Performance of Ultra Reliability and Low Latency Communication (URLLC) with the Composite Effects of Fading and Shadowing

By

Arslan Haider
0000172636

Supervisor
Dr. Syed Ali Hassan
Department of Electrical Engineering

A thesis submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Engineering - Telecommunication and Computer Networks (MS EE (T&CN))

In

School of Electrical Engineering and Computer Sciences,
National University of Sciences and Technology (NUST),
Islamabad, Pakistan.
(January 2019)

Approval

It is certified that the contents and form of the thesis entitled “**Performance of Ultra Reliability and Low Latency Communication (URLLC) with the Composite Effects of Fading and Shadowing** ” submitted by **Arslan Haider** have been found satisfactory for the requirement of the degree.

Advisor: **Dr. Syed Ali Hassan**
Signature: ____________________
Date: ____________________

Committee Member 1: **Dr. Hassaan Khaliq**
Signature: ____________________
Date: ____________________

Committee Member 2: **Dr. Fahd Ahmed Khan**
Signature: ____________________
Date: ____________________

Committee Member 3: **Dr. Syed Taha Ali**
Signature: ____________________
Date: ____________________

To My Parents

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at NUST SEECS or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

Author Name: **Arslan Haider**
Signature: ______________________________

Acknowledgement

My thanks goes first to Almighty Allah, Who gives power to the weak and helps the helpless, The most Gracious and Merciful.

I would like to thank my supervisor, Assistant Professor at School of Electrical Engineering and Computer Sciences, Dr. Syed Ali Hassan, for his moral boosting support, well guiding suggestions and encouragement throughout my research work.

I am also thankful to all the faculty members at SEECS, especially Dr. Hassaan Khaliq, Dr. Fahd Ahmed Khan and Dr. Syed Taha Ali for their moral support and valuable guidance.

Arslan Haider

Abstract

Ultra Reliable and Low Latency is one of the paramount requirements of 5G. Its mission critical applications are extremely sensitive as far as their reliability and latency features are concerned. Fading and shadowing are the core adversities that are responsible for the hindrance in the successful achievement of high reliability and low latency features. This thesis considers the integration of both massive MIMO and macro diversity into the system by demonstrating that they can prove vital because they tend to improve both data rate and reliability of the system. Evaluation of these systems on the basis of their outage probability of the multi-cellular system using Maximal Ratio Combining receivers in the vicinity of composite shadowing-fading environments has been taken into consideration. This is because these evaluations can provide useful insights on the requirements for the attainment of reliability requisites of the URLLC. Furthermore, a mathematical expression for outage probability of the system is also derived. It has been noticed that an increment in the number of antennas does not resulting the averaging out of the shadowing. Moreover, the shadowing severity adversely impacts the performance of massive MIMO systems. Moreover, higher or lower severity of shadowing results in higher or lower outage probabilities, respectively.

List of Abbreviations

URLLC	Ultra-Reliable and Low-Latency Communication
MIMO	Multiple input multiple output
SINR	Signal to interference plus noise ratio
SIR	Signal to interference ratio
MRC	Maximum ratio combining
CDF	Cumulative distribution function
PDF	Probability density function
MT	Mobile Terminal
UT	User Terminal
BS	Base Station

Contents

List of Figures

Chapter 1

Introduction

Ultra-Reliable and Low Latency Communications (URLLC) is one of the most paramount requirements of 5G. Its application in the mission-critical scenarios such as autonomous driving and remote surgery is the driving factor for its extremely high reliability and low latency features. Fading and shadowing are the most prominent adversities that play their part in hindering the achievement of reliable features. The integration of both massive MIMO and macro diversity into the system improves both data rate and reliability of the system. Performance evaluation of such a system can offer useful insights on the requirements for the attainment of reliability requisites of the URLLC.

1.1 What is URLLC?

The contemporary wireless communication systems are aimed at the communication of a large spectrum of human-centric data contents and multimedia. It is also anticipated that the upcoming wireless applications would be reinforced by the services that would be machine-centric as well. These applications will have a very useful impact on the society [1]. Ultra-reliable communication requirements of Machine-type communications

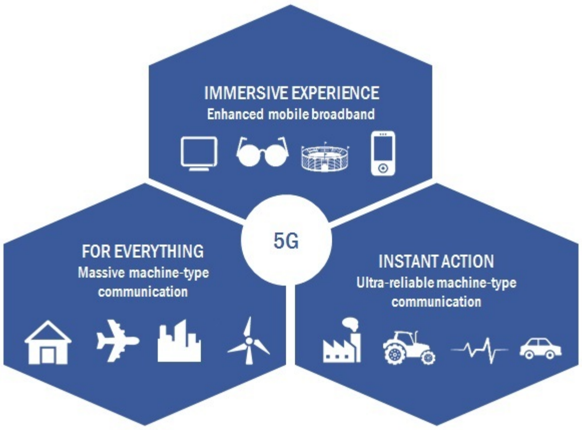

Figure 1.1: URLLC - A 5G Case

.

(MTC) are one of those contemporary cases that attract interest from the international research community. The core meaning of ultra-reliable and low latency communications is in terms of the applications that require the transmission of a specific with high success probability and low latency of 0.99999 and $30 \sim 100$ms, respectively, as shown in figure 1.1[1]. Examples of applications in this class of communication include autonomous driving, tactile internet, vehicular communications for safety, energy management, and industry automation [2], [3], [4].

1.2 What is MIMO System?

MIMO is an abbreviation of Multiple-Input Multiple-Output systems in antennas technology. It utilizes multiple number of antennas at the reception and transmission ends. It is designed on the basis that a higher number of antennas at the Base Stations result in the better system performance. This better performance of the system is due to the utilization

---

[1] Source:“http://www.analysysmason.com/Research/Content/Comments/5G-MENA-GSMA-Nov2016-RDRK0/ ”

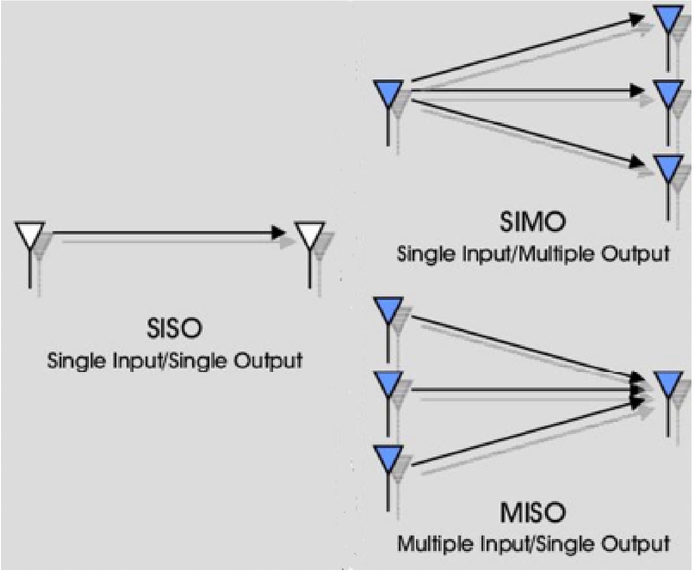

Figure 1.2: SISO, SIMO and MISO Systems

.

of diversity which not only improves the data rate of the system but also makes use of the scattered data for the improvement in the performance of the system [17]. Another benefit that is offered by the MIMO systems is the transmission of the data into a specific location, which results in the improvement of system performance in terms of energy efficiency in order to cater the escalating need for higher data rates [20]Figure 1.2[2].

Power and bandwidth are considered limited resources in the cellular systems [40-45]. MIMO systems can prove extremely effective in order to increase the capacity of the system without utilizing much bandwidth and power. The core improvements in the system can be evaluated on the basis of four categories, i.e. reliability, data rate, interference mitigation, and energy efficiency.

These systems benefit from the multi-path for the enhancement of capacity and reliability therefore enhancing the quality of service Figure 1.3[3]. These advantages are be-

---

[2] Source: “http://www.ntu.edu.sg/home/limo/seminar/MIMO$_{D}eke.pdf''$

[3] Source: “https://en.wikipedia.org/wiki/MIMO”

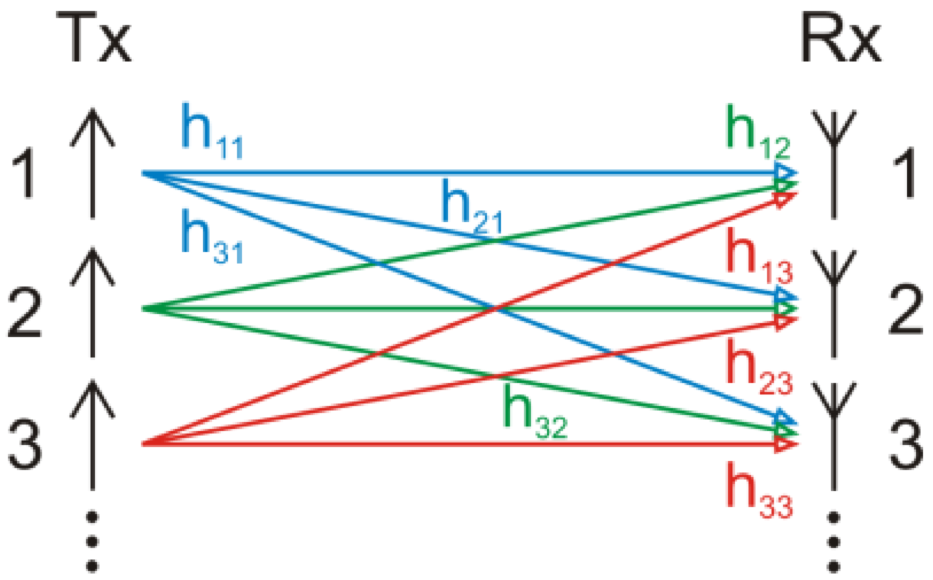

Figure 1.3: MIMO System

.

cause of the presence of multiple antennas that also induce interference cancellation, array gains, and multiplexing gains. A higher degree of freedom is also offered by the MIMO systems in terms of the link reliability, throughput enhancement, and effective channel propagation. The core reason behind it is the fact that the phenomenon of multipath propagation, which usually can play a hindering role in the efficient wireless communication, is exploited in these systems. Other important factors that play their part in the performance enhancement of the MIMO systems include spatial multiplexing gain, diversity gain, interference reduction and array gain.

1.3 Massive MIMO

The increase in demand for high data rates has driven the core of research in both industry and academia for working on the 5G network. 5G will be devised for numerous technologies such as millimeter wave communications, device-to-device, heterogeneous topolo-

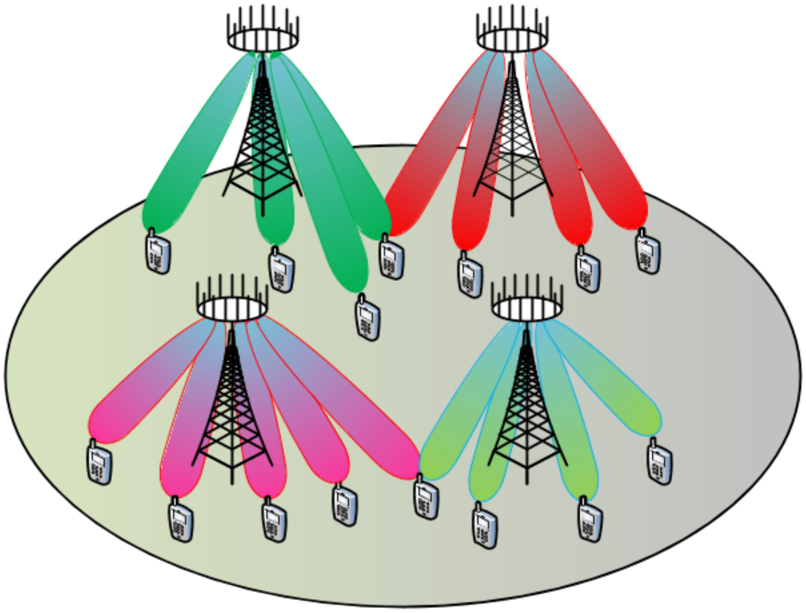

Figure 1.4: Massive MIMO System

.

gies, multi Radio-Access Technologies (RATs), and the massive Multiple-Input Multiple-Output (MIMO) systems. Hundreds of antennas are utilized in a massive MIMO system at the Base Station (BS) for simultaneously serving many users. It offers high throughput [14], [15], which allows to benefit from the conventional MIMO on the larger scale by making use of cheap antennas, therefore improving energy efficiency and increasing data rates [20]. The large arrays of antenna play their role in reducing the downlink (DL) and uplink (UL) transmission power via coherent combining, hence attaining higher rates of data. It will offer the basis of infrastructure of the upcoming digital society due to connection between Internet of things and Internet of people with networks including clouds. Massive MIMO is facilitating the advancements of imminent broadband services that will efficiently make use of the spectrum and energy, in a robust and secure manner [30].

As shown in Figure 1.4 [4], Massive MIMO is operated in TDD multiplexing. There are

---

[4] Source: “Joint Power Allocation and User Association Optimization for Massive MIMO Systems”

a few core reasons behind this mode of operation. In uplink communication, the estimation of Channel State Information is easy for BS by the cultivation of training sequences. First massive MIMO on downlink needs to transmit pilots to the mobile terminal for estimating the CSI. These pilots are needed to be mutually orthogonal and because of the integration of large number of antennas, the creation of these many orthogonal pilots is not easy. Second, the amount of channel responses that is required by every terminal for estimation also increases with the increase of number of BS antennas. Hence, the operation of massive MIMO in TDD mode is beneficial.

1.4 Why Massive MIMO?

Massive MIMO results in the increment of the system capacity because of its energy efficient features. This is because with a higher number of antennas energy can be directed into some specific direction by the integration of coherent superposition of wave-fronts. Wave-fronts can be generated in terms of both destructive and constructive manner. Base stations use this concepts in order to reduce interference that may be present in the system. In order to do so, multiple low power antennas are integrated in such systems for combining them for enhancing the efficiency of the system. Massive MIMO therefore allows the replacement of high power components at the base station with numerous low power antennas that utilize energy within the range of a few milliwatts. This setting also makes for the need of amplifiers and allows to benefit the systems from the combined effects of all the components. Law of large number forms the basis of this concepts, which averages out the effects of the hardware that does not functions accurately. This feature is very useful because it allows the working of the whole system even if some components fail. Energy utilization can further be enhanced by the using wind or solar energy.

Massive MIMO also address the latency issues of the system. Fading is one of the core reasons behind latency. When a fading channel is used for the transmission of a signal, it causes the signal to travel via multi-paths due to scattering. These multi-paths can give rise to destructive interference making the process of signal reconstruction more cumbersome, increasing the latency of the system. Massive MIMO counters the fading effect, which consequently reduces the overall latency.

Another benefit of integration of massive MIMO is that it does not depend upon the scattering properties of the environment in which it operates. The integration of multiple number of antennas itself offers diversity, which improves the system efficiency. Moreover, diversity is improved because multiple copies of the same data are transmitted from the transmitter to the receiver.

1.5 Problem Statement

The performance evaluation of URLLC in the composite fading and shadowing environment has not been addressed yet. Downlink transmission of a multi-cellular massive MIMO system with perfect CSI at the BS and Maximal Ratio Combining at the UT, while analyzing outage probability in the presence of a composite fading and shadowing environment can offer useful insights on the requirements for the attainment of reliability requisites of the URLLC.

1.6 Thesis Contribution

This research work considers a composite shadowing-fading channel. This channel is a combination of Gamma and Rayleigh distributions and has been modeled by K-distribution [31]. We provide a simplistic model for environment that is characterized by the composite fading-shadowing channel. On the contrary, other models which take the product of two random variables for the representation of both shadowing and fading, resulting in cumbersome mathematical analysis and modeling. This research then derives the closed-form expressions for outage probability in MIMO systems with composite channel that follows a K-distribution using MF approach. Simulations have been performed for composite fading and shadowing in already established MIMO framework. These simulations present proof of the derived outage probability expression. Performance analysis in composite environment has been performed for determining the requisites of URLLC system for a specific massive MIMO setting and severity of shadowing-fading in the channel.

1.7 Thesis Organization

This research work considers a composite shadowing-fading channel. This channel is a combination of Gamma and Rayleigh distributions and has been modeled by K-distribution [31]. We provide a simplistic model for environment that is characterized by the composite fading-shadowing channel. On the contrary, other models which take the product of two random variables for the representation of both shadowing and fading, resulting in cumbersome mathematical analysis and modeling. This research then derives the closed-form expressions for outage probability in MIMO systems with composite channel that follows a K-distribution using MF approach. Simulations have been performed for composite fading and shadowing in already established MIMO framework. These simulations present proof of the derived outage probability expression. Performance analysis in composite environment has been performed for determining the requisites of URLLC system for a specific massive MIMO setting and severity of shadowing-fading in the channel.

Chapter 2

Literature Review

There have been consistent advancements in mobile communication system over the past few years. Communication devices are integrated with more powerful processing units that have a better performance in terms of higher data rates. The European Mobile Observatory (EMO) stated that, since the last two decades, there has been more than 90 percent growth in mobile broadband [50]. These demands are increasing even more for wireless communication because more devices are establishing connections via wireless means. The introduction of MIMO technology was intended to accommodate all these devices in the cellular system. 4G was the first cellular network to have MIMO systems integrated into it. This is the very reason why 4G has the capability of providing high data rate for multiple users at the same time [4]. 4G system utilizes orthogonal frequency-division multiplexing (OFDM) integrated into the advanced radio interface. This MIMO system has the capacity of supporting data rates of 100M bps for high mobility and 1Gps for low mobility [5].

Abrupt increment in number of wireless devices leads to the fact that 4G networks do not have the capacity to conform to the demands of the market. Moreover, data is transmitted via high frequency waves which means the consumption of energy is also increasing at the BS [44]. Also high seamless coverage, high mobility, and high spectral efficiency are also some of the core challenges to ought to be dealt with [45]. For accommodating all these challenges, a novel system ought to be designed that must be provide seamless coverage while offering high data rates at the optimum expense of energy. All these challenges have paved the way for research on 5G networks. These networks are integrated with massive MIMO technology for providing low latency, higher data rates, and high reliability while complying with energy efficient means for upholding more efficient means of communication [46, 47].

Ultra-reliable communication requirements of Machine-type communications (MTC) are one of those contemporary cases that attract interest from the international research community. Ultra-reliable communication in 5G refers to the applications that require the transmission of a specific amount of data with success probability of 0.99999 with very low latency [10]. Examples of applications in this class of communication include autonomous driving, tactile internet, and vehicular communications for safety, energy management, and industry automation.

Pocovi et al. investigated different schemes in order to cope with the interference and fading effects. Their analysis concluded that traditional microscopic MIMO techniques with 4x4 or 2x2 configurations for antennas would not prove sufficient for the fulfillment of stringent reliability requirements of URLLC [10]. They also observed that such antenna configurations ought to be supplemented with interference management schemes and macroscopic diversity for ensuring the required SINR outage performance.

Device to device (D2D) communications are being integrated with massive MIMO [6], [7], [8], [9]. MIMO can also prove useful in nullifying the adversities of interference in D2D communications [6]. It is very beneficial in order to reduce the length of pilot symbol by effectively gaining the information about the Channel State Information [42]. It also allows the freedom in order to improve power utilization via usage of an iterative scheme [7].

It have been noted that even though the very large number of antennas integrated at the BS allow averaging out of the small-scale fading, large-scale fading (shadowing) still poses a hindrance in the realization of a massive MIMO system. The composite impression of small-scale and large-scale fading is modeled by expressing it as the multiple of lognormal and Rayleigh distributions [32]. But the requirement of signal-to-interference-noise ratio (SINR) Probability Density Function (PDF) is adamant for the rate analysis over channel exhibiting composite fading-shadowing nature [42]. Approximation schemes are required because no closed form expression is available for this PDF [22], [23] and [24].

The analysis of single cell system having multiple users, while operating under a composite fading-shadowing, has been presented in [22]. Three linear receiver known as MMSE, ZF and MRC have been taken into consideration while assuming perfect CSI [41]. Outage analysis has also been performed in this research while keeping in consideration a composite Rayleigh-lognormal environment. For this purpose, approximation of PDF for both SNR and SINR has been presented while utilizing log-normal random variable and then comparing the results of the three receivers. It has been concluded that the integration of very large number of antennas results in the averaging out of noise and small-scale fading, however does not affect the large-scale fading and it still acts as an adversity.

In [19], the authors attempt to present their research on the effects of shadowing, in which the generalized K-fading channels have been used for capacity evaluation. [22] and [25] used the composite fading-shadowing model for the analysis of outage probability. However, no work has been presented in order to evaluate the performance of a URLLC system in the presence of a composite fading-shadowing channel. No closed-form expression for outage probability has been expressed either.

Chapter 3

System Model

3.1 System Model

Figure 3.1[1] illustrates the network topology of our system model. Wide coverage is provided to a certain area by the strategic deployment of Base Stations (BSs). Every BS serves multiple Mobile Terminals (MTs) as far as they are within the vicinity of their respective coverage area. From the perspective of a MT, interference contaminates the desired signal which the neighboring BSs generate. In order to enhance microscopic diversity, both MT and BS can be integrated with multiple antennas. Moreover, higher order of redundancy and macroscopic diversity are also provided when a MT is cooperatively served by multiple BSs that are spatially-separated.

The presented multi-cellular system consists of L BSs, where each BS is equipped with M antennas to serve its cell. Each MT that resides in a cell is equipped with N antennas. It is assumed that the MIMO scheme is closed-loop, which means that the serving BS receives channel information from its MT. This information is then utilized for precoding, i.e. the determination of antenna transmitter weights. An environment of

---

[1] Source:“http://vbn.aau.dk/files/219673440/DiversityPaper$_{f}inal.pdf''$

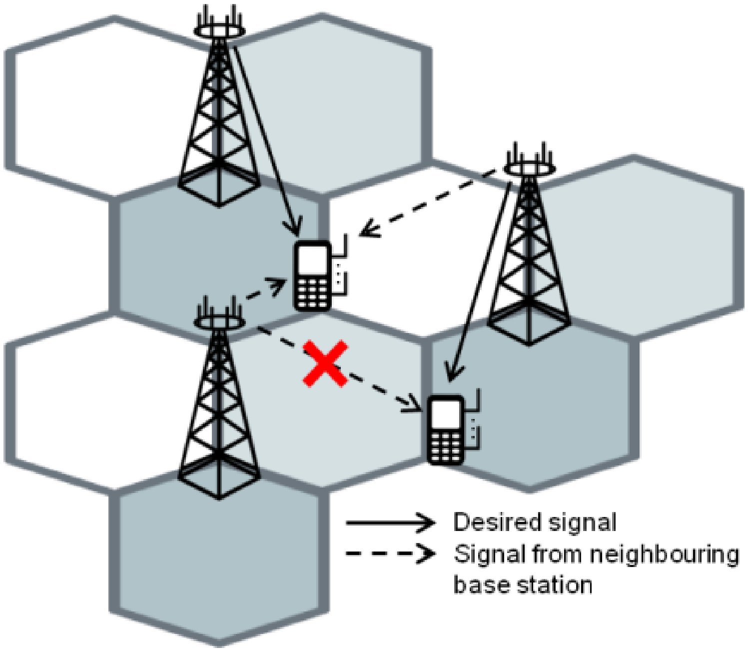

Figure 3.1: Typical Network Layout

.

composite fading-shadowing in nature is considered for the transmission of signals. This composite nature of the wireless medium corresponds to both large-scale and small-scale fading. It is assumed that all random variables corresponding to the channel coefficients are independent and identically distributed (iid), following a K-distributed envelope. The N-dimensional received signal rk by the MT served by BS k is expressed as:

$$r_k = \mathbf{H_k}\sqrt{\Omega_k}\mathbf{w_k^m}s_k + \sum_{j=1}^{I}\mathbf{H_j}\sqrt{\Omega_j}\mathbf{w_j^m}s_j + \mathbf{n} \tag{3.1}$$

where $\mathbf{w}_j^m$ is the M-dimensional vector for precoding at the j-th BS; Ω_j and s_j represent the average received power and transmitted symbol, respectively. $||s_j|| = 1$ for simplicity; I is the number of interferers; $\mathbf{H_j}$ is the M×N matrix whose (n,m)-th entry denotes the complex channel gain between n-th antenna at the receiver and antenna m at the j-th transmitting BS; and n denotes the N×1 zero mean and σ^2 variance Gaussian

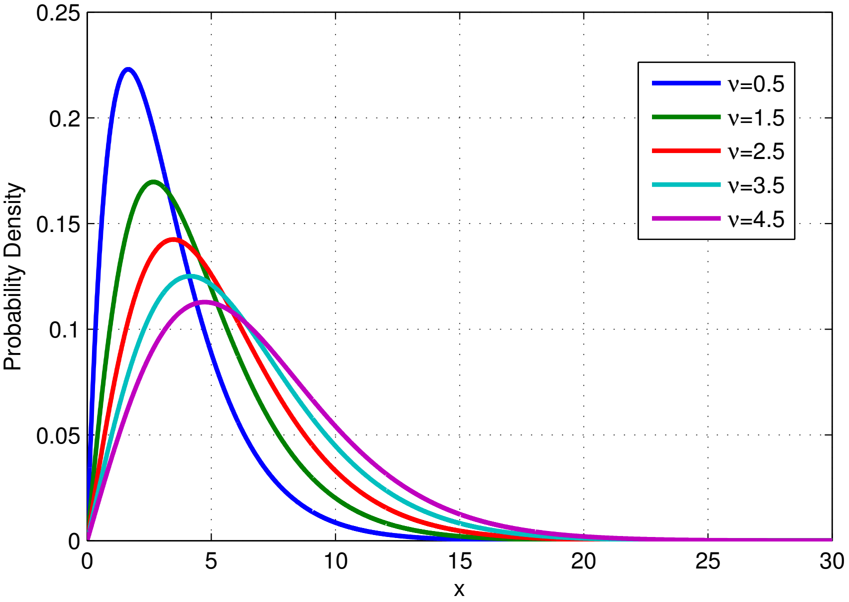

Figure 3.2: PDF of K-Distribution with various shape parameters

.

vector for noise at each antenna at the receiving side. The received signal vector at the MT is expressed as

$$y_k = \mathbf{w_k^n} r_k = \mathbf{w_k^n} \mathbf{H_k} \sqrt{\Omega_k} \mathbf{w_k^m} s_k + \sum_{j=1}^{I} \mathbf{w_k^n} \mathbf{H_j} \sqrt{\Omega_j} \mathbf{w_j^m} s_j + \mathbf{w_k^n} \mathbf{n} \tag{3.2}$$

where $\mathbf{w_k^n}$ is the 1×N weight vector at the receiver; $\mathbf{H_k} \in \mathbb{C}^{MxN}$ is the channel matrix for the composite channel between k-th BS and MT equipped with M and N number of antennas, respectively. Each element in $\mathbf{H_k}$ is a product of square root of a gamma distributed RV and iid zero-mean complex Gaussian RVs as given below

$$h = \sqrt{z}(g_r + jg_i); h \in \mathbf{H_k} \tag{3.3}$$

where z denotes a gamma RV; and g_r and g_i represent the real and imaginary parts of a complex Gaussian RV, respectively. K distribution defines the envelop of h, and its Probability Distribution Function (PDF) is illustrated in Figure 3.2 and is given by

$$f_{|h|}(|h|) = \frac{2}{\alpha \Gamma(\vartheta+1)} \left(\frac{|h|}{2\alpha}\right)^{\vartheta+1} K_{\vartheta}\left(\frac{|h|}{\alpha}\right) \tag{3.4}$$

where ϑ and α denote the shape and scale parameters, respectively. The severity of shadowing is controlled by varying the values of ϑ. A small value of v implies high shadowing and vice versa. The $K_v(.)$ is the modified Bessel function of the second kind. We are using K distribution because it allows us to incorporate a composite fading-shadowing channel whose severity of shadowing is based on the value of its shape parameter [30-35]. Keeping in consideration a perfect CSI at the receiver and an interference-limited scenario, the downlink Signal-to-Interference Ratio (SIR) of k-th BS is expressed as

$$SIR_k = \frac{||\mathbf{w_k^n H_k^H H_k w_k^m}||^2}{\sum_{j=1}^{I} ||\mathbf{w_k^n H_k^H H_j w_j^m}||^2} \tag{3.5}$$

where [.] denotes the Hermitian operator. In order to find the outage probability, the above expression for SIR is used as a general expression of SIR

$$SIR_k = Z = \frac{X}{Y} \tag{3.6}$$

where Z is used to denote SIR for derivation purposes; X is the sum of M×N squared K-distributed RVs; and Y is the sum of (M×N)(L−1) squared K-distributed RVs. The expression for squared K-distribution is given by

$$f_X(x) = 2\left(\frac{1}{\alpha}\right)^{\vartheta+1} x^{\frac{\vartheta-1}{2}} K_{\vartheta-1}\left[2\left(\frac{x}{\alpha}\right)^{1/2}\right]. \tag{3.7}$$

Figure 3.3 illustrates the squared K-distribution for different values of shape parameters v, i.e. shadowing intensity parameter

For the derivation of closed form expression of outage probability, both X and Y are approximated by another RV that Gamma-distributed. On the basis of this assumption, PDF of Y is expressed as

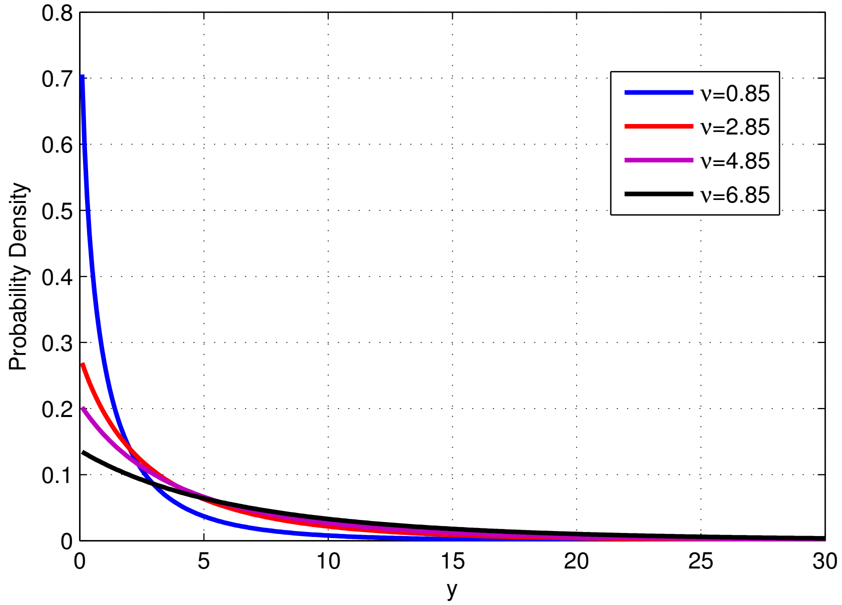

Figure 3.3: Squared K-distribution

.

$$f_X(x) = \frac{\Theta^{-\xi}}{\Gamma(\xi)} x^{\xi-1} e^{-\frac{x}{\Theta}} \tag{3.8}$$

where Θ and ξ are scale and shape parameters, respectively; and $\Gamma(.)$ is the Gamma function. For Gamma approximation of sum of RVs that are K-distributed, moment matching scheme is used. This method yields scale and shape parameter of Gamma distribution in the form of scale and shape parameters of squared K-distributed RVs with some adjustment factor ε. We obtain Θ and ξ expressed in α and ϑ as given by

3.1.1 Theorem 1

We use the results presented in [29 and 49] for the approximation of K-distribution by Gamma distribution for a simplistic scenario in which the BS is equipped with multiple antennas and the user is equipped with only one antenna. In this scenario, the numerator is actually a squared K RV whereas the denominator is the sum of squared K RVs because of the interferers. In order to derive the expression of outage probability for this scenario, we apply this approximation on the denominator having L$-$1 intereferers, we get the shape and scale parameters as:

$$\Theta = (\nu - \varepsilon)\alpha, \tag{3.9}$$

$$\xi = \frac{L-1}{\nu - \varepsilon}, \tag{3.10}$$

where ν is found by

$$\nu = 1 + \frac{2}{\vartheta}, \tag{3.11}$$

We use the following expression for obtaining the outage probability

$$O = \mathbb{P}\big\{SIR < \tau\big\} = \int_0^\infty \left[\int_0^{\frac{x}{z}} f_Y(y)dy\right] f_X(x)dx, \tag{3.12}$$

The inner integral yields the CDF of Gamma distribution which is expressed as

$$\int_0^{\frac{x}{z}} f_Y(y)dy = \frac{\gamma(\xi, \frac{x}{z\Theta})}{\Gamma(\xi)}, \tag{3.13}$$

where $\gamma(.)$ is incomplete gamma function. Incorporating Eq. 3.13 and Eq. 3.7 in Eq. 3.12, the following expression for outage probability is obtained

$$O = \int_0^\infty \frac{2}{\Gamma(\vartheta)}\left(\frac{1}{\alpha}\right)^{\frac{\vartheta+1}{2}} x^{\frac{\vartheta-1}{2}} K_{\vartheta-1}\left[2\sqrt{\frac{x}{\alpha}}\right]\frac{\gamma(\xi, \frac{x}{z\Theta})}{\Gamma(\xi)}dx \tag{3.14}$$

Expanding the above integration gives

$$O = \rho\left[a\left[-1 + F_1\left(\xi, 1-\vartheta, \frac{\tau}{\alpha\Theta}\right)\right] + b_1 F1\left(\xi+\vartheta, 1+\vartheta, \frac{\tau}{\alpha\Theta}\right)\right], \tag{3.15}$$

where b, a and ρ are expressed as

$$\rho = \frac{\alpha^{-\vartheta}}{\Gamma(\vartheta)\Gamma(\xi)} \left(\frac{\Theta}{\tau}\right)^{-\vartheta}, \tag{3.16}$$

$$a = \left(\frac{\alpha\Theta}{\tau}\right)^{\vartheta} \Gamma(\xi)\Gamma(\vartheta), \tag{3.17}$$

$$b = \Gamma(-\vartheta)\Gamma(\xi + \vartheta), \tag{3.18}$$

such that $\Re(\vartheta) > 0$, $\Re(\xi + \vartheta) > 0$, $\Re(\xi) > -1$, $\Re(\frac{\Theta}{\tau}) > 0$ and $a > 0$

3.1.2 Theorem 2

For the case case of massive MIMO, the transmitter and receiver are equipped with M and N number of antennas, respectively. The shape and scale parameters for equation 3.8, which expresses the numerator of the SIR, can then be expressed as:

$$\Theta = (\nu - \varepsilon)\alpha, \tag{3.19}$$

$$\xi = \frac{M \times N}{\nu - \varepsilon}, \tag{3.20}$$

where ν is found by

$$\nu = 1 + \frac{2}{\vartheta}, \tag{3.21}$$

Similarly, the PDF of Y, the denominator of SIR, is expressed as

$$f_Y(y) = \frac{\Theta^{-\xi}}{\Gamma(\xi)} y^{\xi-1} e^{-\frac{y}{\Theta}} \tag{3.22}$$

Using the same process for the denominator, we get

$$\Theta_Y = (\vartheta - \varepsilon)\alpha, \tag{3.23}$$

$$\xi_Y = \frac{(L-1)(M \times N)}{\vartheta - \varepsilon}, \tag{3.24}$$

where ϑ is found by

$$\vartheta = 1 + \frac{2}{\vartheta}, \tag{3.25}$$

We use the following expression for obtaining the outage probability

$$O = \mathbb{P}\{SIR < \tau\} = \int_0^\infty \left[\int_0^{\frac{x}{z}} f_Y(y)dy\right] f_X(x)dx, \tag{3.26}$$

where inner integral is given as

$$\int_0^{\frac{x}{z}} f_Y(y)dy = \frac{\gamma\left(\frac{(L-1)(M\times N)}{\vartheta-\varepsilon}, \frac{x}{z(\vartheta-\varepsilon)\alpha}\right)}{\Gamma\left(\frac{(L-1)(M\times N)}{\vartheta-\varepsilon}\right)} \tag{3.27}$$

using Eq. 16 to solve Eq. 3.26 while keeping the upper limit of the integral as t, gives the outage probability of a single cell as follows

$$\begin{aligned} O = \mathbb{P}\{SIR < \tau\} = \\ & \frac{t^{-\frac{(-1+L)MN\vartheta}{-2+\vartheta(-1+\varepsilon)}}}{\Gamma\left(\frac{MN}{1+\frac{2}{\vartheta}-\varepsilon}\right)\Gamma\left(\frac{(-1+L)MN}{1+\frac{2}{\vartheta}-\varepsilon)}\right)}\left(a\left(1+\frac{2}{\vartheta}-\varepsilon\right)\right)^{\frac{(-1+L)MN}{1+\frac{2}{\vartheta}-\varepsilon)}} \\ & \times\left(\frac{t\vartheta}{\alpha(2+\vartheta-\vartheta\varepsilon)}\right)^{-\frac{(-1+L)MN\vartheta}{-2+\vartheta(-1+\varepsilon)}} \\ & \times\left[\Gamma\left(-\frac{(-1+L)MN\vartheta}{-2+\vartheta(-1+\varepsilon)}\right)-\gamma\left(-\frac{(-1+L)MN\vartheta}{-2+\vartheta(-1+\varepsilon)}, \frac{t\vartheta}{\alpha(2+\vartheta-\vartheta\varepsilon)}\right)\right] \\ & \times\gamma\left(\frac{MN\vartheta}{-2+\vartheta-\vartheta\varepsilon)}, \frac{\vartheta^2}{\alpha(2+\vartheta-\vartheta\varepsilon)}\right) \end{aligned} \tag{3.28}$$

such that

$\Re\left(\frac{2+\vartheta(1+(-1+L)MN-\varepsilon)}{2+\vartheta-\vartheta\varepsilon}\right) > -1$, $\Re\left(\frac{4+\vartheta(2+(-1+L)MN-2\varepsilon)}{2+\vartheta-\vartheta\varepsilon}\right) > -1$,
$\Re\left(\frac{-2+\vartheta(-1+(-1+L)MN+\varepsilon)}{-2+\vartheta(-1+\varepsilon}\right) < 1$, $\Re\left(\frac{-1+(-1+L)MN\vartheta}{-2+\vartheta(-1+\varepsilon}\right) < 0$

Chapter 4

Numerical Results

This chapter demonstrates the effects of varying the number of antennas on the outage probability. Different simulation results in various settings, for example varying the number of antennas at the BS and severity of shadowing. It has been assumed that there is one user situated in a cell that receives signals from both, the BS of its cell and BS from the neighboring cells that act as interferers in the process of calculating the SIR of the system. The values all the variables have been mentioned in the explanation of their respective graphs so that it may be easier to discern them from one another. Outage and success probabilities have been calculated in both simulations and theoretically as given in the derived expression for outage probability. These simulation and theoretical results have been illustrated simultaneously for better understanding of their concurrency. It has been seen that the analytical results that have been expressed in our derived equation for outage probability, are reinforced by the simulations.

Figure 4.1 illustrates the behavior of the simulation and theoretical results in terms of outage probability versus threshold. In this case, the number of interfering BSs has been assumed as one. The intensity of shadowing in the system is considered at 0.85. It can be seen that as the threshold for the received SIR increases, the probability of

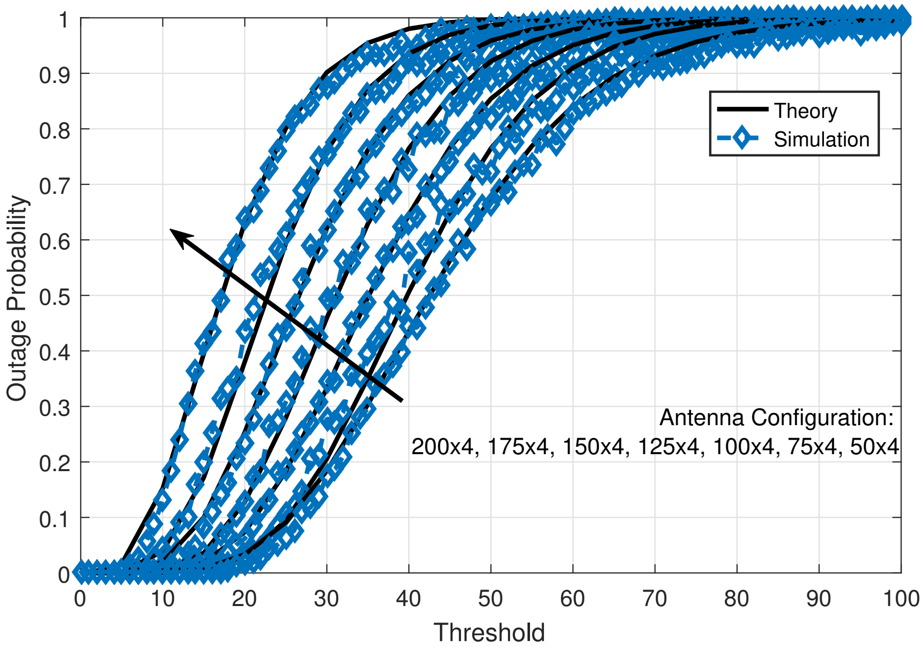

Figure 4.1: Outage probability for different antenna configurations at shadowing intensity of $v = 0.85$

incurring outage also increases. Furthermore, the figure also illustrates that the antenna configuration can play an eminent role in terms of reducing the outage probability. As the number of antennas is increased at the BS, the outage probability tends to decline and vice versa.

Figure 4.2 demonstrates that behavior of outage probability for different values of shape parameter. Different values of shape parameter represent different severity levels of shadowing. Higher the value of shape parameter, lower is the severity of shadowing and vice versa. It is intuitive to reckon that higher value of shape parameter should result in lower outage probability of the system, and lower value of shape parameter should result in higher outage probability of the system. This intuition is also confirmed by the simulation results as presented in figure 4.2. It can be seen that as the value of shape parameter is increases, i.e. the severity of shadowing is decremented and the outage probability of the system also decreases, and vice versa.

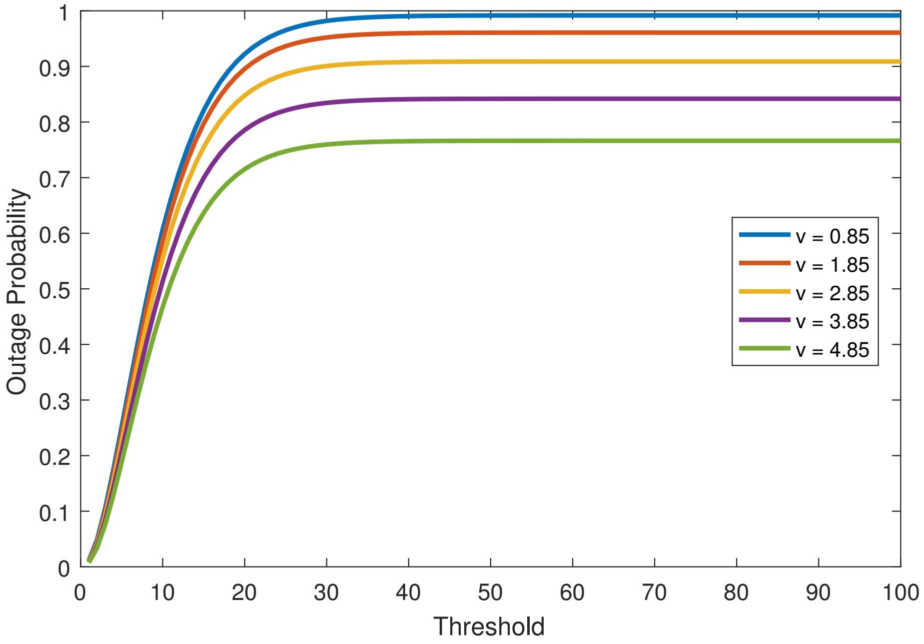

Figure 4.2: Outage probability for antenna configuration of 25x4 at different values of severity of shadowing

It has also been observed that the final expression for outage probability follows the Beta Prime distribution, which is also known as the Beta distribution of the second kind. In order to verify this observation, we compare the PDFs of both, the ratio of our SIR and Beta Prime's theoretical expression for its PDF. It must be noted that the two shape parameters of this Beta Prime distribution are expressed as the shape parameter of the individual Gamma distribution of the numerator and denominator, respectively as they have been found by the Gamma approximation of the K distribution as mentioned in the system model section. Figure 4.3 shows that our simulation results are reinforced by the theoretical model.

Figure 4.4 depicts the performance of the system in MIMO CoMP mode. In this mode, the individual SIRs of the base stations are added together to benefit from the macro-diversity of the whole system. It can be seen that MIMO CoMP has lower outage probability as compared to that of the simple MIMO scheme. This is because the inter-

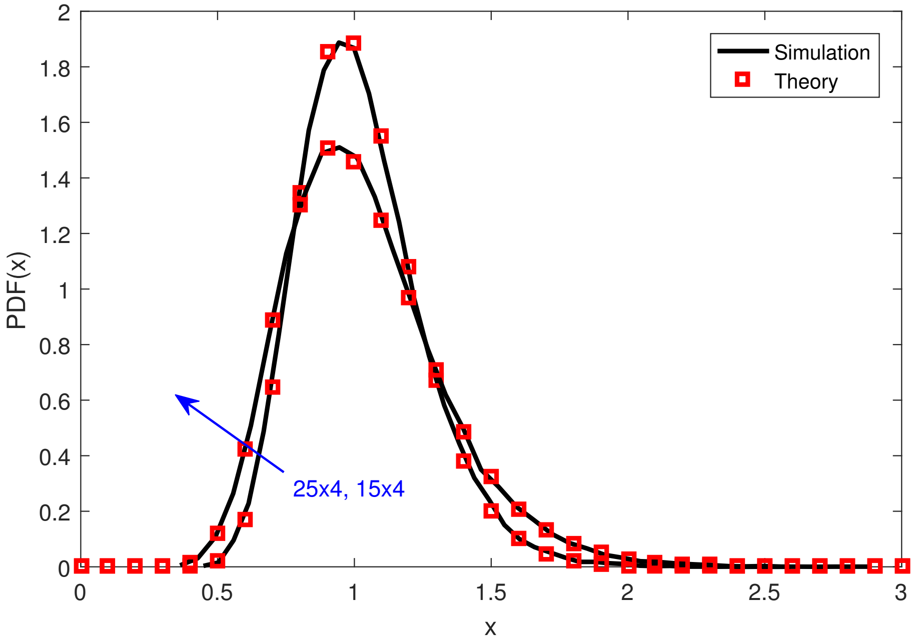

Figure 4.3: PDFs of simulated SIR of our model and theory (Beta Prime) for antenna configurations of 15x4 and 25x4

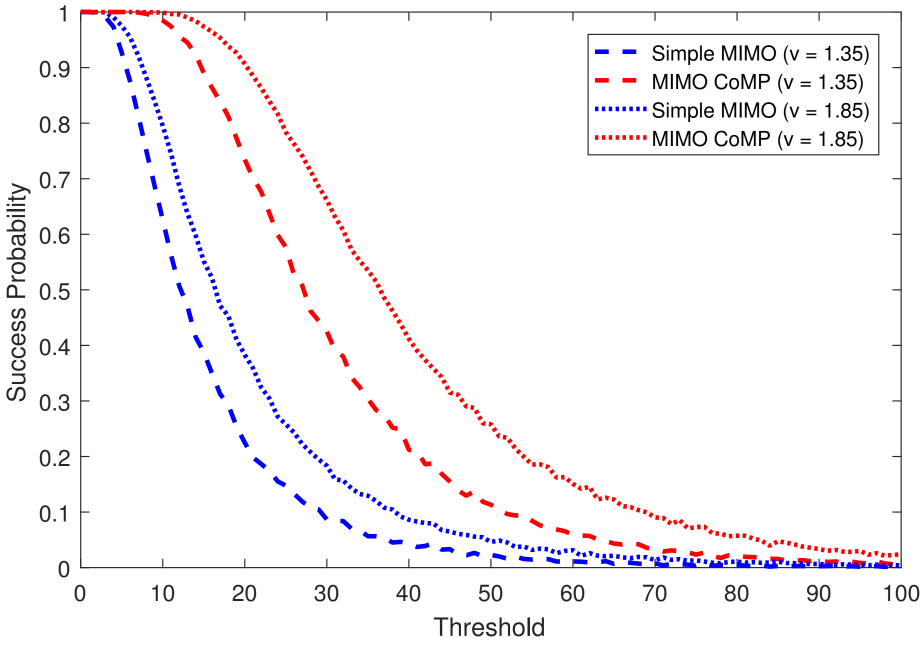

Figure 4.4: MIMO vs MIMO CoMP: Success probability for antenna configuration of 15x4 at different values of severity of shadowing

fering BSs are not only seen as interferers as they play their role in improving the overall SIR of the system.

Chapter 5

Conclusion and Future Work

This chapter presents the conclusion of our work and also adds some potential suggestions that can pave the way for our future research endeavors.

5.1 Conclusion

This thesis presented an analyzation of the effects of shadowing on the ergodic rates of the multi-cell massive MIMO system by taking into consideration a K-distributed channel. Outage and success probabilities have been analyzed for different antenna configurations and severity levels of shadowing for the determination of the optimum setting for the achievement of URLLC requirements. It has been shown that shadowing severity plays an imperative role in terms of determining its impacts on the URLLC systems. Higher the severity level, higher number of antennas required for the achievement of URLLC requirements. However, it has also been observed that even at a very high antenna configuration, the effects of shadowing cannot be completely averaged out. System performance for different antenna configurations has also been demonstrated for system analysis. It has also been shown that the outage probability of the system is directly proportional to the threshold.

5.2 Future Work

For future consideration, we intend to carry out performance analysis of the system with different pre-coders and estimators. We can also perform these analysis in HetNet that operate in the vicinity of composite fading channels in massive MIMO settings. Different channel distributions for more accurate analysis of the outage probability under certain antenna configurations and K-faded channels can also be used. Moreover, Device-to-Device (D2D) massive MIMO can also be taken into consideration in indoor scenarios while operating in K-fading environment.

Appendix A – Communication Systems Symbols

$\mathbf{x}_l^{ul}$	Transmitted data vector from UT to BS in lth cell
$\mathbf{y}_j^{ul}$	Received data vector from UT to BS in jth cell
$\mathbf{H}_{jl}$	Complex channel vector of jth cell
$\mathbf{n}$	AWGN noise vector
$\mathbf{W}_l$	Precoding Vector of lth cell
$\mathbf{s}_l$	Precoded data vecotr of lth cell
$\mathbb{E}\,[]$	Expectation value
$\hat{\mathbf{h}}$	Estimated value of channel
γ_{jm}^{dl}	Downlink SINR of mth user in jth cell

Bibliography

[1] A. Osseiran et al., “Scenarios for the 5G Mobile and Wireless Communications: the Vision of the METIS Project”, *IEEE Communications Magazine*, vol. 52, no. 5, pp. 26-35, May 2014.

[2] G. P. Fettweis, “The tactile internet: applications and challenges”, *IEEE Vehicular Technology Magazine*, vol. 9, no. 1, pp. 64-70, March 2014. A. Frotzscher et al.„ “Requirements and current solutions of wireless communication in industrial automation”, *IEEE ICC Workshops*, , June 2014.

[3] P. Gautam, S. Kaur, R. Kaur, S. Kaur and H. Kundra, “Review Paper on 4G Wireless Technology”, *Int. Journal of Adv. in Sci. and Tech.*, Vol. 2, pp. 15-19, March 2014.

[4] C. Wang, F. Haider, X. Gao, X. You, Y. Yang, D. Yuan, H. M. Aggoune, H. Haas, S. Fletcher and E. Hepsaydir, “Cellular Architecture and Key Technologies for 5G Wireless Communication Networks”, *IEEE Comm. Mag.*, vol. 52, pp 122-130, Feb. 2014.

[5] M. Xie, X. Jia, M. Zhou and L. Yang, “Study on energy efficiency of D2D underlay massive MIMO networks with power beacons”, *8th Int. Conf. on Wireless Comm. and Signal Proc. (WCSP)*, 13-15 Oct. 2016, Yangzhou, China.

[6] L. Cottatellucci, "D2D CSI feedback for D2D aided massive MIMO communications", *IEEE Sensor Array and Multichannel Signal Proc. Workshop (SAM)*, 10-13 July 2016.

[7] T. E. Bogale L. B. Le, "Massive MIMO and mmWave for 5G Wireless HetNet: Potential Benefits and Challenges", *IEEE Veh. Tech. Mag.*, Vol. 11, pp. 64-75, Feb. 2016.

[8] A. Adhikary, H. S. Dhillon and G. Caire, "Massive-MIMO Meets HetNet: Interference Coordination Through Spatial Blanking", *IEEE J. on Sel. Areas in Comm.*, Vol. 33, pp. 1171-1186, June 2015.

[9] B. Xu, Y. Chen, M. Elkashlan T. Zhang and K. Wong, "User association in massive MIMO and mmWave enabled HetNets powered by renewable energy", *IEEE Wireless Comm. and Net. Conf. (WCNC)*, 3-6 April 2016, Doha, Qatar.

[10] Gerardino, G. A. P., Alvarez, B. S., Lauridsen, M., Pedersen, K. I., Mogensen, P. E "Signal Quality Outage Analysis for Ultra-Reliable Communications in Cellular Networks", *Globecom Workshops (GC Wkshps)*, Vol. 26, pp. 530-540, April 2008.

[11] T. L. Marzetta, "Noncooperative cellular wireless with unlimited numbers of base station antennas", *IEEE Trans. Wireless Commun.*, vol. 9, pp. 3590-3600, Nov. 2010.

[12] F. Rusek, D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, and F. Tufvesson, "Scaling up MIMO: opportunities and challenges with very large array", *IEEE Signal Process. Mag.*, vol. 30, pp. 40-60, Jan. 2013.

[13] D. Gesbert , M. Shafi, D. Shiu, P. Smith and A. Naguib, "From theory to practice: An overview of space-time coded MIMO wireless systems", *IEEE J. Sel. Areas Commun.*, vol. 21, no. 3, pp. 281-302. 2003.

[14] M. T. Mushtaq, S. A. Hassan and D. N. K. Jayakody, “Ergodic Rate Analysis of Massive MIMO Systems in K-Fading Environment”, *84th IEEE Vehicular Technology Conference (VTC-Fall)*, 18âĂŞ21 Sep 2016, MontrÃl’al, Canada.

[15] A. Lozano and N. Jindal, “Transmit Diversity vs. Spatial Multiplexing in Modern MIMO Systems”, *IEEE Trans. Wireless Commun.*, vol. 9, pp. 186-197, Jan. 2010.

[16] A. Yang, Z. He, C. Xing and Z. Fei, J. Kuang, “The role of large-scale fading in uplink massive MIMO systems”, *IEEE Trans. Veh. Tech.*, vol. 65, pp. 477-483, Jan. 2016.

[17] H. Q. Ngo, E. G. Larsson and T. L. Marzetta, “Energy and spectral efficiency of very large multiuser MIMO systems”, *IEEE Trans. Commun.*, vol. 61, pp. 1436-1449, Apr. 2013.

[18] M. S. Zia and S. A. Hassan, “On the impacts of composite fading on large-scale multi-user MIMO systems”, *IEEE Commun. Letters*, vol. 19, no.12, pp. 2286-2289, Dec. 2015.

[19] M. Bacha and S. A. Hassan, “Performance analysis of cooperative linear networks subject to composite shadowing fading”, *IEEE Trans. Wireless Commun.*, vol. 12, pp. 5850-5858, Nov. 2013.

[20] A. Rahman and S. A. Hassan, “Analysis of composite fading in a single cell downlink cooperative heterogeneous networks”, *81st IEEE Vehicular Technology Conference (VTC-Spring)*, Glasgow, United Kingdom, May 2015, pp. 1-5.

[21] M. S. Zia and S. A. Hassan, “Outage analysis of multi-user massive MIMO systems subject to composite fading”, *81st IEEE Vehicular Technology Conference (VTC-Spring)*, Glasgow, United Kingdom, May 2015, pp. 1-5.

[22] J. Hoydis, S. Brink and M. Debbah, “Massive MIMO in the UL/DL of cellular networks: how many antennas do we need?”, *IEEE J. Sel. Areas in Commun.*, vol. 31, pp. 160-171, Feb. 2013.

[23] P. S. Bithas and A. A. Rontogiannis, “Mobile communication systems in the presence of fading/shadowing, noise and interference”, *IEEE Trans. Commun.*, vol. 63, pp. 724-737, Jan. 2015.

[24] A. Liu and V. Lau, “Hierarchical interference mitigation for massive MIMO cellular networks”, *IEEE Trans. Signal Proces.*, vol. 62, pp. 4786-4797, July 2014.

[25] Z. Mulk and S. A. Hassan, âĂIJOn Achievable Rates in Massive MIMO-based Hexagonal Cellular System with Pilot ContaminationâĂİ,*81st IEEE Vehicular Technology Conference (VTC-Spring)*, May 2015, Glasgow, United Kingdom.

[26] E. G. Larsson, O. Edfors, F. Tufvesson and T. L. Marzetta“Massive MIMO for Next Generation Wireless Systems”, *IEEE Comm. Mag.*, vol. 52, pp. 186-195, Feb. 2014.

[27] A. Abdi and M. Kaveh, “K distribution: an appropriate substitute for Rayleigh-lognormal distribution in fading-shadowing wireless channels”, *Electron. Lett.*, vol.34, pp. 851-852, Apr.1998.

[28] I. Trigui and A. Laourine, S. Affes, and A. Stephenne, "Performance analysis of mobile radio systems over composite fading/shadowing channels with co-located interference", *IEEE Trans. Wireless Commun.*, vol. 8, pp. 3448-3453, July 2009.

[29] M. Johamm and W. Utschick, J.A. Nossek, “Linear transmit processing in MIMO communications systems”, *IEEE Trans. Signal Proces.*, vol. 53, pp. 2700-2712, Aug. 2005.

[30] G. L. Stuber, *Principles of Mobile Communication*, 3rd ed. Springer+Business Media, 2011.

[31] S. Al-Ahmadi and H. Yanikomeroglu, "On the approximation of the generalized-*K* distribution by a Gamma distribution for modeling composite fading Channels", *IEEE Trans. Wireless Commun.*, vol. 9, pp. 706-713, Feb. 2010.

[32] A. H. Mehana and A. Nosratinia, "Diversity of MIMO Linear Precoding", *IEEE Trans. on Inf. Theory*, vol. 60, pp. 1019 - 1038, Nov. 2013.

[33] A. Abdi, H.A. Barger and M. Kaveh, "A Simple Alternative to the Lognormal Model of Shadow Fading in Terrestrial and Satellite Channels", *54th IEEE Vehicular Technology Conference (VTC-Spring)*, Atlantic City, New Jersey USA, Aug. 2001, pp. 2058-2062.

[34] P. S. Bithas, N. C. Sagias, P. T. Mathiopoulos, G. K. Karagiannidis and A. A. Rontogiannis, "On the Performance Analysis of Digital Communications over Generalized-K Fading Channels", *IEEE Commun. Letters*, vol. 10, no. 5, pp. 353-355, May 2006.

[35] A. Laourine, M. Alouini, S. Affes and A. Stephenne, "On the Capacity of Generalized-K Fading Channels", *IEEE Trans. Wireless Commun.*, vol. 7, pp. 2441-2445, July 2008.

[36] S. Al-Ahmadi and H. Yanikomeroglu, "On the Statistics of the Sum of Correlated Generalized-K RVs", *IEEE International Conference on Communications*, Cape Town, South Africa, May 2010, pp. 1-5.

[37] A. Abdi and M. Kaveh, “Comparison of DPSK and MSK Bit Error Rates for *K* and Rayleigh-Lognormal Fading Distributions”, *IEEE Commun. Letters*, vol. 4, no. 4, pp. 122-124, April 2000.

[38] E. Jakeman and P. Pusey, “A model for non-Rayleigh sea echo”, *IEEE Trans. on Antennas and Prop.*, vol. 24, pp. 806-814, Nov 1976.

[39] E. Jakeman and P. Pusey, “Significance of *K* Distributions in Scattering Experiments”, *Phys. Rev. Lett.*, Vol. 40, Issue 9, Feb. 1978.

[40] P. S. Bithas, P. T. Mathiopoulos and S. A. Kotsopoulos, “Diversity Reception over Generalized-K (KG) Fading Channels”, *IEEE Commun. Letters*, vol. 6, no. 12, pp. 4238-4243, Dec. 2007.

[41] C. Feng, Y. Jing and S. jin, “Interference and Outage Probability Analysis for Massive MIMO Downlink with MF Precoding”, *IEEE Signal Proces. Letters*, vol. 23, pp. 366-370, March 2016.

[42] F. Fernandes, A. Ashikhmin and T. L. Marzetta, “Inter-Cell Interference in Noncooperative TDD Large Scale Antenna Systems”, *IEEE Sel. Areas Commun.*, vol. 31, pp. 192-201, Feb. 2013.

[43] W. Fukuda, T. Abiko, T. Nishimura, T. Ohgane, Y. Ogawa, Y. Ohwatari and Y. Kishiyama, “Low-complexity Detection Based on Belief Propagation in a Massive MIMO System”, *77th IEEE Vehicular Technology Conference (VTC-Spring)*, Dresden, Germany, June 2013, pp. 1-5.

[44] S. Zarei, W. Gerstacker, R. R. MÃijller and R. Schober, “Low-Complexity Linear Precoding for Downlink Large-Scale MIMO Systems”, *24th IEEE International*

Symposium on Personal Indoor and Mobile Radio Communications (PIMRC), London, United Kingdom, Sep. 2013, pp. 1-5.

[45] C. Fragouli, N. Al-Dhahir and W. Turin, “Training-Based Channel Estimation for Multiple-Antenna Broadband Transmissions”, *IEEE Trans. Wireless Commun.*, vol. 2, pp. 384-391, March 2003.

[46] M. Bigues and A. B. Gershman, “Training-Based MIMO Channel Estimation: A Study of Estimator Tradeoffs and Optimal Training Signals”, *IEEE Trans. Signal Proces.*, vol. 54, pp. 884-893, March 2006.

[47] R. Zakhour and S. V. Hanly, “Base station cooperation on the downlink: Large system analysis”, *IEEE Trans. on Inf. Theory*, vol. 58, pp. 2079-2106, April 2012.

[48] S. Atapattu, C. Tellambura and H. Jiang, “A Mixture Gamma Distribution to Model the SNR of Wireless Channels”, *IEEE Trans. Wireless Commun.*, vol. 10, pp. 4193-4203, Dec. 2011.

[49] J. A. Anastasov, G. T. Djordjevic and M. C. Stefanovic, “Analytical Model for Outage Probability of Interference-Limited Systems over Extended Generalized-K Fading Channels”, *IEEE Commun. Letters*, vol. 16, no.04, pp. 473-475, April 2012.

[50] Euro. Mobile Industry Observatory, GSMA, Nov. 2011.