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Performance Analysis of Fading and Interference over MIMO Systems in Wireless Networks

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***Abstract*—The interlaced challenges faced by the wireless network are fading and interference. Fading (information loss) is a random variation of the channel strength with time, geographical position and/or radio frequency due to environmental effects. Due to this, the received signals have random amplitude, phase, and angle of arrival. Interference limits the capacity of spectral resource. Fading can be mitigated with cooperative transmission, as it helps to achieve diversity among users, whereas Multiple Input Multiple Output (MIMO) technique exploits interference by jointly processing the user data and thus increases the data rate in wireless network. The most significant reasons for the use of MIMO techniques are: to increase the maximum data rate, to extend the coverage, and to serve a larger number of users. While wireless broadband necessarily ensures end users are always connected on the move, the limitation on the bandwidth that can be consumed is strikingly several factors lower than that in a connected wire-line network. This makes us to deep see the reasons and thereby the need to grind the average fades duration (AFD) and the level crossing rate (LCR) which results in path loss. The use of multiple antennas causes the amplitude and phase fluctuation and time delay in the received signal, which causes fading of the signal. Mobile radio communication manifests with two types fading effects: large-scale and small-scale fading. In this paper, we have considered Rayleigh (Large-scale) fading channel for mobile radio networks**.

***Keywords*—AFD, LCR, MIMO, Modeling, Path loss, Rayleigh -fading, Wireless mobile networks.**

I. INTRODUCTION

Fading, mathematically modeled as a time-varying random change in the amplitude and phase of the transmitted signal. It is deviation of the attenuation that a carrier-modulated telecommunication signal experiences over certain propagation media. Large scale fading also known as Rayleigh fading is due to path loss and shadowing, affected by prominent topography contours such as hills, forests, clumps of buildings, etc. between the transmitter and receiver. The statistics of large-scale fading provide a way of computing an estimate of path loss as a function of distance. This is described in terms of a mean-path loss (nth-power law) and a log-normally distributed variation about the mean [5].

Path loss is the attenuation of the electromagnetic wave radiated by the transmitter as it propagates through space. When the attenuation is very strong, the signal is blocked. For mobile radio applications, the channel is time-variant because wave (signal) propagation between the transmitter and receiver results in propagation path changes. The rate of change of these propagation conditions accounts for the fading rapidity (rate of change of the fading impairments). If the multiple reflective paths are large in number and there is no line-of-sight signal component, the packet of the received signal is statistically described by a Rayleigh probability density function (pdf).

MIMO transmitter puts data on multiple signal paths and, consequently, increases the amount of information the system can carry and the number of users it can serve. In addition, with this approach it is possible to divide the data in different parts and send it over different paths. The nature of the signal over each path changes depending on the antennas' spacing, the interference and the channel characteristics, and at the receiver side there is a manipulation of the signal in order to reconstruct the original message properly [6]. The advantages of MIMO are higher data rate, increased bandwidth, better signal quality (lesser interference), less power consumption, and reliable (since difficult for hackers to trace the receiver).

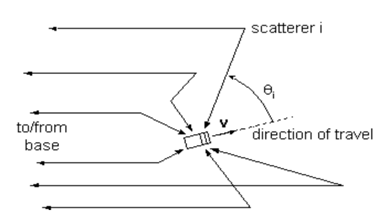


Figure 1. Multipath channel structure.

The above figure 1 shows the reception of multiple scattered copies of the band pass and narrowband signal, each with gain a_i and angle θ_i, by a mobile moving with speed v [3]. Mathematically, the complex envelope of the received signal is:

$$y(t) = \sum_i a_i e^{-j2\pi f_D \cos\theta_i t} S(t-\tau_i) \qquad (1)$$

Where the scatterer i corresponds to a signal copy, that is shifted in time by τ_i and in frequency by $f_D \cos\theta_i$, where $f_D = \frac{v}{\lambda}$ is the Doppler frequency.

The Fading Simulation receives the input signal s (t), adds simulated fading effects based on the Fading Parameters and outputs the signal y (t):

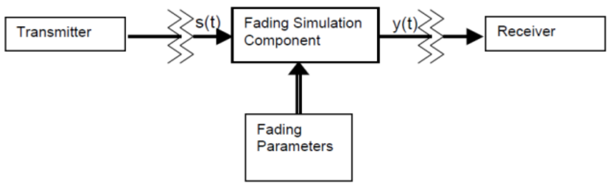


Figure 2: Black-box view of the Simulation Component

The input and output of the simulation components are arbitrary length arrays of complex numbers [3]. The fading effect is usually divided into two types, namely large-scale fading, mainly due to path loss as a function of distance and shadowing by large objects such as mountains and tall buildings, and small-scale fading, due to the constructive and destructive combination of randomly scattered, reflected, diffracted, and delayed multiple path signals. Reflection causes reflection of waves off of an object, occurs when a propagating electromagnetic wave impinges on a smooth surface with very large dimensions compared to the RF signal wavelength (λ). When a radio wave gets reflected, it is partially reflected, partially absorbed, and partially transmitted [1]:

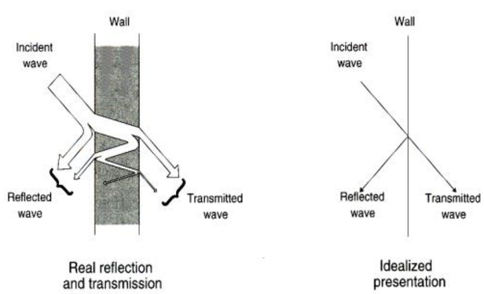
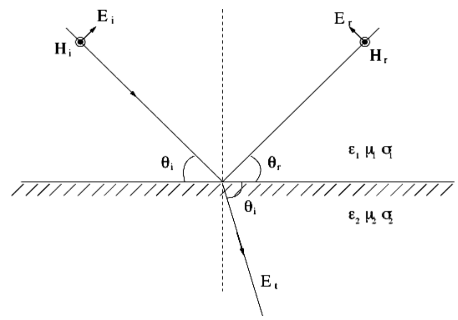


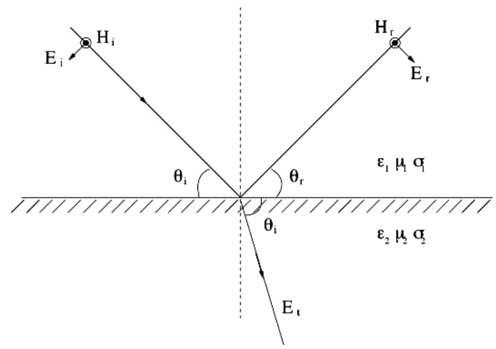
Figure 3. Reflection at a wall

In fact, the reflected wave is the result of multiple reflections against the wall (Figure 3). When a wave is incident on a perfect dielectric, part of the energy is transmitted into the second medium and part comes back to the first medium, without any energy absorption loss. If the second medium is a perfect conductor, all incident energy is reflected back into the first medium without any energy loss.

The electric field intensity of the transmitted and reflected waves is derived from the incident wave by means of a reflection coefficient (Γ), which is a function of the material's properties, the wave's polarization, the angle of incidence, and the wave's frequency [1]:



a) E-field in the plane of incidence



(b) E-field normal to the plane of incidence

Fig.4. Geometric scheme, for calculating the reflection coefficient between two dielectrics.

In Figure 4, E_i, E_r, E_t are respectively the electric field intensity of the incident, the reflected, and the transmitted waves. Parameters $\varepsilon_1, \mu_1, \sigma_1$, and $\varepsilon_2, \mu_2, \sigma_2$ represent the permittivity, permeability, and conductance of the mediums, respectively. If a material is not perfectly dielectric, the incident energy is partly absorbed; described by a complex dielectric constant, defined as

$$\varepsilon = \varepsilon_0 \varepsilon_r - j\varepsilon' \qquad (2)$$

Where ε_0 is the free- space- permittivity (8.85×10^{-12}Farad/meter), ε_r is the relative value of permittivity, $\varepsilon' = \frac{\sigma}{2\pi f}$, where σ is the conductivity of the medium, and f is the frequency of the incident wave. The material parameters at various operating frequencies are:

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Table I
Material frequencies and their relative permittivity

Material	Relative Permittivity ε_r	Conductivity σ (S/m)	Frequency (MHz)
Poor Ground	4	0.001	
Typical Ground	15	0.005	100
Good Ground	25	0.02	100
Sea Water	81	5.0	100
Fresh Water	81	1×10^{-3}	100
Brick	4.44	1×10^{-3}	4000
Limestone	7.51	28×10^{-3}	4000
Glass, Corning 707	4	18×10^{-8}	1
Glass, Corning 707	4	27×10^{-6}	100
Glass, Corning 707	4	5×10^{-3}	10000

The boundary conditions derived from the Maxwell's equations signify that the angle of the incident wave is equal to the angle of the reflected wave while the electromagnetic field vector of both the reflected and transmitted waves is proportional to the incident wave [1].

Diffraction occurs when the radio path without a line-of-sight path between the transmitter and receiver is obstructed by a dense body with large dimensions compared to λ, causing secondary waves to be formed behind the obstructing body. It is often termed *shadowing* because the diffracted field can reach the receiver even when shadowed by an impenetrable obstruction but with reduced amount of energy. Scattering occurs when a radio wave impinges on either a large rough surface or any surface whose dimensions are on the order of λ or less, causing the reflected energy to spread out (scatter) in all directions. The type of fading experienced by a signal propagating through a mobile radio channel depends on the nature of the transmitted signal, as well as on the characteristics of the channel. Different transmitted signals will undergo different types of fading, according to the relationship among the signal parameters, such as the path loss, the bandwidth (BW), the symbol period, etc., and the channel parameters (such as the RMS delay spread and the Doppler spread).

Statistical Characterization of the Multipath faded Mobile Radio Channels can be classified as: **Log-Normal Shadowing:** can be modeled by a lognormal distribution for various outdoor and indoor environments. **Rayleigh fading:** When there is no line-of-sight (LOS), the amplitude of the received signal is Rayleigh distributed. It provides a good fit for multipath fading channels with no direct line-of-sight (LOS) path.

Rayleigh fading, primarily in the UHF (the 300 MHz–3 GHz ultra-high-frequencies) band, affects mobile systems such as cellular and personal communication systems (PCS).**Rician fading:** When there is a line-of-sight (LOS), the amplitude of the received signal is Rician distributed. In contrast to Rayleigh fading, Rician fading is often used to model propagation paths consisting of one strong direct LOS component and many random weaker components.

Nakagami-*m* Fading: Nakagami-*m* fading is a more general fading distribution, which encompasses Rayleigh distribution as a special case, and can approximate well the Rician distribution.

II. Mobile Radio Propagation: Large-Scale Fading

Propagation models are the foundation for channel modeling, as they try to describe the way a radio signal changes during its travel from the transmitter to the receiver. Propagation models have customarily focused on predicting the average signal strength at the receiver, set at a given distance from the transmitter, as well as the variability of the signal strength in close spatial proximity of a particular location. Propagation models that predict the mean signal strength for an arbitrary transmitter-receiver (T-R) separation distance are useful for estimating the radio coverage area of a transmitter; they are called *large-scale* propagation models, since they characterize the average signal strength over long time spans and large T-R separation distances (several hundred meters)[1].

The statistics of large-scale fading provide a way of computing an estimate of path loss as a function of distance. This is described in terms of a mean-path loss (*n*th-power law) and a log-normally distributed variation about the mean. Small-scale fading refers to the dramatic changes in signal amplitude and phase that can be experienced as a result of small changes (as small as a half-wavelength) in the spatial separation between a receiver and transmitter [1].

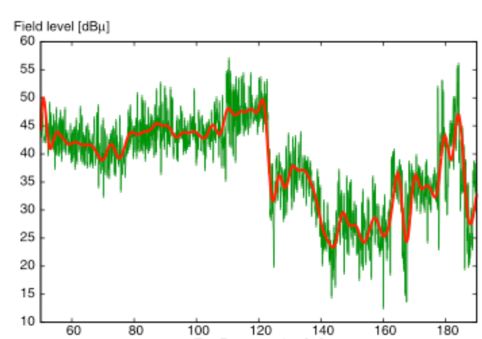

Fig.5. Small-scale fading (green line) and large-scale fading (redline) versus the transmitter -receiver separation distance.

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III. PATH LOSS

The path loss is the amount of energy of the signal that gets lost during the transmission through a channel. It is due to the effects of diffraction, reflection, refraction, and absorption and free-space loss. Also the path loss depends on the environment (rural, urban, suburban or heavy urban), the distance between the BS and the MS, the height and location of the antennas and the propagation medium (dry or humid air). Multi path fading (MPF) occurs when the received signal is the sum of desired line-of-sight (LOS) signal plus one or more non-line-of-sight (NLOS) signals.

If the LOS and NLOS signals are received with nearly equal amplitude and 180^0 out of phase, destructive interference occurs, which results in a loss of carrier power to the receiver feed [2]:

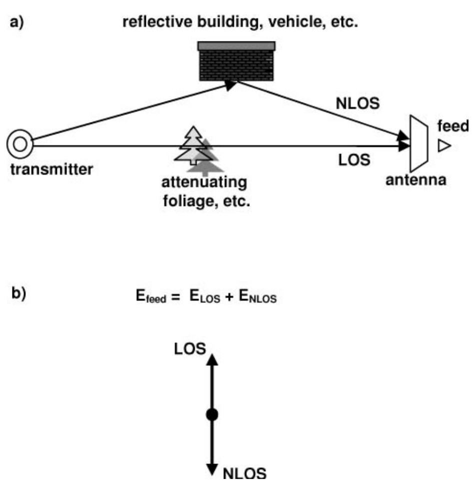

Figure.6, a) A line-of-sight (LOS) and non-line-of-sight (NLOS) signal, both are incident on one antenna. b) LOS and NLOS signals can be received with nearly equal amplitude and 180^0 out of phase, resulting in a loss of carrier power to the receiver feed.

Varying the specific value, reference radius or reference phase (θref), shifts the LOS beam phase with a linear slope through 360^0 (see Figure 5) with only slight changes in antenna gain. It shows the combined signal power of the LOS and NLOS signals at the receiver feed as a function of phase reference. Importantly, the 20^0 off-axis phase of the NLOS signals does not change by an equivalent amount, or it can vary with negative slope at large NLOS angles [2]. This difference in phase sensitivity is exploited to θref in order to eliminate MPF.

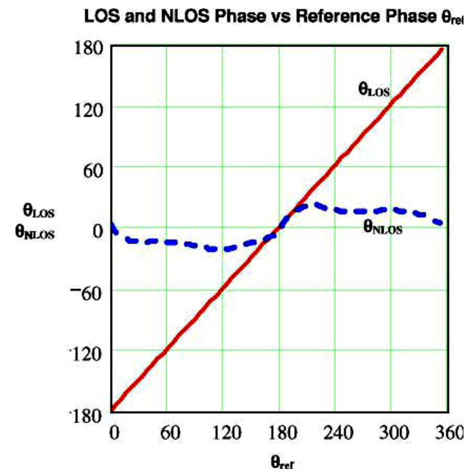

Figure 7. The variation of phase of the LOS signal (θLOS) is 360^0 for a 360^0 variation of θref, both calculated and measured, while the phase of the NLOS signal is different. Path loss (free space loss) is a measure of average signal attenuation suffered by a transmitted signal when it arrives at the receiver, after traversing a path of several wavelengths. It is related to the coverage area of mobile systems and also the effects of the antenna gains, defined by [1]:

$$PL(dB) = 10log\frac{P_t}{P_r} = 10log\left(\frac{P_tG_tG_r}{P_rL}\right) = 20log\left(\frac{4\pi d}{\lambda}\right)$$

$$\text{or } PL = \left(\frac{4\pi d}{\lambda}\right)^2 \qquad (3)$$

And the antenna gain is given by:

$$G = \frac{4\pi A_e}{\lambda^2} \qquad (4)$$

Where A_e is the effective size of the antenna, *d* is the distance between the transmitter and the receiver, and P_t and P_r are the transmitted and received powers, respectively. By the Friis free-space equation, the power received at the receiving antenna is:

$$Pr = (d)\left(\frac{P_tG_tG_r\lambda^2}{(4\pi)^2d^2L}\right) \qquad (5)$$

Where G_t and G_r are respectively the gains of the transmitting and receiving antennas. λ is the wavelength in meters. L is the path loss factor, not related to propagation. Also by the power-law relationship:

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$$PL(d) = PL(d_0) + 10\gamma log\left(\frac{d}{d_0}\right) + X_\sigma \quad (6)$$

Where $\gamma = 2$ characterizes free space and is practically higher for wireless channels. X_σ denotes a zero-mean Gaussian random variable of standard deviation σ which reflects the average variation of the received power.

In the lognormal path loss (NLOS) propagation model the average path loss for an arbitrary T (transmit)-R (receive) couple, $\bar{L}_p$(d), is expressed as a function of the distance d *by* using a *path loss exponent*, independently of the presence of a direct LOS between the transmitter and the receiver units.

$$\bar{L}_P(d)\ \alpha \left(\frac{d}{d_0}\right)^n$$

(7)

Where n is the path loss exponent that indicates the rate at which the path loss increases with the distance, and d_0 is called the *free-space (LOS) close-in reference distance* [11]. The selected value of d_0 must be suitable for the propagation environment. In large cellular systems, 1 km and 1 mile are usually used as reference distances, whereas in microcellular systems much smaller distances are used. The reference distance must always be in the far-field of the antenna to neglect the near-field interference effects in the reference path loss. The path loss exponent n is directly proportional on the specific propagation environment [1].Different environments have different values of *n as* shown in table 2.

Table II.
Reference values of path loss exponent and its average value within the stipulated area.

Environment	Path Loss Exponent, *n*	Average value of n
Free space	2	2
Urban area micro cells	2.7 to 3.5	3.1
Urban macro cells	3.7 to 6.5	5.1
Shadowed UCR	3 to 5	4
In building, line of sight	1.6 to 1.8	1.7
Obstructed in building	4 to 6	5
Obstructed in factories	2 to 3	2.5

The above measurements signify that the path loss $L_p(d)$ is a random variable that has a lognormal distribution around a mean value $\bar{L}_p(d)$. The mean path loss is the sum of the path loss at the reference distance (d_0) and the distance d and the path-loss exponent n:

$$\bar{L}_p(d) = L_{fs}(d_0) + 10nlog\left(\frac{d}{d_0}\right) \quad \textbf{(8)}$$

Also the path loss can be expressed in terms of the mean $\bar{L}_p(d)$ plus a random variable X_σ:

$$L_p(d) = L_{fs}(d_0) + 10nlog\left(\frac{d}{d_0}\right) + X_\sigma \quad (9)$$

Which represents lognormal shadowing that describes the random shadowing effect occurs in a large number of measurements of the received power in a large-scale model at the same distance *d* between transmitter and receiver, but with different propagation paths [2]. Figure 8 shows typical path losses measured in German cities [3].

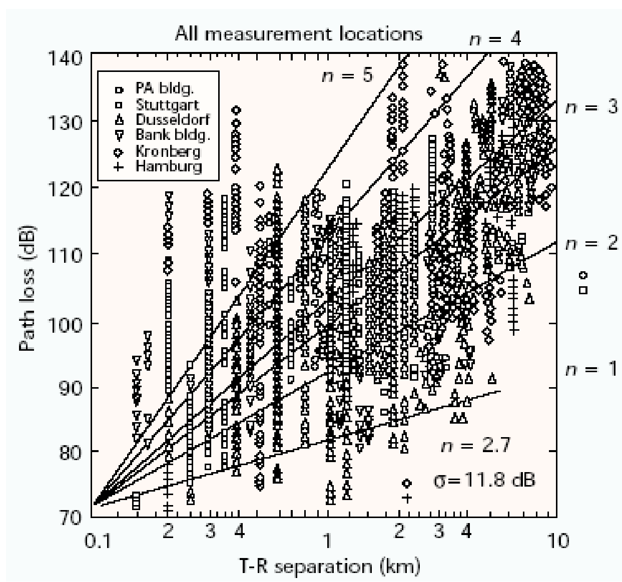

Fig.8. Path loss vs. distance measured in several German cities.

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Table III
Simulated results of path loss exponent and its effect on the coverage and throughput.

Simulation results about path loss.

γ	802.11a (54 Mbps)			802.11b (11 Mbps)			802.11g (54 Mbps)		
	Range (m)	Throughput (Mbps)	Delay (ms)	Range (m)	Throughput (Mbps)	Delay (ms)	Range (m)	Throughput (Mbps)	Delay (ms)
1.6	152	10	0.1183	395	1	0.7235	395	10	0.4539
2	141	10	0.1183	300	1	0.7228	299	10	0.4548
2.5	132	10	0.1182	240	1	0.7232	240	10	0.4547
3	124	10	0.1182	207	1	0.7221	207	10	0.4551
3.5	120	10	0.1183	187	1	0.7222	187	10	0.4551
4	118	10	0.1185	173	1	0.7225	175	10	0.4549
4.5	115	10	0.1184	162	1	0.7213	162	10	0.4555
5	114	10	0.1182	155	1	0.7208	155	10	0.4556
5.5	112	10	0.1185	149	1	0.7208	149	10	0.4552
6	111	10	0.1184	144	1	0.721	144	10	0.4549
6.5	110	10	0.1184	140	1	0.7221	140	10	0.4550

IV. Rayleigh Fading Distribution

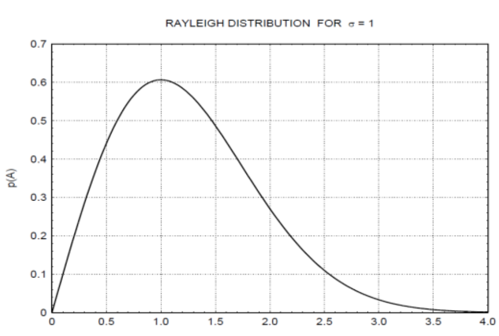
In mobile radio channels, the Rayleigh distribution is usually used to describe the geometric time-varying nature of the envelope detected at the receiver for a flat faded environment. The Rayleigh probability density function (pdf) for a distributed envelope r(t) can be expressed as

$$P(r) = \begin{cases} \frac{r}{\sigma^2} exp\left(-\frac{r^2}{2\sigma^2}\right), & 0 \le r \le \infty \\ 0, & r < 0 \end{cases} \quad (10)$$

Where σ is rms value of the received voltage signal and σ^2 is the time average power at the envelope detector respectively.

The probability of the received signal to a specified given value R can be given as [8]:

$$P(R) = p_r(r \le R) = \int_0^R p(r)\, dr \approx 1 - exp\left(\frac{R^2}{2\sigma^2}\right) \quad (11)$$



A=r, p(r) =p (A).

Figure 10.Rayleigh distribution for rms=1

Similarly, r_{mean} of the distribution is

$$r_{mean} = E[r] = \int_0^\infty r p(r)\, dr = \sigma\sqrt{\frac{\pi}{2}}$$

and the ac power in the envelope of the Rayleigh distribution can be derived as

$$\sigma_r^2 = E[r^2] - E^2[r]$$

$$= \int_0^\infty r^2\, p(r)\, dr - \frac{\sigma^2 \pi}{2}$$

$$= 2\sigma^2 - \frac{\sigma^2\pi}{2} = 0.429\sigma^2 \quad (12)$$

Since the mean value varies widely the middle value of the envelope, is often more useful for analysis of faded data under different fading distributions. This middle value may be computed by treating P(R) as 0.5 and solving the pdf as

$$0.5 = \int_0^{r_m} p(r)\, dr \quad (13)$$

This provides r_m as 1.777σ, which differs slightly from the r_{mean} value. The effect of the dominant (Line of Sight) signal (Rayleigh) over the weaker multipath signal gives rise to a Rician distribution. Figure below illustrates the pdf for Rayleigh distribution.

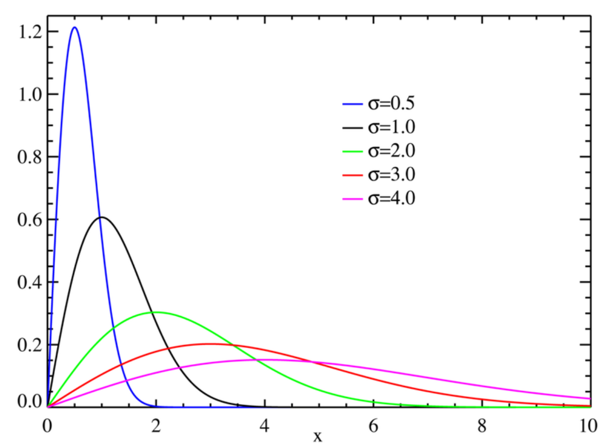


Figure 11.The Rayleigh distribution for different values of σ

From the pdf we can notice that the Rician distribution degenerates to Rayleigh in the absence of LOS dominant signal. The Rician (pdf) can be expressed as

$$p(r) = \begin{cases} \frac{r}{\sigma^2} exp - \left(\frac{r^2 + A^2}{2\sigma^2}\right) I_0\left(\frac{A_r}{\sigma^2}\right) & \text{for } A \ge 0, r \ge 0 \\ 0 & \text{for } r < 0 \end{cases} \quad (14)$$

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Here A is the peak amplitude of the direct LOS signal and $I_0(x)$ is the modified Bessel function of the first kind with zero order.

As shown in the envelope above(Fig.11), the Rician distribution is described by the ratio between the direct signal power and the variance of the multipath. This may be expressed in dB as :

$$K = 10 log \frac{A^2}{2\sigma^2} \ dB \quad (15)$$

This shows that for the absence of the dominant signal K→ $-\infty$ and the Rician distribution degenerates into Rayleigh. This fading mitigation can be solved using error control codes, equalizers, or appropriate diversity schemes. Thus, the level crossing rate (LCR) and the average fade duration (AFD) in faded environment become important statistical information for system design.

V. LEVEL CROSSING RATE

LCR is defined as the rate (in crossings per second) at which the envelope crosses the level in the positive (or negative) going direction. The LCR can be used to estimate velocity that depends on the mobile station velocity (Doppler frequency), as well as the scattering environment [7].

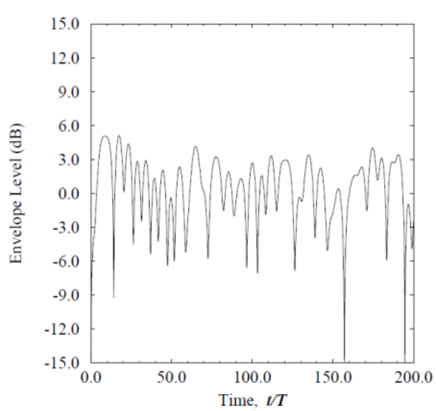

Figure 12.Rayleigh faded envelope with 2-D isotropic scattering.

The number of level crossings/sec for a Rayleigh faded environment can be computed by

$$N_R = \int_0^\infty \dot{r}\, p(R, \dot{r}) dr \quad (16)$$

Where $\dot{r}$ is slope of r (t) and p(R, $\dot{r}$) is the joint density function of r and $\dot{r}$ at r=R. In terms of a specified received signal R normalized with respect to local rms amplitude R_{rms} .This gives

$$N_R = \sqrt{2\pi}\, f_m \rho e^{-\rho^2} \quad (17)$$

Where $\rho = \frac{R}{R_{rms}}$.

This implies that the LCR is smaller for high levels of signal but becomes higher as R becomes 3 dB below the R_{rms} .

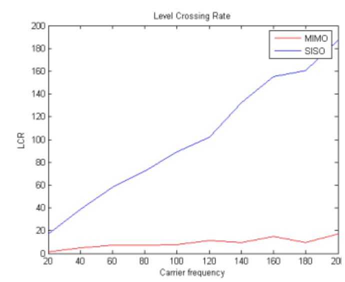

Figure 13. LCR vs Carrier frequency with different channel practically, Green line shows theoretical values.

VI. AVERAGE FADE DURATION

AFD is the average duration that the envelope remains below a specified level R, depends on the mobile station velocity (Doppler frequency), as well as the scattering environment [7].

Similarly AFD, for which the received signal is below a specified level R, can be found for the Rayleigh faded signal by

$$\overline{\tau} = \frac{1}{N_R} P_r[r \le R]$$

$$= \left(\frac{e^{\rho^2} - 1}{\rho f_m \sqrt{2\pi}} \right) \quad (18)$$

The AFD helps to find the lost signaling bits during the deep fades. Obviously, for a vehicular mobile, AFD would be very small but the LCR would be high. During fading, the receiver will experience fluctuations during which the signal (amplitude) cannot be recovered reliably.

Outage probability = Average no. of fades (threshold crossing rate) per second × AFD.

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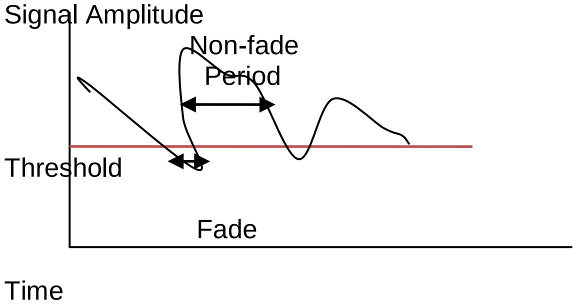

Figure 14. Fade and non-fade periods for a sample of a fading signal

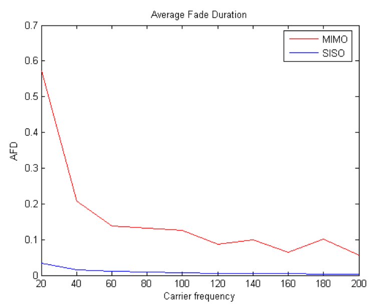

Figure 15. AFD vs Carrier frequency with different channel practically.

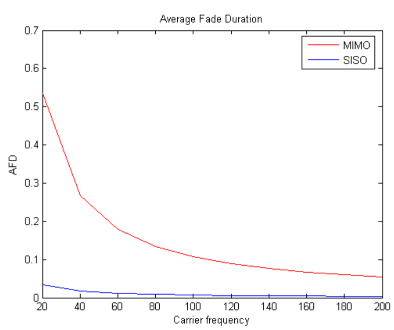

Figure 16. AFD vs Carrier frequency with different channel theoretically.

VII. Conclusion

For design, analysis, and installation of wireless networks, propagation models have become an inevitable tool for mitigating interference. Rayleigh fading is an efficient method for large-scale fading channels. Path-loss, probability density function, mean, and variance are found useful for understanding the AFD and LCR, which are necessary for studying fading causes and its effect on the signal transmission. Simulated results portray that**,** in MIMO channel, fading happens due to the scattering of the reflected waves and these are basically the Raleigh and Rican scattering.

It has been found from theoretical and practical values that AFD is greater for MIMO based ad-hoc network and LCR is lower with respect to Single channel ad-hoc network [4].

Imagination and a desire to build something new is the change we need to effect a change. From the above simulation results of the tables 2 and 3, we can find that the received power will obviously decrease as the path loss exponent increases. The results also show that path loss has almost no impact on throughputs and packet delay, but mainly decreases communication range. And also results show that Rayleigh fading and shadowing fading have an obvious impact on throughput and delay when the distance between the transmitter and the receiver exceeds a threshold. Consequently, more packets are dropped and the throughput decreases due to the increase of BERs. In addition, Rayleigh fading increases the average delay of packets.

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