2.

PERFROMANCE EVALUATION OF MULTIPLE ANTENNAS

2.1 Introduction

In multipath environment, signal from one antenna takes multiple paths to arrive at the another antenna. In the case of mobile communication, signals from base station experiences different phenomena such as reflection, refraction, diffraction, interference, and scattering in the environment then it reach to the mobile user. The signals in the mutipath environment may interfere either constructively or destructively. The peaks in received signal appears due to constructive interferences. When the different signals add destructively, the received signal is likely to suffer sudden dips which are unexpected and will degrade the performance of the channels, shown in Fig. 2.1. When there is no Line-of-Sight (LOS) path between transmitter and receiver, the received signal suffers from Rayleigh fading [Fujimoto and James (2001), Rappaport (2010)]. That means the envelope of the received signal is Rayleigh distributed at every point in time. Due to different propagation effects, the received signal amplitude, phase, polarization, etc. become random. Mobile terminal e.g. handsets, phones, etc., undergo strong fading in multipath environments such as urban and indoor environments. The instantaneous fading of the signal is completely random for different frequency, space, time, and polarization. Signal fading due to the multipath propagation can be reduced using antenna diversity techniques.

However, a multiple antenna system can operate in diversity or MIMO mode according to the Signal-to-Noise Ratio (SNR) level under a rich scattering circumstance. In the case of low SNR level, the diversity mode can be selected. All the antennas at transmitter (or receiver) send (or receive) the same signal over the same channel. Since the transmitting (or receiving) antennas are uncorrelated, the possibility of the fading deeps for all the antennas is reduced. If the SNR is high, the multiple antenna system will work in the MIMO scheme and utilizes the fading to provide several uncorrelated channels [Brown (2002)].

2.2 Mechanism for Achieving Diversity

Using multiple antennas there are different ways of achieving diversity in order to generate de-correlated signals at the same branch of power level. In this work, antenna diversity in mobile phone will be studied. Diversity can be created by multiple means. Brief introduction of some of them, in which Space diversity, Frequency diversity, Angle diversity, Time and Multipath diversity, Polarization diversity, and Pattern diversity can be utilized in antenna systems are discussed below.

- **Space Diversity:** By using two antennas with a separate points in space the phase delays make multipath signals arriving at the antennas differ in fading. In order to achieve the sufficient de-correlation, the antennas must have a minimum spacing at a mobile terminal is usually some 0.5 wavelengths, calculated using the zero order Bessel function [Schwartz (*et al.* (1966)]. Now-a-days, space diversity is commonly used because of the higher frequencies used for transmission making it possible to apply this kind of diversity mechanics in smaller terminals.

- **Frequency Diversity:** Frequency diversity is implemented by transmitting information on more than one carrier frequency. The same signal at sufficiently spaced carrier frequencies will provide independent fading of the signal, thus the probability of simultaneous fading of combined signal at the receiver will be very low. It is costly mechanism to use because of the difficulties in generating several transmitted signals and combining received signals at several different frequencies simultaneously [Zhang *et al.* (2013)].

- **Angle Diversity:** At the antennas, signals are coming from different directions. Being independent in their fading variations these signals can be used for angle or angular diversity. Angle diversity can be achieved using two omni-directional antennas. Each antenna elements are acting as parasitic elements to each other and change their patterns to allow signals to be picked up at different angles [Schwartz *et al.* (1966)].

- **Time and Multipath Diversity:** Time and multipath diversity are the related mechanisms mostly applicable in the digital transmission. Time diversity is achieved by transmitting the same bit of information repetitively at short time intervals. Fading variations of these different repetitions of a signal will be independent. Multipath diversity uses time diversity in multipath environments getting the information from repetitive signals coming from different paths [Sulonen (1999)].

- **Polarization Diversity:** The transmission of one polarization is depolarized by the propagation medium resulting in two orthogonal polarization with uncorrelated fading variations. At the mobile terminal, polarization diversity is also an attractive option because of the size limitations involved. However, there is still a need for more appropriate model to use given scenarios such as low isolation between the branches, polarization impurities, wide angle of arrival, and differing antenna field patterns [Schwartz *et al.* (1966)].

- **Pattern Diversity:** Pattern diversity can be achieved when patterns of two diversity antennas are compared. When using two or more co-located antennas with different radiation patterns, the signals arriving at the antennas will be from different directions and uncorrelated. Pattern diversity never applied alone, it usually appears in addition to space diversity [Plicanic *et al.* (2009)].

In this thesis, pattern diversity is mainly utilized and antennas are mainly designed for mobile phone applications. The antenna elements are placed at each corners of the mobile circuit board which are mirror images to each other. The radiation patterns of each antenna elements are almost mirror images of each other over desired operating bands. That means they are covering the complementary space regions and indicating that the MIMO antenna has good pattern diversity characteristics. The pattern diversity characteristics is used to combat the multipath fading effect. The reason for this choice is that these mechanisms are simple and easy to implement, they do not have any complicated signal or antenna system requirement as other diversity mechanism.

2.3 Diversity Performances

In the multipath propagation scenario signal may be scattered, reflected, refracted, and diffracted which cause the signal fading. In order to mitigate this problem, diversity techniques were developed. Diversity means the receiver should have more than one version of the transmitted signal available, where each version is received through a different channel.

To characterize the diversity channel, several diversity as well as MIMO parameters are available. In this section, these parameters are elaborated sequentially.

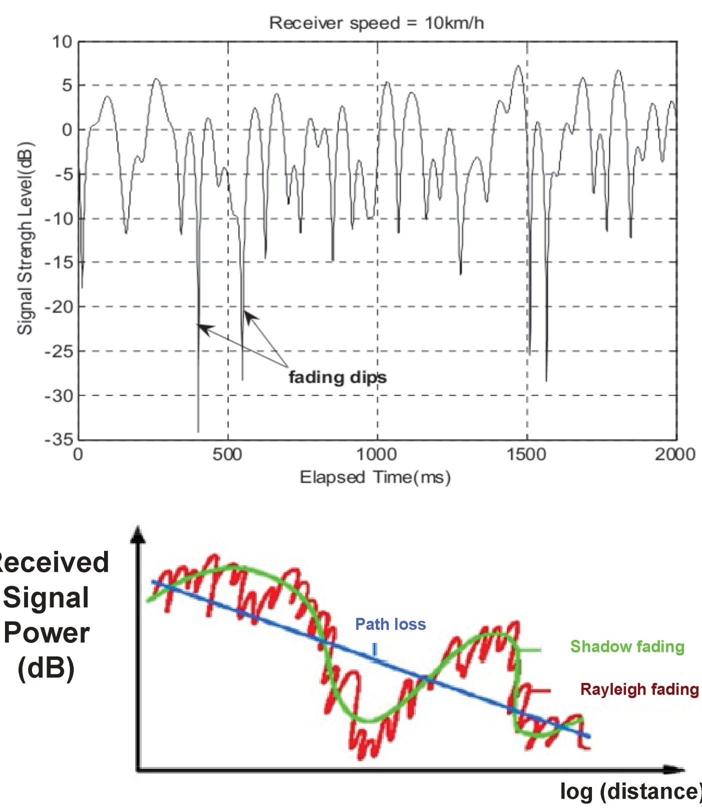

Figure 2.1: A typical Rayleigh fading envelope.

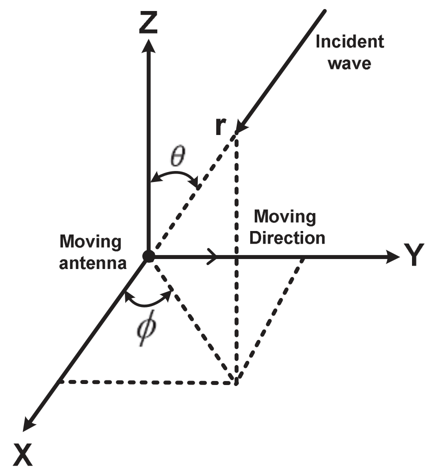

Figure 2.2: Spherical coordinates in mobile radio environments.

2.3.1 Mean Effective Gain (MEG)

In multipath environment of mobile communication, an imbalanced power of the diversity branches will result in a diversity loss which is proportional to the imbalanced level [Plicanic *et al.* (2009)]. The total antenna efficiency is accounted of this imbalanced power level. However, since the diversity is expected to be used under any possible circumstances, the antenna channel mismatch is also quite important. Therefore, the MEG is widely used, which accounts antenna efficiency, diversity gain, and wireless environment. The MEG is figure-of-merit for the average performance of the antenna on a mobile terminal taking into account the incident radio waves in the multipath environment and gain patterns of the antenna. In the mobile environment, MEG is the average gain of an antenna and is defined as the ratio of mean received power of the antenna (P_{rec}) to the total mean incident power ($P_V + P_H$) and given as [Taga (1990)];

$$G_e = \frac{P_{rec}}{(P_V + P_H)} \tag{2.1}$$

The mean incident power ratio P_V / P_H represents the cross polarization power ratio (XPR),

$$XPR = \frac{P_V}{P_H} \tag{2.2}$$

For the spherical coordinates as shown in Fig. 2.2, the mean received power of antennas, (P_{rec}) is expressed as [Taga (1990)];

$$P_{rec} = \int_0^{2\pi}\int_0^{\pi}\{P_1 G_\theta(\theta,\phi)P_\theta(\theta,\phi) + P_2 G_\phi(\theta,\phi)P_\phi(\theta,\phi)\}\, sin\theta d\theta d\phi \qquad (2.3)$$

where, $G_\theta(\theta,\phi)$ and $G_\phi(\theta,\phi)$ are the θ- and ϕ- components of the antenna power gain patterns, respectively. $P_\theta(\theta,\phi)$ and $P_\phi(\theta,\phi)$ are the θ- and ϕ- components of the angular density functions of incoming plane waves, respectively. P_1 and P_2 are the mean power that would be received by a θ -polarized and ϕ -polarized isotropic antenna, respectively.

According to the Fig. 2.2, mobile antenna moves in the *XY*-plane, the θ -components corresponding to the vertical polarization (VP) and horizontal polarization (HP) components, respectively. Thus the term P_1 and P_2 are mean received power of the VP isotropic antenna and HP isotropic antenna, and *XPR* is the ratio of P_1/P_2. By using Eq. (2.2) and (2.3) the expression of MEG is given as [Taga (1990)];

$$MEG = \int_0^{2\pi}\int_0^{\pi}\left[\frac{XPR}{1+XPR}G_\theta(\theta,\phi)P_\theta(\theta,\phi) + \frac{1}{1+XPR}G_\phi(\theta,\phi)P_\phi(\theta,\phi)\right] sin\theta d\theta d\phi \qquad (2.4)$$

where, *XPR* is cross polarization ratio, $G_\theta(\theta,\phi)$ and $G_\phi(\theta,\phi)$ are the θ- and ϕ- components of the antenna power gain patterns, respectively. $P_\theta(\theta,\phi)$ and $P_\phi(\theta,\phi)$ are the θ- and ϕ- components of the angular density functions, respectively. The antenna realized gains in MEG are normalized to [Taga (1990)];

$$\oint\left(G_\theta(\theta,\phi) + G_\phi(\theta,\phi)\right) sin\theta d\theta d\phi = 4\pi \qquad (2.5)$$

The statistical power spectrum distribution of both vertically and horizontally polarized incident radio waves can be represented by $P_\theta(\theta,\phi)$ and $P_\phi(\theta,\phi)$, respectively.

Taga (1990) [Taga (1990)] has already been discussed about incident waves arrive at an antenna. The elevation angles of incoming waves depend on environmental condition between transmitter and receiver. The multipath environment between transmitter and receiver is shown in Fig. 2.3. When mobile user moves in the typical mobile communication environment the incident waves arrived from multipath environment at receiver over a random route. In the typical mobile environment communication, an incident wave arrived at an antenna, most of the incident waves are diffracted, reflected, and scattered by buildings and surrounding objects [Ikegami and Yoshida (1977), Sakagami]. Since buildings have no general rule in shape, size, height, and material. Therefore arrival direction of incident waves vary the number, strength, polarization, and phase of incident waves, depending on the city structure and antenna location. When mobile user moves in such a propagation environment, there are number of incident waves arrived at the moile user over random route. Some of the statistical models was presented in [Clark (1969), Gans (1979), Aulin (1979), Awadalla (1981), Vaughan (1986)]. In such statistical model, assumed that the angular density fucntions of VP and HP incident wave to be uniform in azimuth but in elevation direction there is no such prediction. Some of the studied done by assuming different elevation angle of angular density functions. Lee, reported that the elevation angle is somewhat larger that 16^0 but less than 39^0 [Lee (1982)]. Jakes reported that the elevations are somewhat larger than 11^0 but less than 39^0 [Jakes (1974)]. Watanabe *et al.* measured the average signal strength in the 873 MHz band, received from a collinear dipole array that consisted of six dipole elements, and with which it was possible to tilt the radiation beam at an elevations of 0^0, 30^0, and 60^0**.** They reported that the elevation angles were spread over the angular range from 0^0 to 30^0 [Watanabe *et al.* (1977)]. All the above reported data indicates that the elevation angles are spread over a wide angular range and that the dispersion of elevation angle depends on regional environment condition. It is noted that different types of distribution models was suggested by different researchers. This is due to different locations and environments considered for the study. When a user of a mobile terminal moves along a random route, a uniform distribution is a reasonable assumption for the angular density functions in azimuth direction as was assumed in [Taga (1990)]. However, the angular density functions in the elevation direction are not uniformly distributed and the different distributions can assumed which are following:

- **Gaussian Distribution:** Gaussian distribution is shown in Fig. 2.4. The distribution functions incident plane waves are expressed as follows [Taga (1990)]:

$$P_\theta(\theta,\phi) = A_\theta\, exp\left[-\frac{\left\{\theta-\left[\left(\frac{\pi}{2}\right)-m_V\right]\right\}^2}{2\sigma_V^2}\right], (0\leq \theta \leq \pi) \quad (2.6)$$

$$P_\phi(\theta,\phi) = A_\phi\, exp\left[-\frac{\left\{\theta-\left[\left(\frac{\pi}{2}\right)-m_H\right]\right\}^2}{2\sigma_H^2}\right], (0\leq \theta \leq \pi) \quad (2.7)$$

- **Laplacian Distribution:** The angular density functions of incoming plane waves are expressed as follows [Knudsen (2001)]:

$$P_\theta(\theta,\phi) = A_\theta\, exp\left[-\frac{\sqrt{2}\left|\theta-\left(\frac{\pi}{2}-m_V\right)\right|^2}{\sigma_V}\right], (0\leq \theta \leq \pi) \quad (2.8)$$

$$P_\phi(\theta,\phi) = A_\phi\, exp\left[-\frac{\sqrt{2}\left|\theta-\left(\frac{\pi}{2}-m_H\right)\right|^2}{\sigma_H}\right], (0\leq \theta \leq \pi) \quad (2.9)$$

where, m_V and m_H are the mean elevation angle of VP and HP wave distribution, respectively and σ_V and σ_H are, the standard deviation of each VP and HP wave distribution, respectively. A_θ and A_ϕ are constants are determined by;

$$\int_0^{2\pi}\int_0^{\pi} P_\theta(\theta,\phi)\sin(\theta)\, d\theta d\phi = \int_0^{2\pi}\int_0^{\pi} P_\phi(\theta,\phi)\sin(\theta)\, d\theta d\phi = 1 \quad (2.10)$$

In this thesis, indoor, outdoor, and isotrpic environments are considered to evaluate diversity perfromance of the proposed MIMO antenna for mobile handset. In the azimuth plane, uniform distribution is considered while Gaussian distribution is considered in elevation plane. The value of Angle of Arrival (AOA) and *XPR* for each environment is applied on Gaussian statistical model.

Table 2.1 sumarized the propagation statistical model which is considered for evaluation of diversity parameters in this thesis [Plicanic (2004), Ying (2004)].

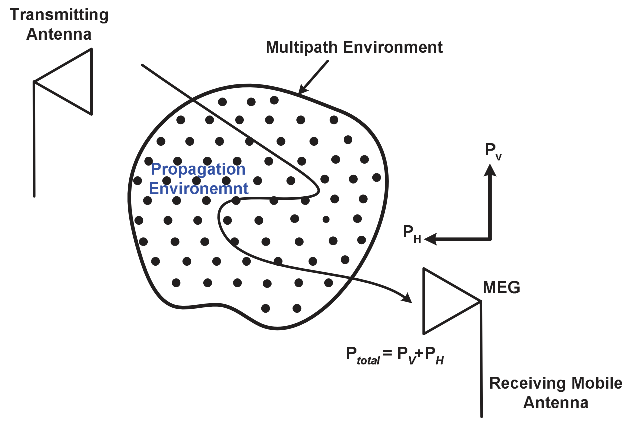

Figure 2.3: Incident radio wave arriving at the receiving antenna in multipath environment.

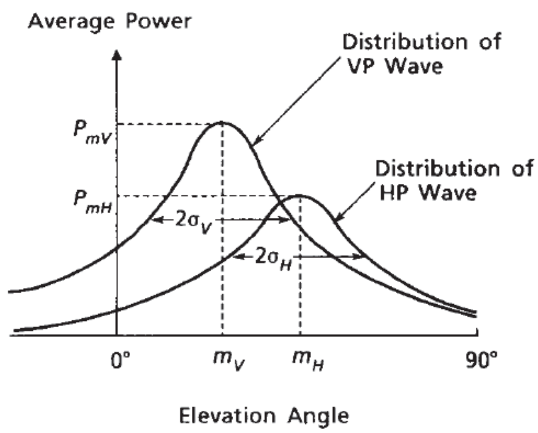

Figure 2.4: Gaussian distribution model of incident waves.

Table 2.1: Propagation model considered for this thesis.

Scenario	**Statistical Model (Azimuth Plane/ Elevation Plane)**
	Gaussian/ Uniform
Indoor	$m_V = 10^0, m_H = 10^0$ and $\sigma_V = 15^0, \sigma_H = 15^0$ XPR = 5dB
Outdoor	$m_V = 10^0, m_H = 10^0$ and $\sigma_V = 15^0, \sigma_H = 15^0$ XPR = 1dB
Isotropic	$m_V = 10^0, m_H = 10^0$ and $\sigma_V = 15^0, \sigma_H = 15^0$ XPR = 0dB

2.3.2 Envelope Correlation Coefficient (ECC)

In the MIMO antenna systems, multiple antennas are deployed at both tranmitter and receiver to improve the link reliability in rich electromagnetic scattering environment. In general, at the reciever terminal number of signals are arriving from different directions. In practice, the independence of the received signals will depend on angular distribution in the channel, the arrangement and radiation pattern of the antennas, and their polarization. The independency of the received signals provide the low mutual coupling between MIMO antenna elements. The low mutual coupling provides lower correlation between MIMO antenna elements. The avoidance of mutual coupling and the ability to distinguish between paths arriving at closely spaced angles is favoured by larger antenna spacing, whilst practical constraints often demand compact arrangements, especially in mobile systems.

However, in the practical system, it is not possible that the signals are being fully independent and show zero correlation. So, in developing practical MIMO antenna systems, a straightforward means to evaluate the spatial, complex-envelope correlation will be useful [See *et al.* (2008), See *et al.* (2009)].

The correlation between signals can be evaluated either by scattering parameters approach or by far field data approach. In *S*-parameters approach, the ECC is evaluated using *S*-parameters of the MIMO antenna system, reported in reference [Stein (1962), Salonen and Vainikaien (2002), Blanch (2003)] under the assumptions of i) the antenna system is a lossless structure, ii) one antenna is excited while the other is terminated with a reference impedance (such as 50 Ω); and iii) the antenna system is in a uniform scattering environment. The envelope correlation coefficient in terms of the *S*-parameter of the antenna system can be expressed as:

$$\rho_e = \frac{\left|S_{ii}^{*}S_{ij}+S_{ji}^{*}S_{jj}\right|^2}{\left(1-\left(\left|S_{ii}^2\right|+\left|S_{ji}^2\right|\right)\right)\left(1-\left(\left|S_{jj}^2\right|+\left|S_{ij}^2\right|\right)\right)} \tag{2.11}$$

where, i and j are antenna port 1 and port 2, respectively and corresponding S-parameters are given in above formula. The above equation is valid for ideal antenna cases but practically the mobile terminal antenna efficiency is not ideal in multipath propagation environment. Therefore, it is not possible to satisfy the i) and iii) assumptions.

For more accurate calculation of ECC, we can follow far field data approach in place of the S-parameters data approach. So, far field pattern approach [Taga (1990)] is followed in this thesis for calculation of ECC, in which the envelope correlation coefficient (ρ_e) given in terms of complex cross correlation (ρ_c);

$$\rho_e = |\rho_c|^2 \tag{2.12}$$

under the assumption that the received signals have a Rayleigh distributed envelope and randomly distributed phase. The complex cross correlation ρ_c is evaluated using far field data given in [Vaughan (1987)];

$$\rho_{c_{ij}} = \frac{\int_0^{2\pi} A_{ij}(\phi)d\phi}{\sqrt{\int_0^{2\pi} A_{ii}(\phi)d\phi \int_0^{2\pi} A_{jj}(\phi)d\phi}} \tag{2.13}$$

where,

$$A_{ij} = \left\{XPR \cdot E_{\theta i}(\theta,\phi)E_{\theta j}^*(\theta,\phi)P_\theta(\theta,\phi) + E_{\phi i}(\theta,\phi)E_{\phi j}^*(\theta,\phi)P_\phi(\theta,\phi)\right\} sin\theta d\theta d\phi,$$

in which XPR is time averaged vertical power to time averaged horizontal power in the fading environment. E_θ and E_ϕ are the electric field components in θ- and ϕ-direction respectively. $P_\theta(\theta,\phi)$ and $P_\phi(\theta,\phi)$ are the angular density functions of the vertical and horizontal planes, respectively. The rule of thumb for good diversity/MIMO performance is ρ_e<0.5.

2.3.3 Diversity Gain

In a diversity antenna system, the antennas are not ideally uncorrelated, hence the correlation between two antennas always exists. Diversity gain is the most important characteristic of the diversity system. In general, the diversity gain is the difference between the combined cumulative distribution function (CDF) and a reference CDF at a certain CDF-level, normally chosen to be 1%. There are three main definitions on diversity gain distinguished by different reference CDF. Apparent diversity gain, the reference CDF is that of strongest average signal level; effective diversity gain, the reference CDF is that of an ideal single antenna which means 100% radiation efficiency; actual diversity gain, the reference CDF is that of the exiting practical single antenna which is to be replaced by the diversity antenna. This definition is conditioned by the probability that the SNR is above a reference level. The probability value is optional but is usually set to 50% or 99% reliability [Plicanic (2004)]. The general mathematical expression for diversity gain is as follows [Fujimoto and James (2001)]:

$$DG = \left[\frac{\gamma_c}{\Gamma_c} - \frac{\gamma_1}{\Gamma_1}\right]_{P(\gamma_c<\gamma_s/\Gamma)} \tag{2.14}$$

where, γ_c is instantaneous SNR of the diversity combined signal, Γ_c means SNR of the comibined signal, γ_1 is the highest SNR of the diversity branch signals, Γ_1 is the mean value of γ_1 and γ_s/Γ is a threshold or reference level. The above definition of diversity gain is illustrated in Fig. 2.5.

The results of diversity gain can be written in either of the two equivalent forms. The first form of diversity gain is given as [Guo (2008)];

$$\Pr(\gamma < x) =$$

$$1 - \exp\left(\frac{-x}{\Gamma_1}\right) Q\left(\sqrt{\frac{2x}{\Gamma_2(1-|\rho|^2)}}, |\rho|\sqrt{\frac{2x}{\Gamma_1(1-|\rho|^2)}}\right) - \exp\left(\frac{-x}{\Gamma_2}\right)\left[1 - Q\left(|\rho|\sqrt{\frac{2x}{\Gamma_2(1-|\rho|^2)}}, |\rho|\sqrt{\frac{2x}{\Gamma_1(1-|\rho|^2)}}\right)\right] \tag{2.15}$$

$$=1 - \exp\left(\frac{-x}{\Gamma_1}\right) Q\left(\sqrt{\frac{2x}{\Gamma_2(1-|\rho|^2)}}, |\rho|\sqrt{\frac{2x}{\Gamma_1(1-|\rho|^2)}}\right) - \exp\left(\frac{-x}{\Gamma_2}\right) Q\left(\sqrt{\frac{2x}{\Gamma_1(1-|\rho|^2)}}, |\rho|\sqrt{\frac{2x}{\Gamma_2(1-|\rho|^2)}}\right) +$$

$$\exp\left[-\frac{x}{1-|\rho|^2}\left(\frac{1}{\Gamma_1} + \frac{1}{\Gamma_2}\right)\right] I_0\left[-\frac{2|\rho|x}{(1-|\rho|^2)\sqrt{\Gamma_1\Gamma_2}}\right] \tag{2.16}$$

In which, Γ_1 and Γ_2 are the mean SNR for antenna 1 and antenna 2 in the diversity antenna system, respectively. The Q function is the Marcum function, I_0 is the modified zero order Bessel function of first kind and ρ is the complex cross correlation coefficient.

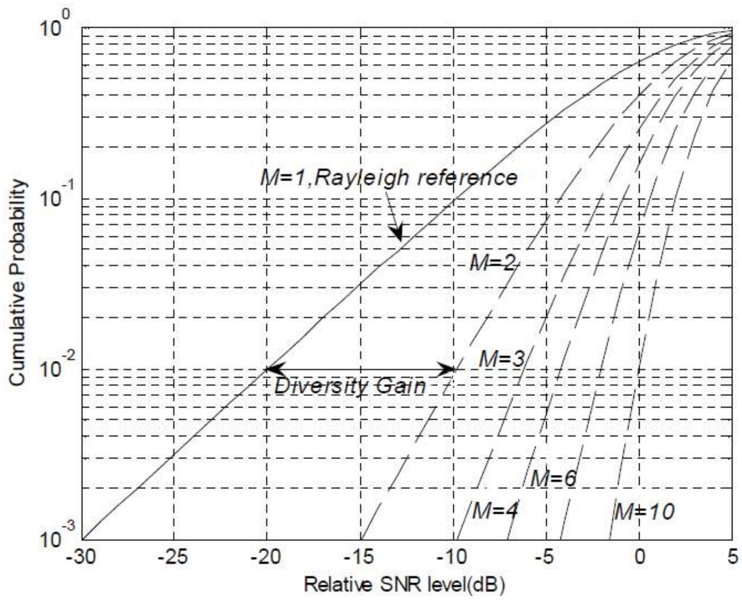

Figure 2.5: Probability for different number of branches of an *M*-port antenna system and diversity gain definition for $M = 2$.

The conditions for achieving good diversity gain are illustrated as: the correlation coefficient between branch signals should be zero or low, and the mean SNR in each branch should be similar. An assumption is that Γ_1 and Γ_2 are set equal to fulfill the condition, lets say Γ, for mean SNR of both the antennas. From the assumption, the formulas (2.15) and (2.16) become;

$$\Pr(\gamma < x) =$$

$$1 - \exp\left(\frac{-x}{\Gamma}\right)\left[1 - Q\left(|\rho|\sqrt{\frac{2x}{\Gamma(1-|\rho|^2)}}, \sqrt{\frac{2x}{\Gamma(1-|\rho|^2)}}\right) + Q\left(\sqrt{\frac{2x}{\Gamma(1-|\rho|^2)}}, |\rho|\sqrt{\frac{2x}{\Gamma(1-|\rho|^2)}}\right)\right] \tag{2.17}$$

$$=1 - 2 * \exp\left(\frac{-x}{\Gamma}\right) Q\left(|\rho|\sqrt{\frac{2x}{\Gamma(1-|\rho|^2)}}, \sqrt{\frac{2x}{\Gamma(1-|\rho|^2)}}\right) + \exp\left(-\frac{2x}{\Gamma(1-|\rho|^2)}\right) I_0\left[\frac{2|\rho|x}{\Gamma(1-|\rho|^2)}\right] \tag{2.18}$$

From which, the cumulative probability as a function of relative SNR at a certain correlation coefficient value can be calculated. According to a certain level (for instance, 1%) of cumulative probability and comparing with the reference, diversity gain can be obtained.

There is second approximate approach is available to obtain diversity gain. The relation between diversity gain and correlation coefficient can also be approximated and is given as [Guo (2008)];

$$G_{app} = 10 * e_\rho \text{ with } e_\rho = \sqrt{1 - |\rho_e|^2} \quad (2.19)$$

where, G_{app} is the apparent diversity gain, 10 is the maximum apparent diversity gain at 1% CDF level using selection combining. e_p is the correlation efficiency, also known as the reduction in diversity gain due to correlation coefficient. If the correlation close to unity, ρ is scaled with a factor 0.99, and the formula becomes;

$$e_\rho = \sqrt{1 - |0.99 * \rho_e|^2} \quad (2.20)$$

The effective diversity gain can be defined by the following formula;

$$\text{Effective Diversity Gain (EDG) } G_{eff} = \eta_{total} * G_{app} \quad (2.21)$$

where, η_{total} is the antenna total efficiency and G_{app} is the apparent diversity gain.

In this thesis, second approach is made to calculate the effective diversity gain.

2.4 MIMO Performances

In an environment of strong fading, a multiple antenna system can usually be used in MIMO mode or diversity mode according to SNR level [Zheng and Tse (2003)]. If the SNR is low, a diversity mode will be utilized and diversity performance will be evaluated through MEG, ECC, and EDG. In high SNR environment, the MIMO mode will be selected and the highest data rate can be achieved [Holter (2011)]. The MIMO channel performance is discussed in this section through MIMO capacity and multiplexing efficiency.

2.4.1 MIMO Capacity

In the Chapter 1, capacity of multi antenna system have been derived without Channel State Information (CSI) at the transmitter. In such case, power will be equally allocated to the transmitter and the channel capacity of the MIMO system can be expressed by [Winter (2011)];

$$C_{equal\ power} = \sum_{i=1}^{r} log_2\left(1 + \frac{E_S}{N_0 M_T}\lambda_i\right) \quad (2.22)$$

where, r is the number of orthogonal sub-channel (i.e. rank) and λ_i is the Eigen values of the matrix HH^H (if ($M_T < M_R$) or $H^H H$ ($M_T > M_R$). $(\cdot)^H$ denotes the conjugate transpose (or Hermitian) operator. If the CSI is available at the transmitter, the power allocation can be optimized to the stronger sub-channels rather that the weaker ones via a water filling algorithm [Vaughan and Anderson (2003)];

$$C_{water\ filling} = \sum_{i=1}^{r} log_2(\lambda_i \cdot D) \tag{2.23}$$

$$D = \frac{1}{\lambda_i} + p_i \tag{2.24}$$

where, D is the 'water leve'l for each of the sub-channels to be filled up to and $p_i = SNR_i/\lambda_i$ is the input power to i^{th} sub-channels.

2.4.2 Multiplexing Efficiency

In order to evaluate the MIMO perfromance in simple way, the Multiplexing Efficiency (ME) is introduced. It is defined as the power penalty of a realistic multiple antenna system in achieving a given capacity, compared with an ideal antenna system with 100% total efficiency and zero correlation [Tial *et al.* (2011)].

For two receive antennas, the antenna efficiency and normalized correlation matrices of $R = \Lambda^{1/2}\bar{R}\Lambda^{1/2}$are given by;

$$\Lambda = \begin{bmatrix} \eta_1 & 0 \\ 0 & \eta_2 \end{bmatrix} \quad \bar{R} = \begin{bmatrix} 1 & r \\ r^* & 1 \end{bmatrix} \tag{2.25}$$

where, r denotes the complex correlation coefficient between the two antennas. With the assumption of high SNR and isotropic environment (i.e. likelihood of impinging waves from any direction), the approximate closed-form of multiplexing efficiency can be given as;

$$\eta_{mux} = \sqrt{\eta_1 \eta_2 (1 - |\rho_c|^2)} \tag{2.26}$$

where, $\eta_1$and η_2 are the total efficiencies of the MIMO antenna elements, and ρ_c is the correlation coefficient.

2.5 Performance Parameters in User Proximity

After the successful study of MIMO antenna elements in free space, implementation of the antenna on actual platform is done. In this cotext, user body is placed near to the mobile phone (antenna with mobile environment). To check the robustness of the antenna performances with user proximity, two different parameters are considered for perfromance evaluation of MIMO antenna i.e. Specific Absorption Rate (SAR) and Total Radiated Power (TRP).

2.5.1 Specific Absorption Rate (SAR)

In dosimetry, SAR is defined as the transfer of energy from electric and magnetic field to charged particles in an absorber is described in terms of the SAR . SAR is defined, at a point in the human head tissue, as the time rate of change of energy transferred to charged particles in an infinitesimal volume at that point divided by the mass of the infinitesimal volume and given as [Durney *et al.* (1986)];

$$SAR = (\partial W_c/\partial t)/\rho_m \tag{2.27}$$

where, ρ_m is the mass density of the object at that point. For sinusoidal fields, the time-average SAR at a point is given by the term $<Pc>/\rho_m$. This is also called the local SAR or SAR distribution to distinguish it from the whole-body average *SAR*. The average SAR is defined as the time rate of change of the total energy transferred to human head tissue, divided by the total mass of the head tissue. From Poynting theorem for the time-average sinusoidal steady-state case, the whole body average SAR is given by [Durney *et al.* (1986)];

$$Average\ SAR = \int_V \langle P_C \rangle dV/M \tag{2.28}$$

When mobile phone antenna (especially MIMO antenna) is placed near to human head, the electromagnetic absorption by human head tissues is estimated through average SAR. In this thesis, average SAR is calculated inside the human head phantom by Eq. (2.29). Based on the FCC standard, the SAR value of the mobile handsets needs to be measured on two kind of phantoms: the first is a Specific Anthropomorphic Mannequin (SAM) head phantom, in which measure the electromagnetic radiation from mobile phones inside the human head. The other one is the flat phantom, which is for measuring the SAR when mobile handsets is close to the human body.

The SAR value is calculated as maximum of mass-averaged SAR and is strictly limited by the governments. Now-a-days, two standards of SAR are adopted: Europe and country uses 2W/kg averaged over 10g tissue (average mass of human tissue is 10g) [Hadjem *et al.* (2011)]. Meanwhile, the U.S. Federal Communication Commission (FCC) requires that the SAR should be lower than 1.6W/kg averaged over 1g tissue.

However, with the existing equipments, it is hard to measure the total SAR inside the human tissue when multi antenna elements operate simultaneously. In such a scenario, SAR to PEAK Location Spacing Ratio (SPLSR) is utilized to evaluate the SAR performance [FCC Report (2012)], which is given as;

$$SPLSR = (SAR_1 + SAR_2)/D \tag{2.29}$$

where, SAR_1 and SAR_2 are the average value of SAR (W/kg) for the antenna element 1 and 2, respectiely, over human head tissue based on the FCC standard. D is the separation distance (cm) of the two *SAR* peaks as illustared in Fig. 2.6. From the safety point of view, FCC defined the limit that the SPLSR is required to be less than 0.3 when the separation between the dual elements is less than 5 cm.

In this thesis, to perform the whole study on MIMO antenna system, SPLSR is included as it is an important parameter for SAR estimation. The SAR calculation simulation setup is created in Computer Simulation Technology Microwave Studio (CST MWS) which is based on Finite Integration Technique (FIT). The value of SARs of each antenna elements and separation between SAR peaks is calculated by using CST MWS.

2.5.2 Total Radiated Power (TRP)

CTIA defines the TRP as The TRP is the sum of all power radiated by the antenna, regardless of direction or polarization . If the antenna were enclosed by in a perfectly absorbing sphere, the TRP would be the power that would be absorbed by that sphere. TRP can be related to P_A as follow [CTIA Report (2005)];

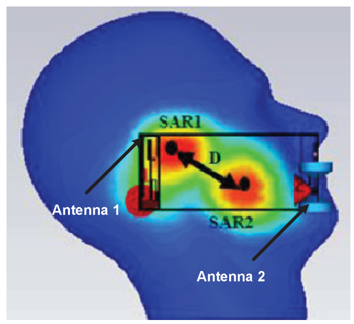

Figure 2.6: The illustration of SPLSR.

$$TRP = P_A \cdot \eta_{Rad\ Eff} \quad (2.30)$$

where, $\eta_{Rad\ Eff}$ is radiation efficiency of the antenna which is defined as ratio of the power radiated by an antenna to the power delivered to the antenna and P_A is power delivered to the antenna.

The total radiated power from given antenna is;

$$TRP = \oint U(\theta, \phi) d\Omega$$

where, $U(\theta, \phi)$ is radiation intensity in Watt/steradian, and $d\Omega = sin(\theta) d\theta d\phi$. The Effective Isotropic Radiated Power (EiRP) is written in the form of radiation intensity as;

$$EiRP(\theta, \phi) = P_T G_T(\theta, \phi) = 4\pi U(\theta, \phi)$$

where, $P_T G_T$ is the product of the power delivered to the antenna and the antenna power gain. Therefore,

$$U(\theta, \phi) = \frac{EiRP(\theta, \phi)}{4\pi}$$

So integral form of TRP becomes;

$$TRP = \frac{1}{4\pi}\int_{\theta=0}^{\pi}\int_{\phi=0}^{2\pi} EiRP(\theta,\phi)\sin(\theta)d\theta d\phi \quad (2.31)$$

In addition, simplified farmula for TRP can be defined approximately as:

$$TRP = Conducted\ Power\ (W) \times E_{miss} \times E_{rad} \quad (2.32)$$

where, E_{miss} and E_{rad} are the mismatch and radiation efficiency of antenna, respectively. The conducted power is the transmitted power. In this thesis the conducted power is considered as 1W or 30 dBm.

In the case of multi element MIMO system, the TRP is calculated for each element of MIMO antenna system and named as TRP1 and TRP2 for each of the Antenna 1 and Antenna 2, respectively.

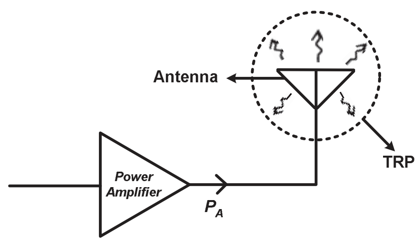

Figure 2.7: Total power radiated from antenna.

2.6 Summary

In the presented chapter, different diversity techniques are discussed to mitigate the multipath fading effect. Since, to mitigate the multipath fading effect, multi antenna system is deployed at the transmitter and reciver side. Therefore, the diversity parameters are important to discuss for multi antenna system. All the diversity parameters like envelope correlation coefficient, mean effective gain, and effective diversity gain are discussed. Further, in the user proximity, parameters like SAR and TRP are considered and elaborated.

Having discussed the diversity mechanism, diversity parameters, MIMO parameters, propagation environment, specific absorption rate, and total radiated power, the investigation of different MIMO/Diversity antennas are taken up in the following chapters and are characterized using above discussed parameters.