleh-Valenzuela model uses the clutters to allow the multipath components (MPCs) to arrive to the other side. In contrast, Zwichk model MPCs can arrive to other side individually.

2.2.2 Analytical models

Analytical models are completely different from physical models in the study of Guzman (2008) as it is focused on the impulse response (equivalent, the transfer function) of the channel between individual receiver (Rx) and transmitter antennas in a mathematical or analytical manner without considering the accuracy of the wave propagation. Usually, analytical models are dealing with synthesizing MIMO matrices in the context of system, algorithm and verification. However, analytical models can be divided into two models, correlation-based models and propagation motivated.

2.2.2.1 Correlation-based models

Correia (2006) says correlation based models describe the complexity properties between all pair receive and transmit antennas. Basically, the correlations depend on the actual configuration of the antennas. The correlation models can be useful when analysing the impact of correlation on any performance. However, correlation models can be further subdivided into several models, but the most popular models used are Kronecker model and Weichselberger model.

2.2.2.2 Propagation motivated analytical model

Burr (2003) Propagation motivated model represents the MIMO channel matrix through propagation parameters. Propagation motivated models can be subdivided into several models, but more popular models are the finite scatterer model, maximum entropy model and virtual channel model. More details will be described for finite scatterer model since there is some relation between finite scatterer model and geometry-based stochastic models.

2.2.2.3 Finite scatterer model

Finite scatterer model is the propagation model that is modelled as a finite number □ of multipath components (MPCs). Each of these components such as DoD □□, DoA Ψ□ complex amplitude □□ and delay is specified. (Jakes, 1973) adds finite scatterer can be applied for signal-bounce and multiple-bounce which is in contrast to GSCMs that only apply for single-bounce and double-bounce. Another feature of finite scatterer model allows further splits components that can have a single DoD but subsequently subdivided into two or more paths, the splits can be either have same components or different components. However, this literature review is only interested in single-bounce and double bounce which are part of GSCMs.

2.3 Geometry-based stochastic physical models

Ozcelik (2007) says that geometry-based models can be obtained based on the scatterer location. In contrast, geometry-based stochastic channel model (GSCM) decide the scatterer location in stochastic (random) based on certain distribution. Therefore, the impulse response of the channel can be simply found by ray tracing (RT) procedure. However, the point of GSCM is that has a number of important advantages according to (Schmalenberger, 2003) which are:

- GSCM has an immediate relation to physical reality such as scatterer location that can be obtained easily through simple geometrical consideration,

- Many effects can be reproduced as before, for instant small-scale fading is created by the superposition of wave form individual scatterer; direction of arrival (DoA) and delay drifts effect by MS movement are totally joined.
- All information can be passed to next scatterer that allows dependencies of power delay (DPD) and angular power spectrum (APS) has an easy model that does not include any complication.
- Tx (transmitter)/ Rx (receiver) and scatterer movement as well as shadowing and disappearance of propagation paths can be easily implemented which allows for a long term channel correlation in straightforward way.

There are three basic geometric channel models representations

- One ring model
- Two ring model
- Elliptical model

This literature review is focusing on one-ring model and two-ring models since these two are the main elements of this dissertation.

2.3.1 one-ring model

One-ring model according to (Kahan, 2000) has been presented to study the correlation and capacity of the MMO system. In one-ring model the transmitter (Tx) assume to be elevated and hence has no scatterer around it while the receiver (Rx) is surrounded by scatterer. The effective scatterer are located on a ring which the reason to call it one-ring model. Each effective scatterer has a random phase shift which uniformly distributed over $(-\pi,\pi)$. Therefore, each ray that is reflected once by scatterer allow all rays to reach the receiver with same power. The MIMO channel coefficient can be calculated by using geometric consideration of the path length.

2.3.2 Single-bounce scatterer

(Lee, 1973) says the predecessor of the GSCM located scatterer in a deterministic way on the circuit around the Tx and assumes only single scattering occurs as one interacting object between Tx and Rx. Twenty years later, a couple of groups tried to replace the single-scattering model by using randomly placed scatterers. According to Rappaport (2002), in reality, the random scatterers placed allow for a much better physical reflection. Moreover, the random single scattering makes the transmitter much simpler, apart from the line of sight (LoS) it can have all paths containing two sub-paths connecting the scatterers to the Tx and Rx respectively. These paths usually are DoD, DoA and propagation time which usually have a low power. Also, the scatterer interaction can be taken into account through additional random phase. However, (Bonek, 1998) adds the proposed scatterer distributions can be distinguished based on the versions of the GSCM. The GSCM can be obtained by assuming that the scatterers are spatially uniformly distributed. Basically, contributions from far scatterer can carry less power because the propagation of scatterers have longer distance and hence attenuation more strongly. To sum up, the only different between the single-bounce scatterer and one ring is that the location of the scatterer is random in single-bounce scatterer.

2.3.3 two-ring model

In two-ring model Maharaj (2007) believes that two-ring model has similar behaviour to one-ring model. Instead of having only one scatterer at transmitter (Tx) or receiver (Rx), both of them are surrounded by the scatterer. Therefore, both transmitter (Tx) and receiver (Rx) have a ring and this has led to its reference as the two-ring model. Kaiser (2005) says in the two-ring model, the MIMO channel coefficient can be calculated by using the same approach as the one-ring model. However, there will be no complex Gaussian in general since there are two double reflections of each ray.

2.3.4 Multiple-bounce scatterer

Multiple-bounce scatterer is completely different than single-bounce scatterer. According to (Bonek, 2002) multiple-bounce scatterer is limited as the position of a scatterer completely determines DoD, DoA and delay and only two parameters can be chosen independently. However, some environments such as micro and picocells feature multiple-bounce scattering for which DoA, DoD and delay are totally decoupled. In microcells, the base station is located under rooftop and hence propagation mostly consists of waveguides via street canyons that involve multiple reflection and diffraction. For picocells, propagation within a single large room can be determined by LoS propagation and single-bounce reflection. Assuming that the Tx and Rx are in different rooms or places then the radio wave propagate through the walls or window and that can be diffracted into other room or place with Rx.

In a MIMO system, the equivalent scatterer idea cannot be applied since the angular channel characteristics are reproduced in only one link end. (Molisch, 2004) suggested another way to perform double scattering as the scatterers around the BS and those around MS is established by means of a so-called illumination function usually DoD spectrum relative to the scatterers. However, (Molisch, 2006) proposed another concept that includes multiple bounce scattering into GSCM models and is known as the twin-cluster concept by using COST 273. In both BS and MS, the scatterer positions are different and a coupling is found in terms of a stochastic link delay that allows for decoupled DoA, DoD and delay statics.

2.4 Summary

There are many different methods to generate MIMO channels and each of that has its own advantage and disadvantage, in this literature review, the focus has been the one-ring model and two-ring model which can be modified to be more simpler to simulate and calculate through the single-bounce scatterer and twin-cluster respectively. In general, the basic important requirements for MIMO channel models are shown in the following points:

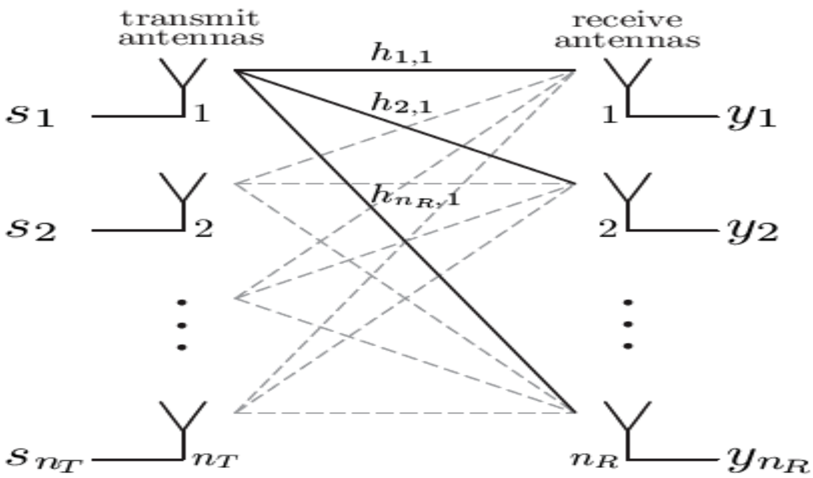
- The impact of real-life MIMO channel statistics base on environment and system parameters such as antenna spacing, polarization and antenna element directionalities.
- The ability to easily cover wide range of best-case to worst-case scenarios.
- The simplest in use and possibility to understand the relevant parameters between various groups of researchers so that the results can be easily compared.

Chapter 3:

MIMO system capacity Analysis

3.1 Basic system model

In this chapter, the MIMO system operation has to be explained. JÄanner (2006) says consider on a single-user communication model and point to point link where the transmitter refer to ▯▯ antennas and the receiver known as ▯▯ antenna as shown in figure 2. Moreover, assuming that there are no inter-symbol interference (ISI) occur which implies the bandwidth to be very small and can be assume frequency flat (narrow band), so that each single path can be represented as complex-valued gain factor. Modelling the channel at flat frequency is more comment than selective frequency for practical purpose.



Since there are many elements that are still unknown, in this case there will be some assumptions which allow the system to operate. One of these assumptions is to operate in a time-invariant setup which allows us to use standard complex-valued baseband representation of narrowband single as it can be written in discrete form.

Where 𝒉□,□ represent the complex-valued path gain from transmit antenna □ to receive antenna □ which also known as fading coefficients. Assuming that a certain time instant the complex single {□1,……..□□□} are travelled from transmit □□ antenna to receive □□ antenna, the received signal at antenna □ can be expressed as

□□=□=1□□𝒉□,□ □□+□□

(3.1)

□□ is known as the additive noise. Since (3.1) is a linear equation, it can be easily rewritten in matrix form. As s can be vector of size □□ containing the transmitted values and y can be vector of size □□containing received values respectively. If we defined the channel transfer matrix H as

□=𝒉1,1 𝒉1,2 𝒉1,□□ 𝒉2,1 𝒉2,2 𝒉2.□□ 𝒉□□,1 𝒉□□,2 𝒉□□,□□

(3.2)

We can obtain

□=□□+□ (3.3)

3.2 MIMO channel model

There are different types of MIMO channel models based on the transmitted signal is assumed to be received after a complicated propagation process including scattering, reflections, refractions and diffractions caused by the objects present in the communication scenario. This project will focus on two models one-ring model and two-ring model that are discussed in details below.

3.2.1 One ring channel model

One ring model is known as geometric model for MIMO channel shown in figure 3. According to Kaveh (2002) MIMO system use multi-element antenna arrays that containing of □□□=*2* antenna at the BS and □□□=*2* antenna at MS. This is standard multi-element antenna configuration can be applied for linear, triangular and hexagonal antenna and can be easily obtained.

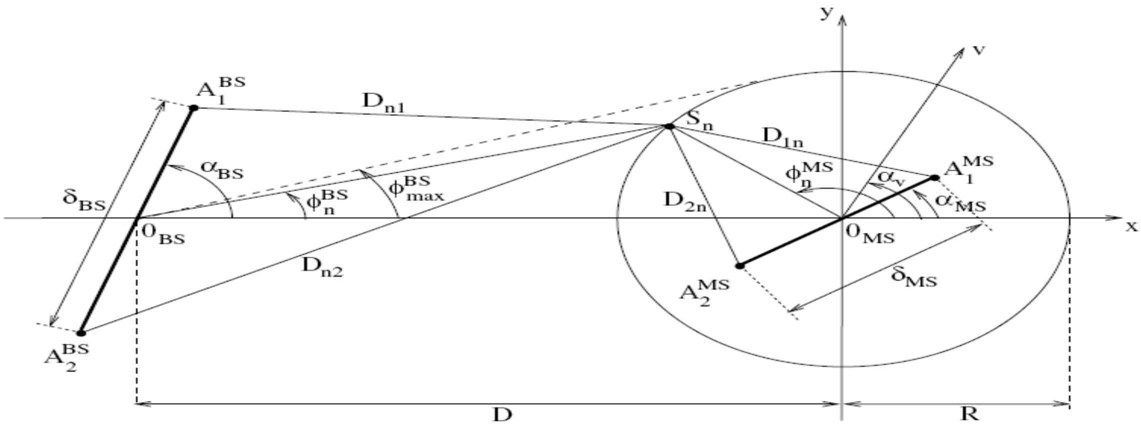


Figure 3: one-ring for 2x2 channel model with local scatterers around the MS (Kaveh, 2002)

Figure 3.2 shows that the antenna spacing at the BS and the MS are denoted by □□□ and □□□respectively. The BS and MS plays very important role as the transmitter and receiver respectively. One ring model is appropriate for describing environment, since one of the transmitter or receiver is elevated and free from scatterers and the other one is surrounded by a large number of local scatterers. Figure 3.2 shows the BS is free of local scatterers and the MS is the one surrounded by local scatterers and also can be vice versus. Nevertheless, it is more appropriate if the MS is the one surrounded by local scatterers since the MS receives the signal from different directions determined by the distribution of the local scatterers. These scatterers are located on a ring with radius R. Usually the radious assumed to be smaller than D which represents the distance between the transmitter and receiver. Another parameter is ∅□□□□□ which refers to the angle at the BS. Furthermore, R and D are assumed to be larger compared to antenna spacing ☐☐☐ and ☐☐☐ ☐ ≫☐≫max { ☐☐☐,☐☐☐ } . Moreover, ☐☐☐ and ☐☐☐ are known as the angles between the x-axis and orientation of the BS and MS antennas array. Also figure 3.2 indicates the MS move with speed ☐ in the direction determined by the angle of motion ☐☐. However, each scatterer assumed to be reflected once and all the scatterers have equal power. For simplicity, there are no line-of-sight is assumed between the transmitter and the receiver.

Figure 3.2 shows a one ring model for the 2 X 2 MIMO channel with local scatterers laying on a ring around the MS. We assume that there are a number of scatterers laying on the ring and also as it is mentioned early D>> R >> max {☐☐☐,☐☐☐}. The time variant complex gains ℎ☐,☐☐ (☐,☐=1,2) that connecting the receiver antenna element ☐☐☐☐ and the transmitter antenna element ☐☐☐☐ are given by

ℎ11☐=lim☐→∞1☐☐=1☐☐☐☐☐☐☐(2☐☐☐ ☐+ ☐☐)
(3.4)

ℎ12☐=lim☐→∞1☐☐=1☐☐☐∗☐☐☐☐(2☐☐☐ ☐+ ☐☐)
(3.5)

ℎ21☐=lim☐→∞1☐☐=1☐☐☐☐☐∗☐☐(2☐☐☐ ☐+ ☐☐)
(3.6)

ℎ22☐=lim☐→∞1☐☐=1☐☐☐∗☐☐∗☐☐(2☐☐☐ ☐+ ☐☐)
(3.7)

Where

☐☐=☐☐☐☐☐☐☐[cos☐☐☐+∅☐☐☐☐☐sin☐☐☐sin∅☐☐☐]
(3.8)

☐☐=☐☐☐☐☐☐☐cos∅☐☐☐−☐☐
(3.9)

☐☐=☐☐☐☐cos(☐☐☐☐−☐☐)
(3.10)

(*) denotes the complex conjugation.

□□□□ is known as the maximum Doppler frequency.

□ represents the wavelength.

Knowing that only parameter ∅□□□□□ has the control on distance (D) and radius (R). According to Hogstad (2004) *h*□,□□ is zero complex Gaussian process with variance equal 1, and therefore, the envelop of *h*□,□□ follows Rayleigh distribution. Furthermore, it should be mentioned that the stochastic process *h*□,□□ is first order stationary and ergotic even though the scatterers are finite number. However, the capacity of the proposed MIMO channel depend on the correlation between the channel gain *h*□,□□

H=*h*11(□)*h*12(□)*h*21(□)*h*22(□)
(3.11)

For this MIMO frequency non-selective channel, the capacity C (t) in bit/s/Hz is then defend as

□□=□□□2[det□1+□□□, □□□□□□□□□□ □□□□□]
(3.12)

det (.) denotes the determinant.

□1 represents the 2 X 2 identity matrix.

□□ is the noise power.

□□□, □□□□□ is the total transmitted BS power allocated uniformly to all the □□□ antenna elements.

(·)□ represent the complex conjugate transpose operator.

Note that the capacity □□ is a stochastic process, since the ∅□ are random variables.

From this reference model, it can be easily to implement a stochastic and deterministic simulation model, as it is shown in chapter 4.

3.2.2 two-ring channel model

Tow-ring model is also known as geometric model for MIMO channel shown in figure 4 and to be more specific two-ring model for narrowband MIMO system with two omni-directional antenna at both receiver and transmitter. According to Hogstad (2006) this standard 2 X 2 antenna configuration can be applied to construct any other types of two-dimensional multi-element antenna array such as uniform linear array, hexagonal array and circular antenna array which can be easily obtained. In two-ring model, it is assumed that there is no line-of-sight between the receiver and transmitter which make it simpler. However, two ring-model is quite similar to one ring-model as both models are appropriate models for describing propagation scenarios. The difference between one-ring and two-ring modes is that two-ring model at both receiver (BS) and transmitter (MS) are surrounded by large number of local scatterers around the ring.

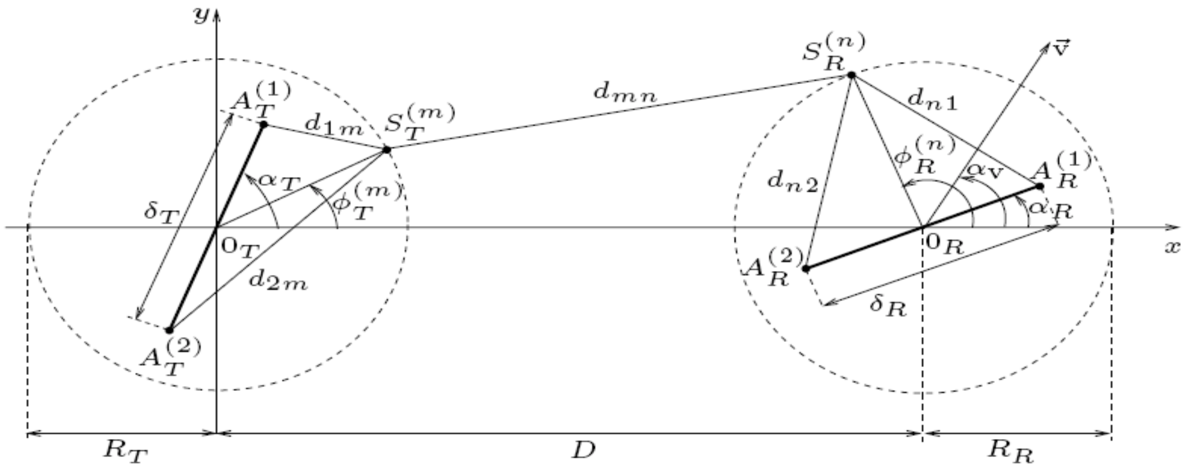


Figure 3.3 shows that the local scatterere around the transmitter is known as □□(□) where (m = 1, 2 ...) and located on ring of radius □□ , while the local scatterers around the receiver is denoted by □□(□) where (n = 1, 2 ...) and located on ring of radius □□. Both radii □□ and □□ are assumed much smaller than the distance (D) between the receiver (BS) and transmitter (MS) i.e. max□□,□□ ≪□ . The antenna spacing at the receiver and transmitter are denoted by □□,□□, respectively. Usually, antenna spacing □□ and □□ are assumed to be smaller in comparison with radii □□ and □□ i.e. {□□,□□}≪□□□□□,□□ . These antennas at receiver and transmitter are set at specific angle that depend on their situation. Figure 3.3 shows the title angle between the x-axis and the orientation of the transmitter's antenna array is known as □□ and □□ represents the angle between the x-axis

and the orientation of the transmitter's antenna array. Assuming that the transmitter is fixed, at the same time as the receiver moves with speed □ in the direction determined by the angle of the motion □□. Basically, The time variant complex gains ℎ□,□□ (□,□=1,2) that connecting the receiver antenna element □□□□ and the transmitter antenna element □□□□ are given by

ℎ11□=lim□→∞□→∞1□□□=1□□=1□□□ □□ □□□□□(2□□□□+□□□+□0)
(3.13)

ℎ12□=lim□→∞□→∞1□□□=1□□=1□□□∗ □□ □□□□□(2□□□□+□□□+□0)
(3.14)

ℎ21□=lim□→∞□→∞1□□□=1□□=1□□□ □□∗ □□□□□(2□□□□+□□□+□0)
(3.15)

ℎ22□=lim□→∞□→∞1□□□=1□□=1□□□∗ □□∗ □□□□□(2□□□□+□□□+□0)
(3.16)

Where

□□=□□□□□□cos(□□□−□□)
(3.17)

□□=□□□□□□cos(□□□−□□)
(3.18)

□□□=□□22□□(□□□□□∅□□−□□□□□∅□□)
(3.19)

□□=□□□□cos(∅□□−□□) (3.20)

□0=−2□□(□□+□+□□) (3.21)

(*) denotes the complex conjugation.

□□□□ is known as the maximum Doppler frequency.

□ represents the wavelength.

Those four diffuse components ℎ▯,▯ where (i,j= 1,2) of the antennas at the receiver and transmitter (▯▯▯,▯▯▯) link can be combined to obtain the channel matrix gain

H=ℎ11(▯)ℎ12(▯)ℎ21(▯)ℎ22(▯)
(3.22)

For this MIMO frequency non-selective channel, the capacity C (t) in bit/s/Hz is then defend as

▯▯=▯▯▯2[det▯1+▯▯▯▯▯0 ▯▯▯▯▯] (3.22)

det (.) denotes the determinant.

▯1 represents the 2 X 2 identity matrix.

▯▯ is the noise power.

▯▯ is known as the total transmitted power allocated uniformly to all the ▯▯ antenna element of the transmitter.

(.)▯ represents the complex conjugate.

3.3 MIMO capacity

Channel capacity is an important issue in MIMO system, as it can provide high rate of data. However, there are two types of power capacity that are applied in this thesis equal power and water-filling

3.3.1 MIMO system capacity with equal power

One of the methods to transmit the power through channel model is equal power. According to Gans (1998) the transmitted signal power is divided equally over the transmitting antenna. From that the equal power capacity can be rewritten as

▯▯▯=▯▯▯2▯▯▯▯+▯▯▯HH† ▯▯▯/▯▯ (3.23)

Where

det(·) denotes the determinate of a matrix

□ is known as □□×□□ identity matrix

□ is the average received signal to noise ratio (SNR)

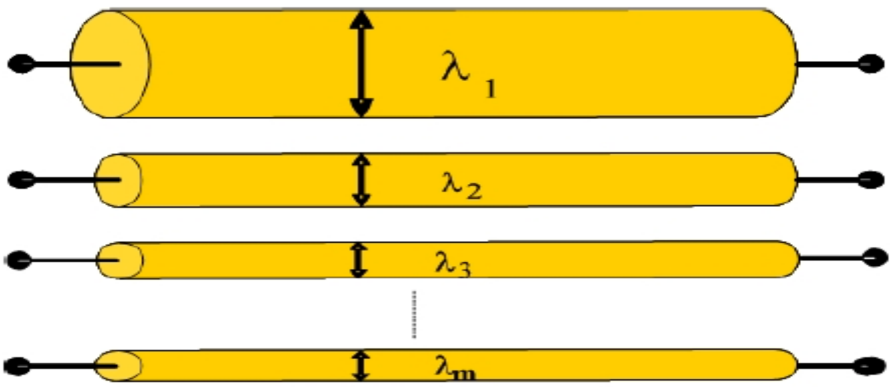
H† is the complex conjugate transpose of H

To be able to find the characteristics H, we need to perform a singular value decomposition (SVD) of H so that to diagonalize H and obtain eigenvalues. SVD can expand any matrix H □□×□□ that can be rewritten as

H=□□□† (3.24)

As □(□□×□□) and □(□□×□□) represent unitary matrix which make □□†=□□†=□.□(□□×□□) is non-negative and diagonal with entries specified by

□=□□□□ (□1, □2,□3………□□,0……0) (3.25)



Where diag (A) is the vector consisting of diagonal element □1.□2,……□□ (m = min (NR, NT)) which are nonzero eigen-values of W, where W is

□=HH† □/□□□ □□≤□□ □□ □= H†H □/□□□ □□<□□ (3.26)

The columns □ represents eigenvectors of HH† and the columns □ represents the eigenvectors of H†H. As result of that, the SVD equation () shows the channel matrix H can be diagonalized to a number of independent orthogonal sub-channels, where the power gains of the ▯▯ℎis ▯▯, as it is shown in figure

Therefore, the equation can be rewritten to be

▯▯▯=▯=1▯▯▯▯2▯▯▯1+▯▯▯HH† ▯▯▯/▯▯ (3.27)

3.3.2 MIMO system capacity for water-filling

The difference between the water-filling and equal power is that the water-filling power occurs when the transmitter has prefect knowledge about the channel. Valenzuela (2002) says with this knowledge about the channel, the total power can be divided in the most efficient way over different transmitters which allow the capacity to achieve the highest possible bit rate. From that the water-filling power capacity can be written

▯▯▯=▯=1▯▯▯▯2▯▯▯+ ▯▯/▯/▯▯

(3.28)

Where

▯▯= HH† (3.29)

And ▯ is chosen to satisfy

▯=▯=1▯(▯−▯▯−1)+ (3.30)

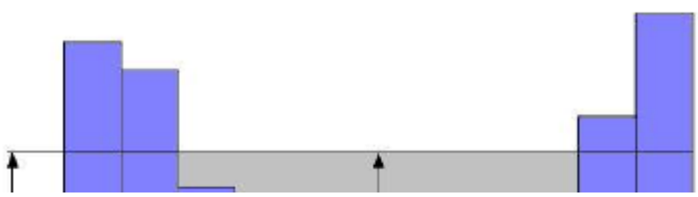
Where

(+) denotes to have only the positive side

▯ is a complicated non-linear function of ▯1,▯2……▯▯

The advantage of water-filling is that behave much better at low signal noise ratio (SNR) compared to equal power. However, as the (SNR) increased this advantage is decreased as well. Figure 6 shows the concept of water-filling

.



3.4 mutual coupling

One of the elements that should be considered in MIMO channel modelling is mutual coupling, since it has an important impact on the correlation of MIMO channel model. RAPAJIC (2007) says the principle feature of antenna is to convert electromagnetic field into an induced voltage or current. Mutual coupling can be occurred when the antennas are very close from each other and the total measurement of voltage is a function that not only based on the excited field but also of the voltage on the other element. However, mutual coupling can be included in the received voltage model by inserting coupling matrix

□= □□□+□

Therefore, the new channel matrix applies the mutual coupling which has impact in the multi-antenna is □□□=□□ and it can be calculated as

□=□□+□□(□+□□)−1

Where □□is the isolated antenna impedance

□ is the mutual impedance matrix. While

□□ is the impedance at the receiver loads of each element and it is chosen as the complex conjugate to □

Since the receiver antenna element can be considered very close to each other, the fading correlation has to be included into the channel matrix. Therefore, the channels that contain both spatial correlations, fading and electromagnetic can be written as

□□=□□□

3.5 Summary

Reference model for both one-ring and two channel models has been introduced in more details to understand the corresponding between the antennas in both side transmitter and receiver. Those calculations can assist to implement the capacity of one-ring and two-ring channel models. However, there are two ways to measure the capacities of equal power and water-filling. Equal power has no knowledge about the channel model which allows the power to be divided equally over the transmitting antenna. Water-filling has prefect knowledge about the channel model that allows the total power to be divided in the most efficient way over different transmitter. Another element that affects the capacity is mutual coupling. Mutual coupling can be occurred when the antenna are very close form each other.

Chapter 4

MIMO capacity system based on one-ring model channel

4.1 Introduction

In this chapter, the MIMO system results using one-ring channel model are represented. From the reference model described in chapter 3, the capacity of 2 x 2 MIMO channel model can be obtained by using mat-lab code simulation to find out the mean capacity verses single noise ratio (SNR). Several simulation results for 2 x 2 MIMO channel capacity were presented which are based on number of scatterers, antenna spacing and the distance between the receiver antenna and receiver antenna. Each output has difference influence on the capacity that depends on the variable parameters of the model and single correlation. However, there were two methods preformed to measure the capacity in one-ring channel model equal power and water-filling.

4.2 results and discussion

One of the methods to obtain the results of geometric channel model is to simulate the circuit in figure 3 by using mat-lab programming which can show an ideal performance of the circuit. Basically, the simulations were preformed to investigate the behaviour of one-ring channel model by using vary parameters in each stage. However the values of the parameters that used in the simulation has been introduced in the following table

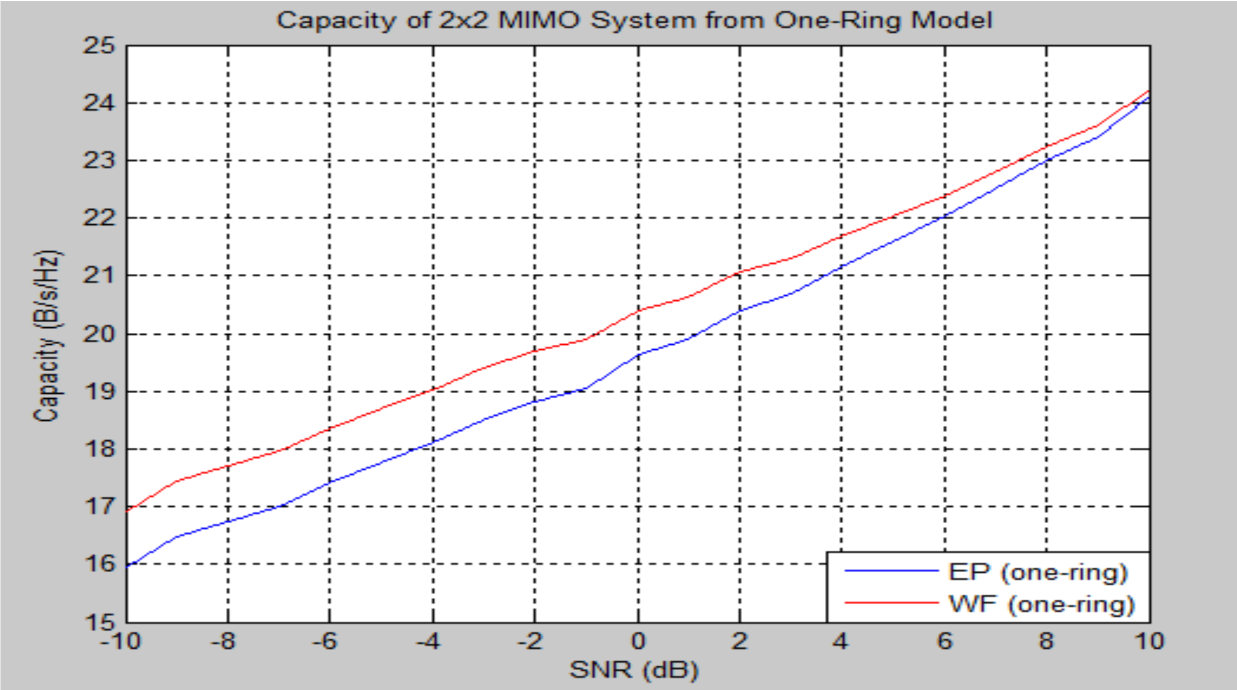
Parameters / symbol	Values
Distance between Tx and Rx (D)	0.5 - 4 km
Radius of the ring (R)	0.01 km
Number of scatterers (L)	50 – 1000
Number of transmitter antennas (NT)	2
Number of receiver antennas (NR)	2
Antenna spacing of the transmitter (□□□)	0.1 □ – 1 □
Antenna spacing of the receiver (□□□)	0.1 □ – 1 □
Signal noise ratio (SNR)	-10 – 10 dB

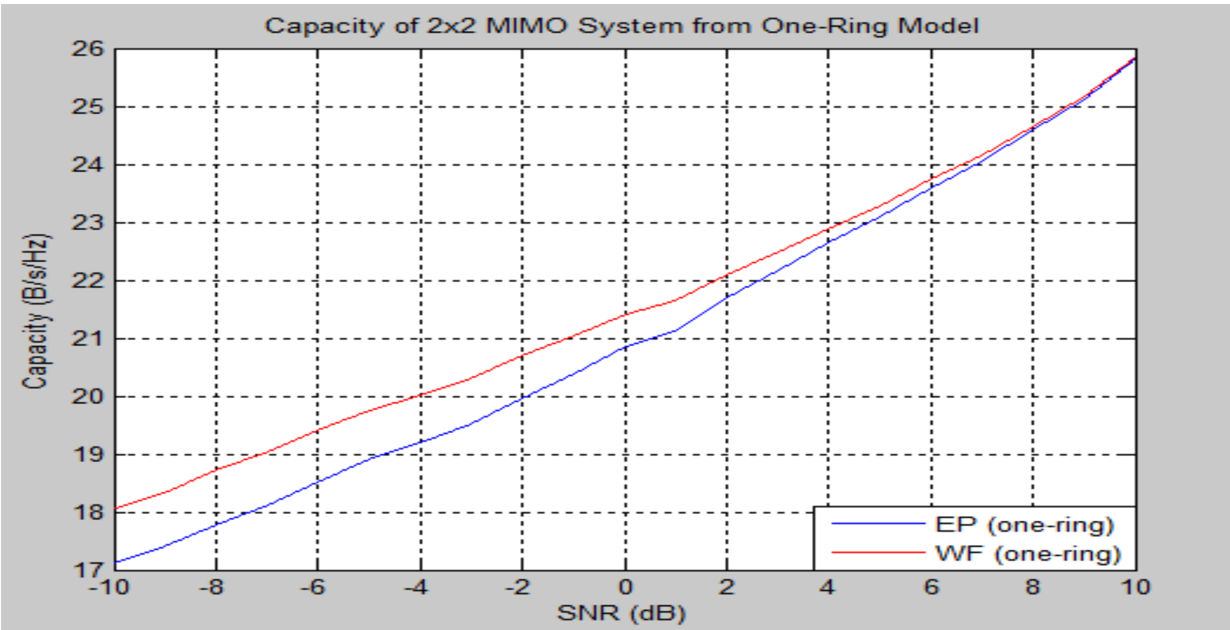
Table 1: main simulation parameters for one-ring channel model

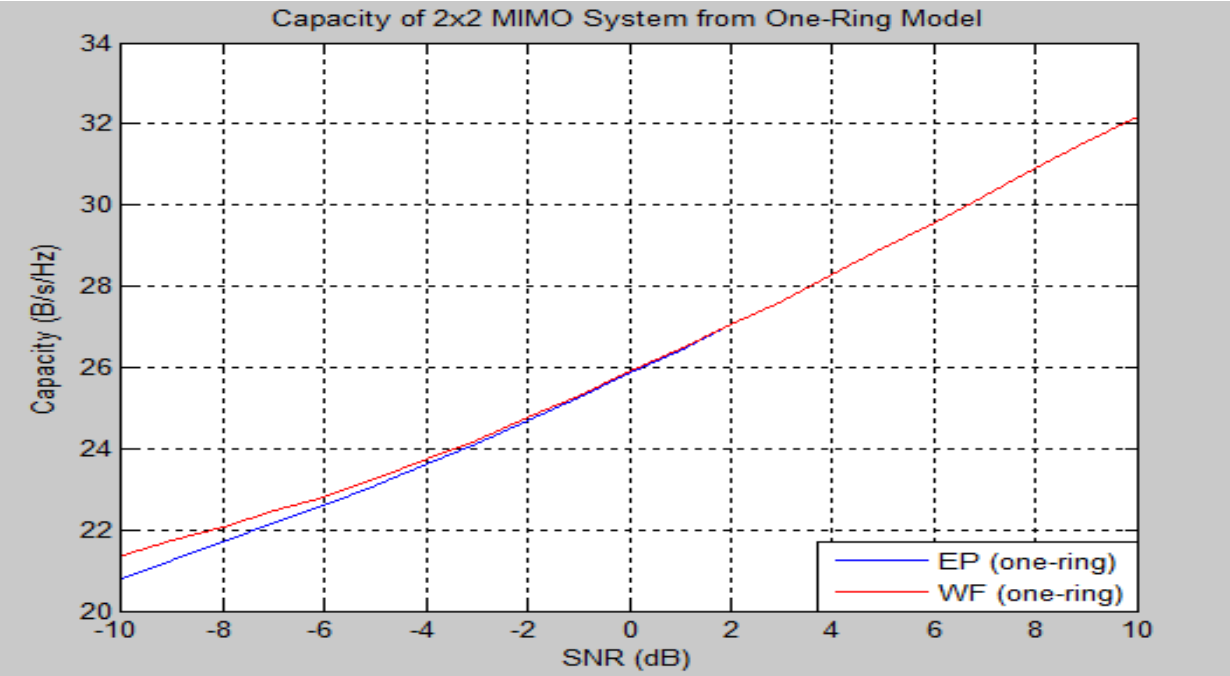
4.2.1 Mean capacity versus different Number of scatterers

MIMO channel capacity depends on the statistical properties and antenna element correlation of the channel. Figure 7, 8 and 9 show that the capacity result as function of signal noise ratio (SNR) at fixes number of transmitter and receiver antennas 2 in both side. For reference model, the parameters fixed value were chosen as □□□=□□□=90□, □□=45□ , □□□□=0 , R =0.01 km, D = 1 km, □□□=□□□= 0.1 □ and the rest of other parameter were measured based on the fixed parameters. Mean capacity of equal power and water-filling increased linearly as the signal noise ratio is increased as well. However, in the law signal noise ratio (SNR) the capacity of water-filling has greater capacity than the equal power capacity, since water-filling capacity has prefect knowledge about the channel of the transmitter as the transmitter can adapt its transmission strategy relative to the channel and therefore channel capacity is characterized by the ergodic, outage and minimum capacity. In the other hand, capacity equal power has no knowledge about the channel of the transmitter so the total power can be divided equally for each transmitter antenna. As the signal noise ratio increased, mean capacity of equal power and water-filling is getting much closed to each other. Therefore, water-filling has much better responded at low signal noise ratio (SNR) than higher signal noise ratio (SNR). For higher signal noise ratio (SNR), both capacities of equal power and water-filling become very close to each other and have almost same capacity.

Number scatteres on one-ring mode has significant effect on capacities of the equal power and water-filling of one-ring channel model. Figure 7, 8 and 9 increased the number of scatterers respectively by starting with 50 scatterers until 1000. In all three figure, they have similar correspond as the capacity increased at both equal power and water-filling while the signal noise ratio is increased. By comparing the three outputs to each other, the only difference between the three figures is that at high number of scatterers, the capacity is raised for both equal power and water-filling and at low number of scatterers, the capacity has less capacity compared to the high number of scatterers. Moreover, the water-filling has greater capacity than the equal power at lower signal noise.

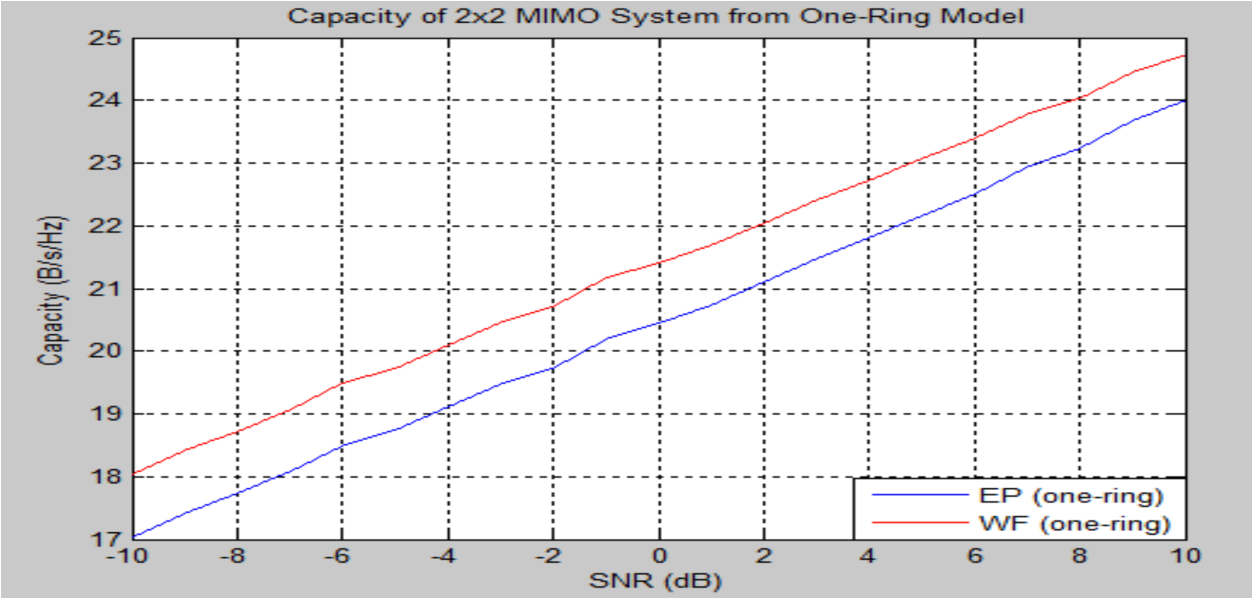

Capacity of 2x2 MIMO System from One-Ring Model
Capacity (B/s/Hz)
SNR (dB)
EP (one-ring)
WF (one-ring)
25
24
23
22
21
20
19
18
17
16
15
-10
-8
-6
-4
-2
0
2
4
6
8
10


Capacity of 2x2 MIMO System from One-Ring Model
Capacity (B/s/Hz)
SNR (dB)
EP (one-ring)
WF (one-ring)
26
25
24
23
22
21
20
19
18
17
-10
-8
-6
-4
-2
0
2
4
6
8
10



4.2.2 Mean capacity versus different antenna spacing

Figure 10, 11 and 12 show the capacity result as function of signal noise ratio (SNR) at fixes number of transmitter and receiver antennas 2 in both sides. those simulations have the same parameters values as above except that the antenna spacing between antennas are vary so we can observe any different correlation in one-ring channel model. According to the simulations, it can be noticed that the spacing antenna has a significant effect on equal power and water-filling capacities for one-ring channel model as the spacing antenna become close to each other. We started the spacing antenna from 0.05 � until 1 � to observe any differences. Mean capacity of equal power and water-filling increased as the single noise ratio is raised in different range of spacing antenna. However, when the spacing antenna is greater than 0.4�, the capacity result increased in both equal power and water-filling as mutual coupling can be neglected and have no effect, as shown in figure 12. When the spacing antenna is less than 0.4 �, the capacity result decreased in both equal power and water-filling due to higher correlation in channel fading correlation. Moreover, water-filling has much better capacity than the equal power, because of the prefect knowledge of the channel model at low spacing antenna, as shown in figure 10 and 11.


Capacity of 2x2 MIMO System from One-Ring Model
Capacity (B/s/Hz)
SNR (dB)
EP (one-ring)
WF (one-ring)
25
24
23
22
21
20
19
18
17
-10
-8
-6
-4
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0
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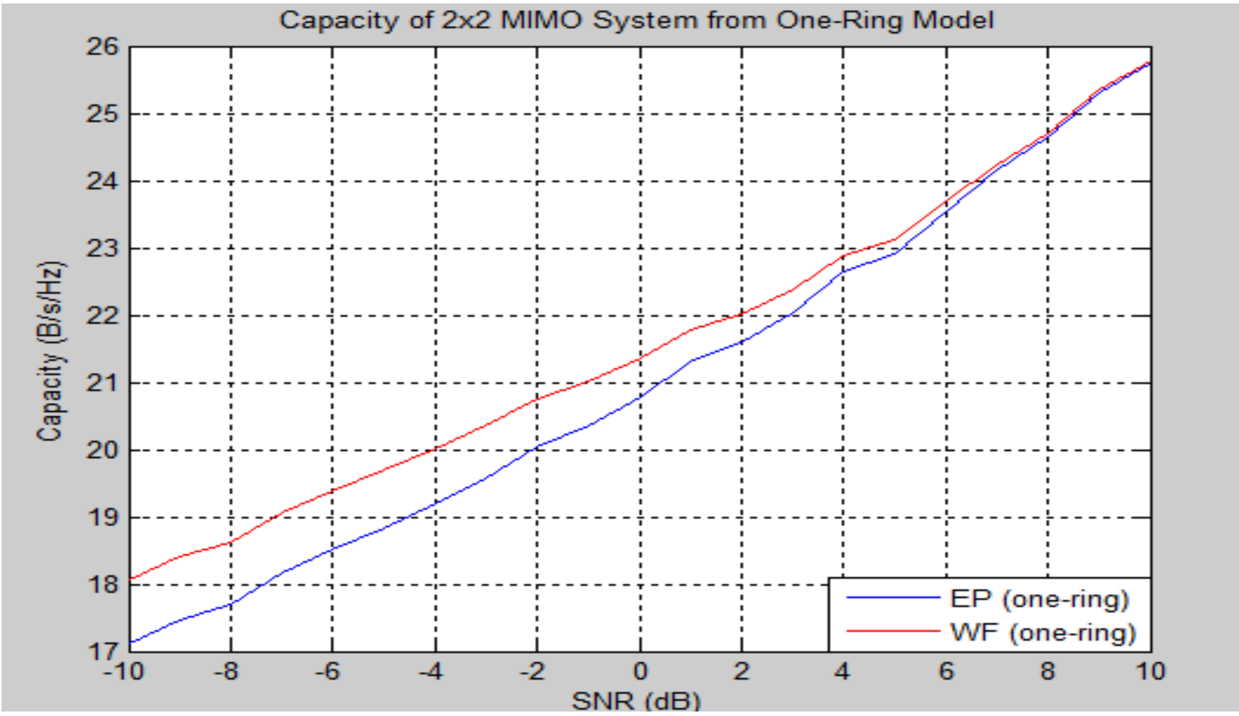
Capacity of 2x2 MIMO System from One-Ring Model
Capacity (B/s/Hz)
SNR (dB)
EP (one-ring)
WF (one-ring)
26
25
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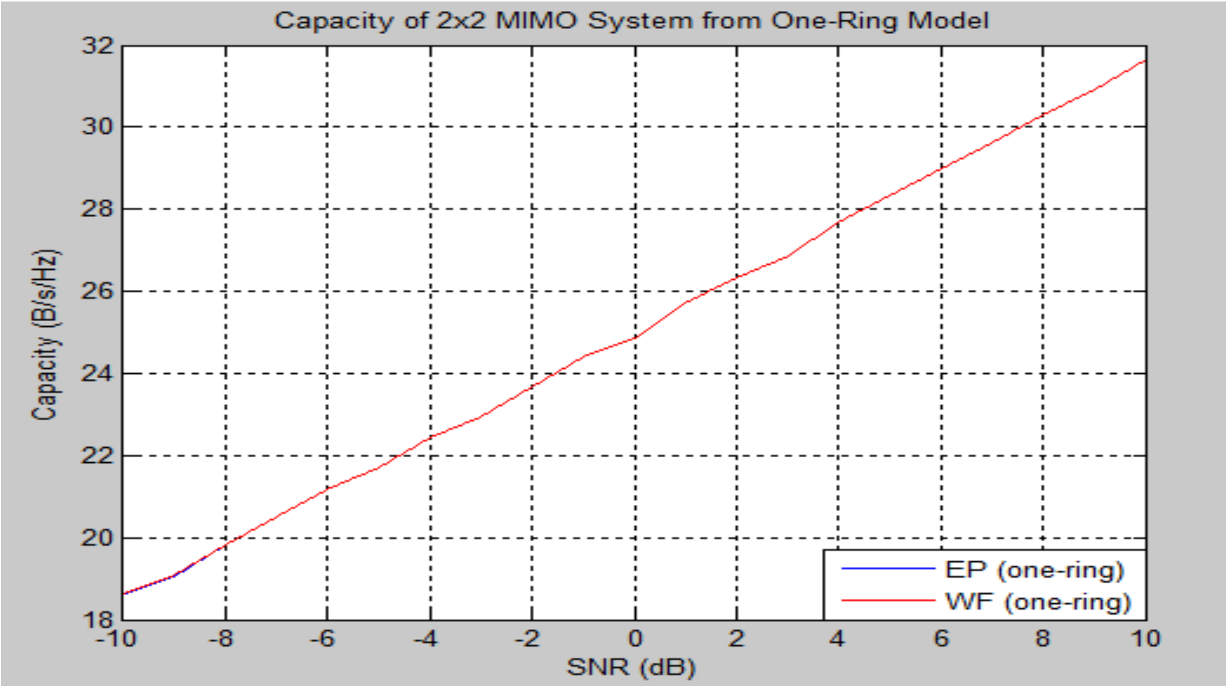


Figure 12: mean capacity vs. Signal noise ratio based on one-ring channel model at 0.4

4.2.3 Mean capacity versus different distance between the receiver antenna and transmitter antenna

Figure 13, 14 and 15 show the capacity result as function of signal noise ratio (SNR) at fixes number of transmitter and receiver antennas 2 in both sides. Those simulations have the same parameters values as above except the distance between the transmitter antennas and receiver antenna are varied, so we can observe any difference responded of capacity in one-ring channel model. In all different distance, mean capacity of equal power and water-filling are increased linearly as the signal noise ratio (SNR) raise. However, there are two different causes when the distance between the transmitter antennas and receiver antennas changed. The first cause, short distance indicates greater capacity in both equal power and water-filling, but water-filling has greater capacity than equal power capacity at lower signal noise ratio (SNR) and have same capacity at higher signal noise ratio (SNR) shown in figure 13. This is due to the fact that small distance between the transmitter antennas and receiver antennas allow antennas signal become less correlated. The second cause, long distance shows less capacity in both equal power and water filling, nevertheless water-filling capacity has greater capacity than the equal power even though at higher signal noise ratio (SNR) shown in figure 14 and 15. Since the long distance between the transmitter antennas and receiver antennas cause signal become more correlated.

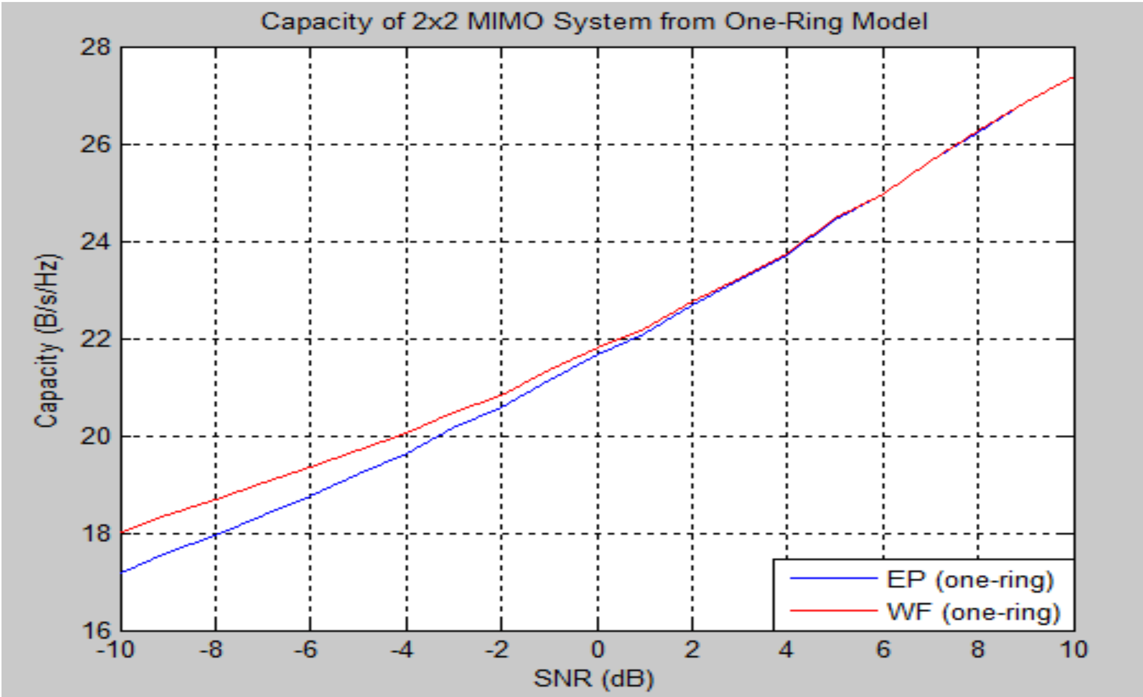


Figure 13: mean capacity vs. Signal noise ratio based on one-ring channel model at 0.5 Km distance between RX and TX

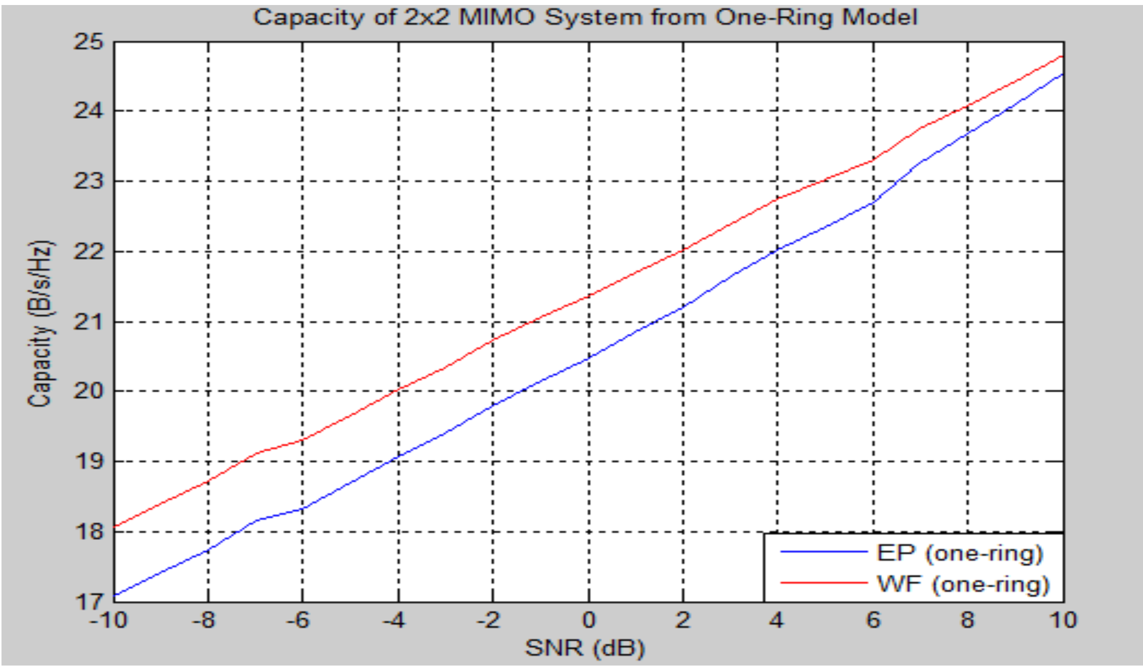
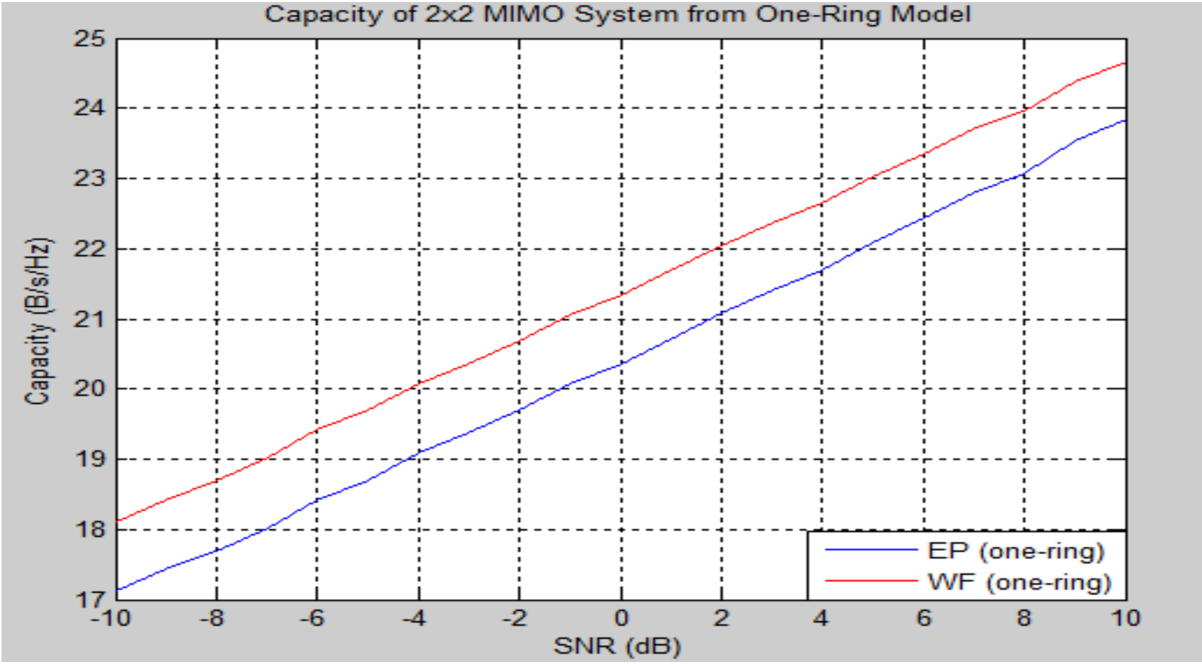


Figure 14: mean capacity vs. Signal noise ratio based on one-ring channel model at 2 Km distance between RX and TX



4.3 Summary

In this chapter, mean capacity results as function of signal noise ratio (SNR) have been introduced. The method that was used to implement the mean capacity is mat-lab simulation code. So the mean capacity can be investigated in more details for on one-ring channel model by using equal power and water-filling schemes. Several simulation results for 2 x 2 MIMO channel capacity were presented which are based on number of scatterers, antenna spacing and the distance between the receiver antenna and receiver antenna. Each output has difference affect on the capacity that depends on the variable parameters of the model and single correlation. To sum up, short distance between receiver antennas and transmitter antennas and long spacing antennas have positive effect on both equal power and water-filling which led to have greater capacity at low signal noise ratio (SNR).

Chapter 5

MIMO capacity system based on two-ring model channel

5.1 Introduction

In this chapter, the MIMO system results using two-ring channel model are represented. Two-ring channel model is an extension of the one-ring channel model. From the reference model described in chapter 4, the capacity of 2 x 2 MIMO channel model can be obtained by using mat-lab simulation code to find out the mean capacity verses single noise ratio (SNR). Several simulation results for 2 x 2 MIMO channel capacity were presented that based on number of scatterers, antenna spacing and the distance between the receiver antenna and receiver antenna. Each output has difference influence on the capacity that depends on the variable parameters of the model and single correlation. However, there were two methods preformed to measure the capacity in one-ring channel model equal power and water-filling.

4.2 results and discussion

One of the ways to indicate the results of geometric channel model is to simulate the circuit in figure 3 by using mat-lab programming which can implement an ideal performance of the circuit. Basically, the simulations were preformed to investigate the behaviour of two-ring channel model by using vary parameters in each stage. However the values of the parameters that used in the simulation has been introduced in the following table

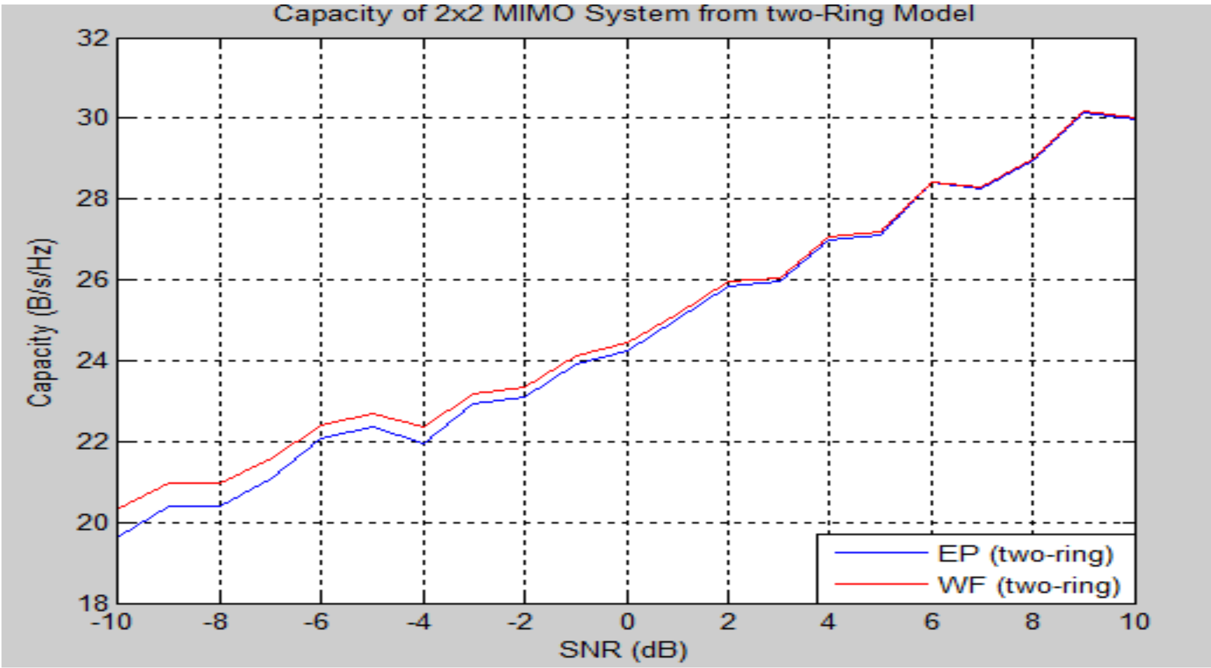
Parameters / symbol	Values
Distance between Tx and Rx (D)	0.5 - 4 km
Radius of the ring (R)	0.01 km
Radius of the ring (T)	0.01 km
Number of scatterers for NR (L1)	50 – 1000
Number of scatterers for NT (L2)	50 – 1000
Number of transmitter antennas (NT)	2
Number of receiver antennas (NR)	2
Antenna spacing of the transmitter (□□□)	0.1 □ – 1 □
Antenna spacing of the receiver (□□□)	0.1 □ – 1 □
Signal noise ratio (SNR)	-10 – 10 dB

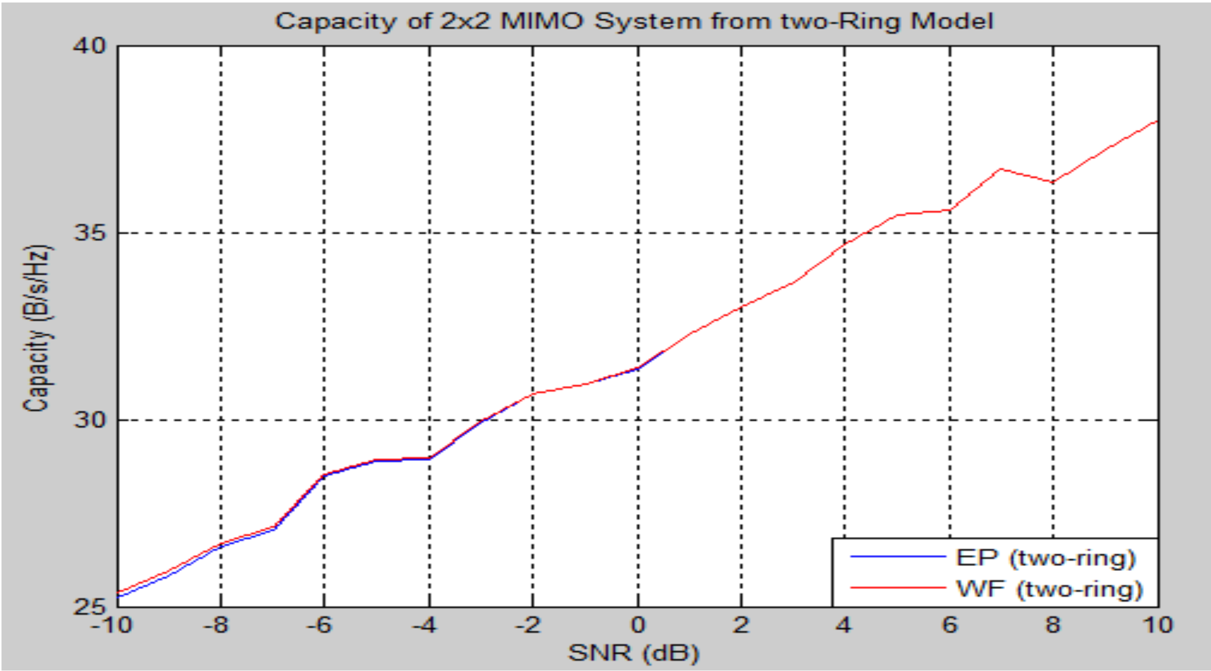
Table 2: main simulation parameters of two-ring channel model

5.2.1 Mean capacity versus different Number of sactteres

MIMO channel capacity depends on the statistical properties and antenna element correlation of the channel. Figure 16 and 17 show that the capacity result as function of signal noise ratio (SNR) at fixes number of transmitter and receiver antennas 2 in both side. For reference model, the parameters fixed value were chosen as □□□=□□□=*90*□, □□=*45*□ , □□□□=*0* R =0.01 km, D = 1 km, □□□=□□□= 0.01 □ and the rest of other parameter were measured based on the fixed parameters. Mean capacity of equal power and water-filling increased shakily as the signal noise ratio is increased as well. This is due to the signal reflection as the signal is reflected twice once in the receiver reign and again in the transmitter area. However, in the law signal noise ratio (SNR) the capacity of water-filling has greater capacity than the equal power capacity, since water-filling capacity has prefect knowledge about the channel of the transmitter as the transmitter can adapt its transmission strategy relative to the channel and therefore channel capacity is characterized by the ergodic, outage and minimum capacity. In the other hand, capacity equal power has no knowledge about the channel of the transmitter so the total power can be divided equally for each transmitter antenna. As the signal noise ratio increased, mean capacitiy of equal power and water-filling is getting much closed to each other. Therefore, water-filling has much better responded at low signal noise ratio (SNR) than higher signal noise ratio (SNR). For higher signal noise ratio (SNR), mean capacity of equal power and water-filling become very close to each other and have almost same capacity.

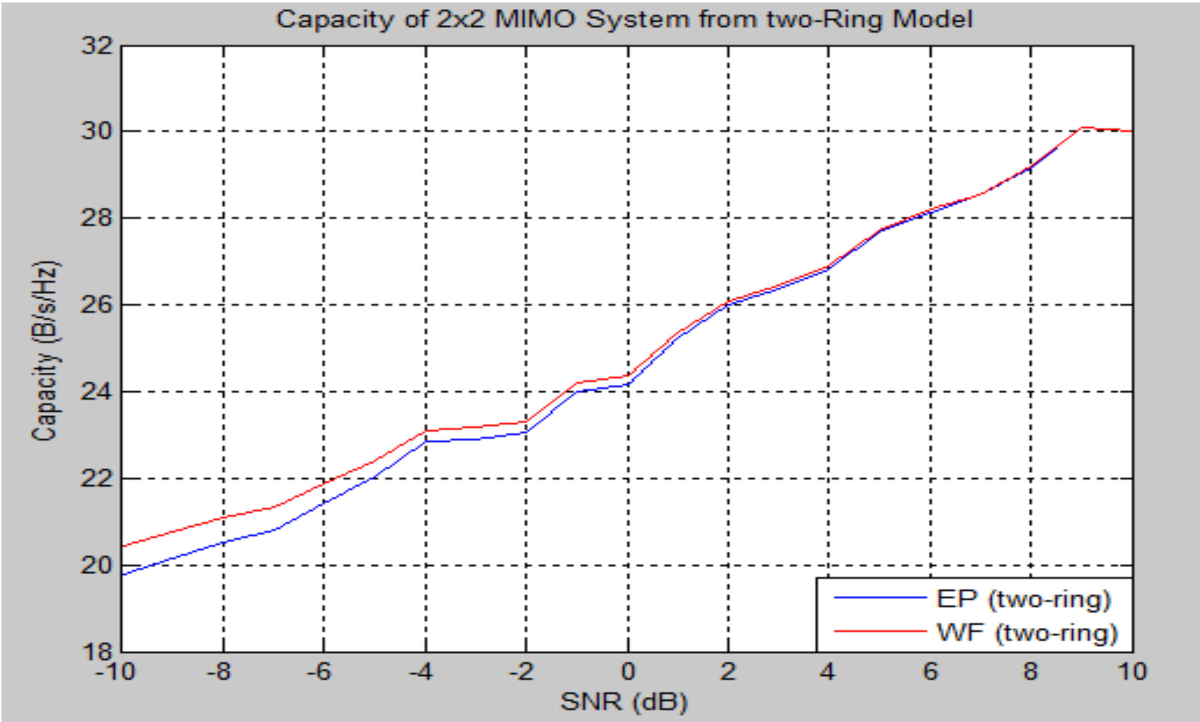
Number scatteres has significant effect on capacities of the equal power and water-filling of one-ring channel model. Figure 16 and 17 indicates the mean capacity of equal power and water-filling by increasing the number of scatteres from 50 to 100. As the number of scatterers increased, the mean capacity of equal power and water-filling are increased. This is because of each scatterer can be uniformly distributed which cause a rich multipath environment. However, water-filling has greater capacity than the equal power at lower signal noise ratio (SNR).

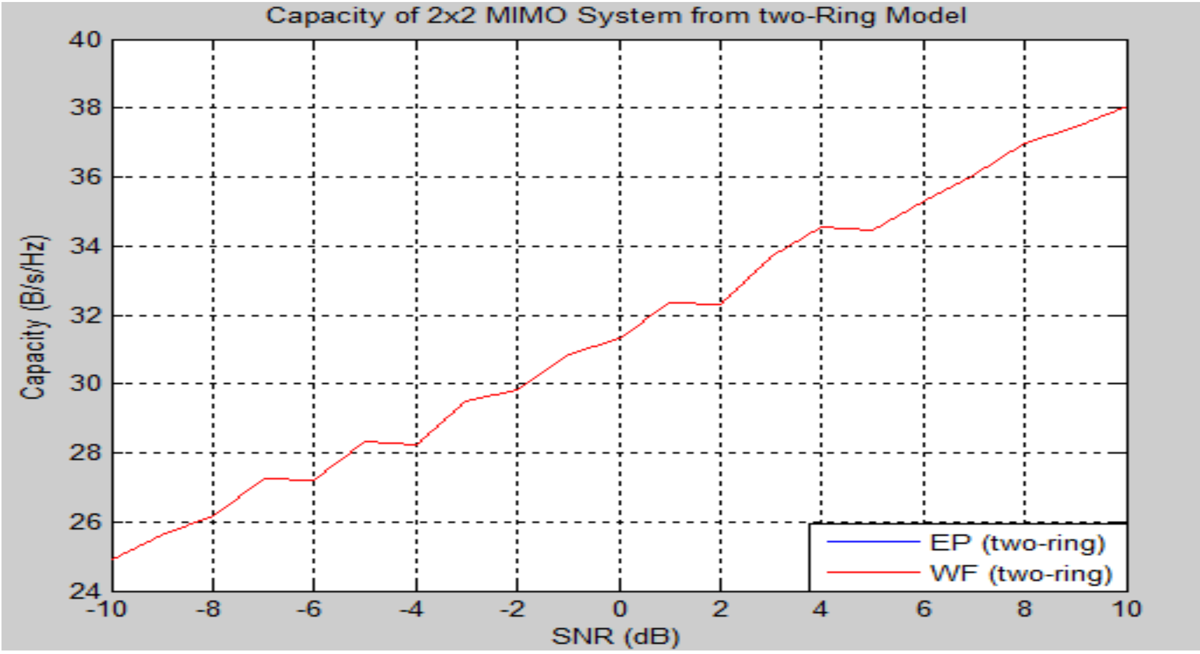




5.2.2 Mean capacity versus different antenna spacing

Figure 18 and 19 indicates the capacity result as function of signal noise ratio (SNR) at fixes number of transmitter and receiver antennas 2 in both sides. those simulations have the same parameters values as above except that the antenna spacing between antennas are vary so we can observe any different correlation in one-ring channel model and number of scatteres are fixed at 50 for both transmitter and receiver. According to the simulations, it can be noticed that the spacing antenna has a significant effect on equal power and water-filling capacities for one-ring channel model as the spacing antenna become close to each other. We started the spacing antenna from 0.01 λ until 1 λ to observe any differences. Mean capacity of equal power and water-filling increased as the single noise ratio is raised in different range of spacing antenna. However, when the spacing antenna is greater than 0.04λ, the capacity result increased in both equal power and water-filling as mutual coupling can be neglected and have no effect, as shown in figure 19. When the spacing antenna is less than 0.4 λ, the capacity result decreased in both equal power and water-filling due to higher correlation in channel fading correlation. Moreover, water-filling has much better capacity than the equal power, because of the prefect knowledge of the channel model at low spacing antenna, as shown in figure 18. However, the only different between the one-ring channel model and two-ring channel model is that the capacity result of one-ring model is more stable than two-ring model. This is due to higher number of scatteres which led to have more multipath and unstable output at two-ring channel model.





5.2.3 Mean capacity versus different distance between the receiver antenna and transmitter antenna

Figure 20 and 21 indicate the capacity result as a function of signal noise ratio (SNR) for a 2 number transmitter and receiver antennas. These simulations have the same parameter values as the previous section except the distance between the transmitter antennas and receiver antenna and number of scatteres are fixed at 50 for both transmitter and receiver, so we can observe any difference responded of capacity in two-ring channel model. For the different element distances, mean capacity of equal power and water-filling are increased shakily as the signal noise ratio (SNR) increases. However, there are two different causes when the distance between the transmitter antennas and receiver antennas is changed. In the shorter distance, both equal power and water-filling indicates greater capacity compared to longer distance between the transmitter and receiver, but water-filling has higher capacity than equal power capacity at lower signal noise ratio (SNR) and have same capacity at higher signal noise ratio (SNR) shown in figure 20. The reason of that, short distance between the transmitter and receiver create less correlated from antenna signal. In other hand, long distance shows less capacity for both equal power and water filling that due to antenna signal have higher correlated. Nevertheless water-filling capacity has greater capacity than the equal power even though at higher signal noise ratio (SNR) shown in figure 21.

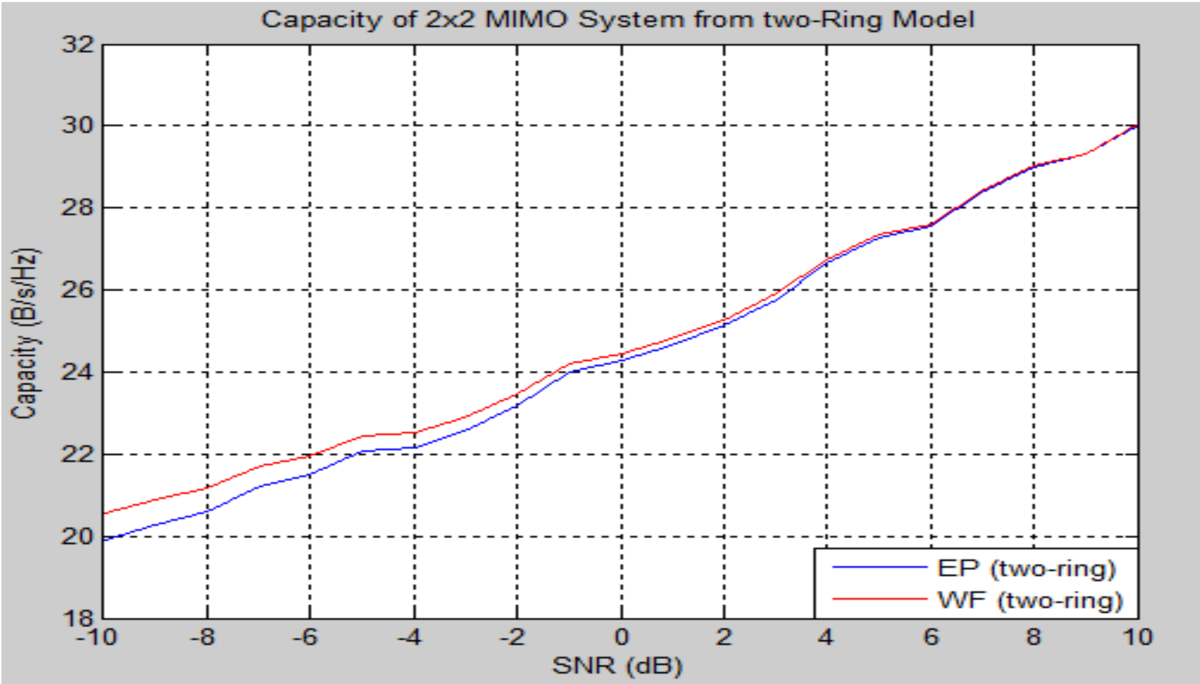


Figure 20: mean capacity vs. Signal noise ratio based on two-ring channel model at 0.5 Km distance between RX and RT

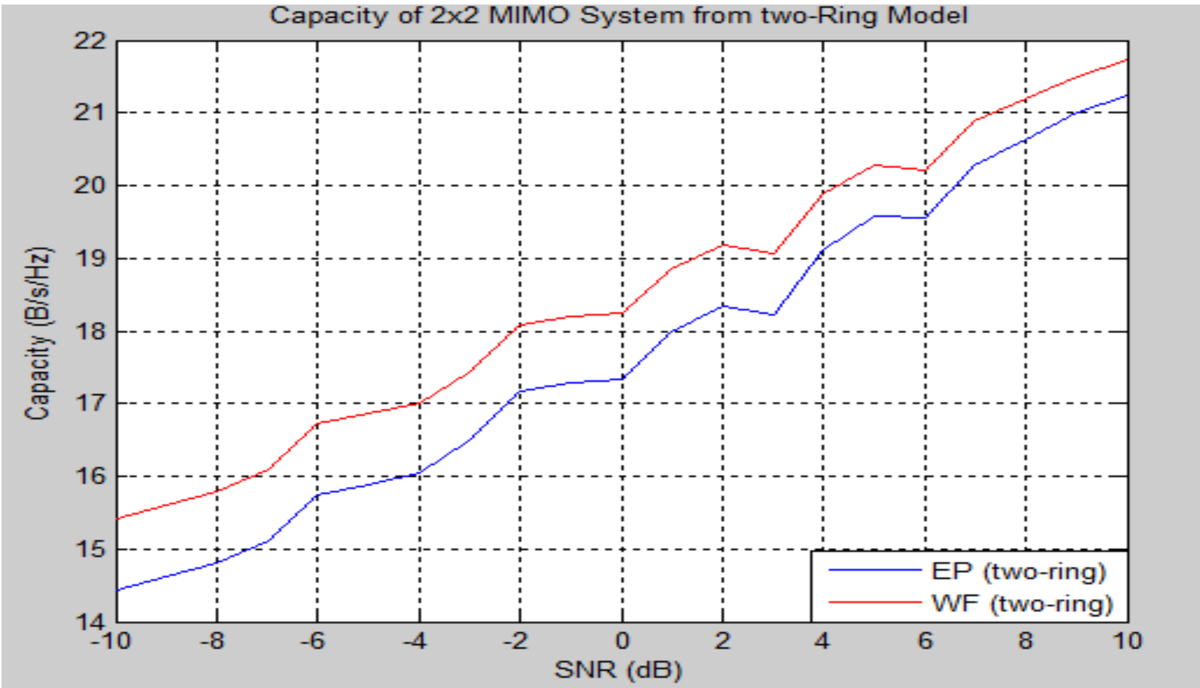


Figure 21: mean capacity vs. Signal noise ratio based on two-ring channel model at 2 Km distance between RX and RT

5.3 Summary

In this chapter, mean capacity results as function of signal noise ratio (SNR) have been introduced. The method that used to implement the mean capacity is mat-lab simulation code. So the mean capacity can be investigated in more details for two-ring channel model by using equal power and water-filling schemes. Several simulation results for 2 x 2 MIMO channel capacity were presented which are based on a number of scatterers, antenna spacing and the distance between the receiver antenna and receiver antenna. Each output has a different effect on the capacity that depends on the variable parameters of the model and single correlation. However, two-ring channel model is quite similar to one-ring channel model, but there are some differences between those two models that needs to be introduced

- two-ring channel model is an extension of the one-ring channel model
- two-ring channel model is more suitable for indoor and outdoor wireless environment, since it contains more number of scatterers that creates a richer multipath environment
- The one-ring channel model is considered useful, because a base station is usually high above the average ground which allows the BS to be modelled without any distraction of the local scatterers.
- Two-ring channel model has greater capacity than one-ring channel model due to the higher number of scatterers.

Chapter 6

Conclusion and future work

6.1 Conclusion

One-ring and two-ring channel models were investigated in more details to understand the concept of geometrical model. Geometrical channel model is a part of MIMO channel model which has been developed very fast in the last two decades. MIMO channel model is considered to be one of the faster technologies on communication system, since it can provided high speed data rate without extending the demand of the bandwidth.

In chapter 2, there are different categories of MIMO channel model which were introduced that depend on a number of parameters observed at the receiver (RX). Those categories can be classified based on the type of channel such as flat fading or the modelling approach taken such as physical model. Moreover, the geometric channel model has been investigated in more details, since it is the main aim of this thesis.

In chapter 3, MIMO system capacity has been investigated for both one-ring and two-ring channel models. MIMO capacity can be calculated in two methods which are equal power and water-filling. Equal power capacity has no knowledge about the channel that the transmit signal power is divided equally over the transmitting antenna. Water-filling capacity has prefect knowledge about the channel which allows the total power to be divided in the most efficient way over different transmitter. Another element that affects the capacity is mutual coupling. Mutual coupling can be occurred when the antennas are very close from each other.

In chapter 4 and 5, the results of capacity as function of single noise ratio (SNR) at fixed number antenna were obtained. Those results were simulated by using mat-lab program to investigate the capacity response of one-ring and two-ring channel models. From reference model, the circuit of one-ring and two-ring channel model were implemented by chosen the values of some parameters and other parameters were measured based on the chosen parameters. However, the capacities of one-ring and two-ring channel model for both equal power and water-filling were divided into three parts that based on number of scatterers, antenna spacing and the distance between the receiver antenna and receiver antenna. Each output has difference influence on the capacity that depends on the variable parameters of the model and single correlation. The results show that short distance between the transmitter, large number of scatteres and long space between antennas has greater capacity for both one-ring and two-ring channel mode. By comparing between the-one ring and two-ring channel model, it can be noticed that the capacity of two-ring channel model has higher capacity than one-ring channel model.

6.2 Future work

This thesis has introduced the capacity of geometric model as part of MIMO channel model, to be more specific one-ring and two ring channel model. There is many more way to increase the capacity of one-ring and two channel models that could selected for future and implementation in MIMO channel model such as

- implement one-ring and two-ring channel model in selective frequency instead of fading frequency which allow the capacity to increase
- Another type of geometric model is elliptical model which can be investigated to understanding the increase of capacity and compared with other types of geometric models.

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Appendix

One-ring model for MIMO channel with different values of scatterers

```
% capacity of MIMO Link with NR=2, NT=2

NR=2;                        % number of transmit and receive antennas
nTime = 100;                 % number of times to simulate
DeltaTime = 1;               % time step
Alpha_v = pi/4;              % direction of movement of MS
D = 1;                       % km distance between mobile and base stations
R = 0.01;                    % radius of circle of scatterers
nScat = 100;                 % number of scatterers

% work out water filling capacity
global OneOverEigVals snr

% work out geometry of scatterers
```

```
Phi_MS = (1:nScat)/nScat*2*pi;  % space scatterers evenly around circle
Phi_BS = atan( R*sin(Phi_MS)./(D-R*cos(Phi_MS)) );
Phi_max_BS = atan(R/D);      % maximum angular spread at base station

SNR_Array = -10:10;
nSNR = length(SNR_Array);

fmax = 0;                    % maximum doppler frequency
fn = fmax*cos(Phi_MS - Alpha_v);

DeltaBS_Lamdba = 0.1;        %Antenna spacing at Base Station in wavelength
units
DeltaMS_Lamdba = 0.1;        %Antenna spacing at Mobile Station in
wavelength units

AlphaBS = pi/2;              % angle between antenna array and LoS
AlphaMS = pi/2;              % angle between antenna array and LoS

An = exp( j*pi*DeltaBS_Lamdba* ( cos(AlphaBS) +
Phi_max_BS*sin(AlphaBS)*sin(Phi_MS)   ) );
Bn = exp( j*pi*DeltaMS_Lamdba* cos(Phi_MS-AlphaMS) );

% loop over each SNR

MeanCapacity_EP = zeros(nSNR,1);
MeanCapacity_WF = zeros(nSNR,1);
for iSNR = 1:nSNR
    snr=10^(SNR_Array(iSNR)/10);

    % loop over times

    CEP = zeros(nTime,1);
    CWF = zeros(nTime,1);
    for iTime = 1:nTime

        Time = iTime*DeltaTime;

        Theta_n = rand(1,nScat)*2*pi;             % random phase from each
scatterer
        Cn = exp(2*pi*fn*Time + Theta_n);

        h11= sum( An .* Bn .* Cn );
        h21= sum( conj(An) .* Bn .* Cn );
        h12= sum( An .* conj(Bn) .* Cn );
        h22= sum( conj(An) .* conj(Bn) .* Cn );
        H = [ h11 h12; h21 h22] / sqrt(nScat);

        CEP(iTime) = log2 ( det ( eye(NR) + snr / NR * H * H'));

        EigenValues = eig( H'*H );
        OneOverEigVals = 1./EigenValues;

        First_Guess = 1;
        mu = fzero( 'Power_WF' , First_Guess);
%           Pi = mu - OneOverEigVals;
%           Pi(Pi<0) = 0;
        Ci = log2( mu * EigenValues );
        Ci(Ci<0) = 0;
```

```
        CWF(iTime) = sum( Ci );

    end

    MeanCapacity_EP(iSNR)=mean(CEP);
    MeanCapacity_WF(iSNR)=mean(CWF);
end
plot(SNR_Array,MeanCapacity_EP,'b')
hold on
plot(SNR_Array,MeanCapacity_WF,'r')
xlabel('SNR (dB)');
grid on
legend('EP (one-ring)','WF (one-ring)')
ylabel('Capacity (B/s/Hz)');
title('Capacity of 2x2 MIMO System from One-Ring Model');
```

mean capacity versus vary distance for antennas spacing for one-ring

```
% capacity of MIMO Link with NR=2, NT=2

NR=2;                        % number of transmit and receive antennas
nTime = 100;                 % number of times to simulate
DeltaTime = 1;               % time step
Alpha_v = pi/4;              % direction of movement of MS
D = 1;                       % km distance between mobile and base stations
R = 0.01;                    % radius of circle of scatterers
nScat = 100;                 % number of scatterers

% work out water filling capacity
global OneOverEigVals snr

% work out geometry of scatterers
Phi_MS = (1:nScat)/nScat*2*pi;  % space scatterers evenly around circle
Phi_BS = atan( R*sin(Phi_MS)./(D-R*cos(Phi_MS)) );
Phi_max_BS = atan(R/D);      % maximum angular spread at base station

SNR_Array = -10:10;
nSNR = length(SNR_Array);

fmax = 0;                    % maximum doppler frequency
fn = fmax*cos(Phi_MS - Alpha_v);

DeltaBS_Lamdba = 0.05;        %Antenna spacing at Base Station in wavelength
units
DeltaMS_Lamdba = 0.05;        %Antenna spacing at Mobile Station in
wavelength units

AlphaBS = pi/2;              % angle between antenna array and LoS
AlphaMS = pi/2;              % angle between antenna array and LoS

An = exp( j*pi*DeltaBS_Lamdba* ( cos(AlphaBS) +
Phi_max_BS*sin(AlphaBS)*sin(Phi_MS)   ) );
Bn = exp( j*pi*DeltaMS_Lamdba* cos(Phi_MS-AlphaMS) );

% loop over each SNR

MeanCapacity_EP = zeros(nSNR,1);
MeanCapacity_WF = zeros(nSNR,1);
```

```
for iSNR = 1:nSNR
    snr=10^(SNR_Array(iSNR)/10);

    % loop over times

    CEP = zeros(nTime,1);
    CWF = zeros(nTime,1);
    for iTime = 1:nTime

        Time = iTime*DeltaTime;

        Theta_n = rand(1,nScat)*2*pi;              % random phase from each
scatterer
        Cn = exp(2*pi*fn*Time + Theta_n);

        h11= sum( An .* Bn .* Cn );
        h21= sum( conj(An) .* Bn .* Cn );
        h12= sum( An .* conj(Bn) .* Cn );
        h22= sum( conj(An) .* conj(Bn) .* Cn );
        H = [ h11 h12; h21 h22] / sqrt(nScat);

        CEP(iTime) = log2 ( det ( eye(NR) + snr / NR * H * H'));

        EigenValues = eig( H'*H );
        OneOverEigVals = 1./EigenValues;

        First_Guess = 1;
        mu = fzero( 'Power_WF' , First_Guess);
%          Pi = mu - OneOverEigVals;
%          Pi(Pi<0) = 0;
        Ci = log2( mu * EigenValues );
        Ci(Ci<0) = 0;
        CWF(iTime) = sum( Ci );

    end

    MeanCapacity_EP(iSNR)=mean(CEP);
    MeanCapacity_WF(iSNR)=mean(CWF);
end
plot(SNR_Array,MeanCapacity_EP,'b')
hold on
plot(SNR_Array,MeanCapacity_WF,'r')
xlabel('SNR (dB)');
grid on
legend('EP (one-ring)','WF (one-ring)')
ylabel('Capacity (B/s/Hz)');
title('Capacity of 2x2 MIMO System from One-Ring Model');
```

mean capacity versus vary number of scatterers for two-ring

```
% capacity of MIMO Link with NR=2, NT=2

NR=2;                       % number of transmit and receive antennas
nTime = 100;                % number of times to simulate
DeltaTime = 1;              % time step
Alpha_v = pi/4;             % direction of movement of MS
```

```
D = 1;                          % km distance between mobile and base stations
lambda = 0.12;                  % wavelength in m
R_MS = 0.1;             % radius of circle of scatterers of MS
R_BS = 0.1;             % radius of circle of scatterers of BS
nScat_MS = 50;                % number of scatterers of MS
nScat_BS = 50;                % number of scatterers of BS

% work out geometry of scatterers
Phi_MS = (1:nScat_MS)/nScat_MS*2*pi;        % space scatterers evenly around
circle of MS
Phi_BS = (1:nScat_BS)/nScat_BS*2*pi;        % space scatterers evenly around
circle of MS
Phi_max_BS = atan(R_BS/D);                     % maximum angular spread at
base station

SNR_Array = -10:10;
nSNR = length(SNR_Array);

fmax = 0;                       % maximum doppler frequency
fn = fmax*cos(Phi_MS - Alpha_v);

DeltaBS_Lamdba = 0.01;          %Antenna spacing at Base Station in wavelength
units
DeltaMS_Lamdba = 0.01;          %Antenna spacing at Mobile Station in
wavelength units

AlphaBS = pi/2;                 % angle between antenna array and LoS
AlphaMS = pi/2;                 % angle between antenna array and LoS

Am  = exp( j*pi*DeltaBS_Lamdba* ( cos(Phi_BS - AlphaBS )));
Bn  = exp( j*pi*DeltaMS_Lamdba* ( cos(Phi_MS - AlphaMS )));
Cm = exp( j*2*pi/lambda*(R_BS*cos(Phi_BS)));
Cn = exp( -j*2*pi/lambda*(R_MS*cos(Phi_MS)));
Cmn = Cm*transpose(Cn);
Gmn_11 = Am*transpose(Bn) .* Cmn;
Gmn_22 = conj(Am)*Bn' .* Cmn;
Gmn_12 = Am*Bn' .* Cmn;
Gmn_21 = conj(Am)*transpose(Bn) .* Cmn;
Theta_zero = - 2*pi/lambda *(R_BS + D + R_MS);

% loop over each SNR

MeanCapacity_EP = zeros(nSNR,1);
MeanCapacity_WF = zeros(nSNR,1);
for iSNR = 1:nSNR
    snr=10^(SNR_Array(iSNR)/10);

    % loop over times

    CEP = zeros(nTime,1);
    CWF = zeros(nTime,1);
    for iTime = 1:nTime

        Time = iTime*DeltaTime;


        Theta_mn = rand(nScat_MS,nScat_BS)*2*pi;            % random phase
from each scatterer
```

```
        Dmn = exp(j*(repmat(2*pi*fn*Time,nScat_MS,1) + transpose(Theta_mn)
+ Theta_zero));

        h11 = sum( sum ( Gmn_11 .* Dmn) );
        h22 = sum( sum ( Gmn_22 .* Dmn) );
        h21 = sum( sum ( Gmn_21 .* Dmn) );
        h12 = sum( sum ( Gmn_12 .* Dmn) );

        H = [ h11 h12; h21 h22] / sqrt(nScat_BS * nScat_MS);
        CEP(iTime) = log2 ( det ( eye(NR) + snr / NR * H * H'));

        EigenValues = eig( H'*H );
        OneOverEigVals = 1./EigenValues;

        First_Guess = 1;
        mu = fzero( 'Power_WF1' , First_Guess);
%          Pi = mu - OneOverEigVals;
%          Pi(Pi<0) = 0;
        Ci = log2( mu * EigenValues );
        Ci(Ci<0) = 0;
        CWF(iTime) = sum( Ci );

    end

    MeanCapacity_EP(iSNR)=mean(CEP);
    MeanCapacity_WF(iSNR)=mean(CWF);
end
plot(SNR_Array,MeanCapacity_EP,'b')
hold on
plot(SNR_Array,MeanCapacity_WF,'r')
xlabel('SNR (dB)');
grid on
legend('EP (two-ring)','WF (two-ring)')
ylabel('Capacity (B/s/Hz)');
title('Capacity of 2x2 MIMO System from two-Ring Model');
```

mean capacity versus vary spacing antenna for two-ring

```
% capacity of MIMO Link with NR=2, NT=2

NR=2;                         % number of transmit and receive antennas
nTime = 100;                  % number of times to simulate
DeltaTime = 1;                % time step
Alpha_v = pi/4;               % direction of movement of MS
D = 1;                        % km distance between mobile and base stations
lambda = 0.12;                % wavelength in m
R_MS = 0.1;            % radius of circle of scatterers of MS
R_BS = 0.1;            % radius of circle of scatterers of BS
nScat_MS = 50;               % number of scatterers of MS
nScat_BS = 50;               % number of scatterers of BS

% work out geometry of scatterers
Phi_MS = (1:nScat_MS)/nScat_MS*2*pi;        % space scatterers evenly around
circle of MS
Phi_BS = (1:nScat_BS)/nScat_BS*2*pi;        % space scatterers evenly around
circle of MS
```

```
Phi_max_BS = atan(R_BS/D);                    % maximum angular spread at
base station

SNR_Array = -10:10;
nSNR = length(SNR_Array);

fmax = 0;                  % maximum doppler frequency
fn = fmax*cos(Phi_MS - Alpha_v);

DeltaBS_Lamdba = 0.04;       %Antenna spacing at Base Station in wavelength
units
DeltaMS_Lamdba = 0.04;       %Antenna spacing at Mobile Station in
wavelength units

AlphaBS = pi/2;            % angle between antenna array and LoS
AlphaMS = pi/2;            % angle between antenna array and LoS

Am  = exp( j*pi*DeltaBS_Lamdba* ( cos(Phi_BS - AlphaBS )));
Bn  = exp( j*pi*DeltaMS_Lamdba* ( cos(Phi_MS - AlphaMS )));
Cm = exp( j*2*pi/lambda*(R_BS*cos(Phi_BS)));
Cn = exp( -j*2*pi/lambda*(R_MS*cos(Phi_MS)));
Cmn = Cm*transpose(Cn);
Gmn_11 = Am*transpose(Bn) .* Cmn;
Gmn_22 = conj(Am)*Bn' .* Cmn;
Gmn_12 = Am*Bn' .* Cmn;
Gmn_21 = conj(Am)*transpose(Bn) .* Cmn;
Theta_zero = - 2*pi/lambda *(R_BS + D + R_MS);

% loop over each SNR

MeanCapacity_EP = zeros(nSNR,1);
MeanCapacity_WF = zeros(nSNR,1);
for iSNR = 1:nSNR
    snr=10^(SNR_Array(iSNR)/10);

    % loop over times

    CEP = zeros(nTime,1);
    CWF = zeros(nTime,1);
    for iTime = 1:nTime

        Time = iTime*DeltaTime;


        Theta_mn = rand(nScat_MS,nScat_BS)*2*pi;             % random phase
from each scatterer

        Dmn = exp(j*(repmat(2*pi*fn*Time,nScat_MS,1) + transpose(Theta_mn)
+ Theta_zero));

        h11 = sum( sum ( Gmn_11 .* Dmn) );
        h22 = sum( sum ( Gmn_22 .* Dmn) );
        h21 = sum( sum ( Gmn_21 .* Dmn) );
        h12 = sum( sum ( Gmn_12 .* Dmn) );

        H = [ h11 h12; h21 h22] / sqrt(nScat_BS * nScat_MS);
        CEP(iTime) = log2 ( det ( eye(NR) + snr / NR * H * H'));
```

```
        EigenValues = eig( H'*H );
        OneOverEigVals = 1./EigenValues;

        First_Guess = 1;
        mu = fzero( 'Power_WF1' , First_Guess);
%         Pi = mu - OneOverEigVals;
%         Pi(Pi<0) = 0;
        Ci = log2( mu * EigenValues );
        Ci(Ci<0) = 0;
        CWF(iTime) = sum( Ci );

    end

    MeanCapacity_EP(iSNR)=mean(CEP);
    MeanCapacity_WF(iSNR)=mean(CWF);
end
plot(SNR_Array,MeanCapacity_EP,'b')
hold on
plot(SNR_Array,MeanCapacity_WF,'r')
xlabel('SNR (dB)');
grid on
legend('EP (two-ring)','WF (two-ring)')
ylabel('Capacity (B/s/Hz)');
title('Capacity of 2x2 MIMO System from two-Ring Model');
```