



# EFFECT OF NEGATIVE SPATIAL/TEMPORAL CORRELATION ON THE PERFORMANCE OF MAXIMAL RATIO COMBINING IN A WCDMA CELLULAR SYSTEM

By

Arvind Nath Pandey  
(9917159)

Submitted In partial fulfilment of the requirement for the award of  
Masters (Engineering) degree

in the

Department of Electrical, Electronics and Computer Engineering

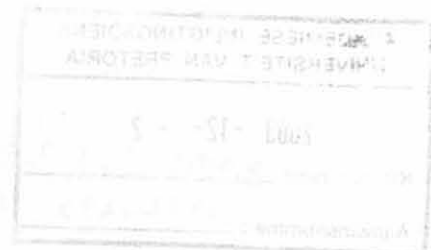
in the

Faculty of Engineering

at

UNIVERSITY OF PRETORIA

August 2003





# Dissertation Summary

## EFFECT OF NEGATIVE SPATIAL/TEMPORAL CORRELATION ON THE PERFORMANCE OF MAXIMAL RATIO COMBINING IN A WCDMA CELLULAR SYSTEM

**Arvind Nath Pandey**

**Supervisor: Prof. L. P. Linde**

**Dept of Electrical, Electronic and Computer Engineering**

**University of Pretoria**

**Masters (Engineering)**

This dissertation deals with the study of *smart antenna concepts* for *Wideband Code Division Multiple Access (WCDMA)* systems. A smart antenna model with spatial/temporal channel, correlated fading and maximal-ratio combining (MRC) is proposed. An analytical approach is used to develop a robust and accurate model. The proposed model provides considerable improvement in system gain at no extra cost to hardware. This system uses inherent signal information such as direction of arrival, fading and correlation between multipath components of arriving signals, to significantly improve system performance under certain conditions. The proposed technique is realised by combining three sub models namely direction of arrival, fading and diversity combining. The model is then evaluated for system performance.

The first sub-system model, viz. the *spatial or direction of arrival model*, is realised by considering *scatterer distribution* and *angular location* of mobiles. A *Gaussian bell shape distribution* for scatterers is considered, with the assumption that the density of scatterers is highest near the mobile and progressively reduces as we go further from the centre of the bell, i.e., away from the mobile. Although a *uniform angular distribution* of mobiles is



---

assumed, the mobile user distribution can be easily modified or adapted to match any real life operational scenario.

The second sub-model is the *temporal fading model*. Two temporal models, namely the *exponential* and *Gaussian*, are used to calculate channel parameters for *Line-of-Sight (LOS)* (typically urban) and *Non-Line-of-Sight (NLOS)* (typically bad urban) environments respectively. The channel parameters represent the combined effect of direction of arrival and temporal fading.

The third sub-model is the *diversity combiner model*. A probability density function for an MRC is calculated that takes into account the number of *diversity branches*, *signal power*, *temporal fading*, *constant correlation model* and *correlation coefficient* that gives a relationship between multipath signals. An important contribution is made to the existing research in this field by calculating system gain for signals with negative correlation coefficients.

The overall performance of the proposed spatial/temporal system model is evaluated using two evaluation criteria, namely *bit error rate (BER)* and *probability of outage*. The system is evaluated for *Non-Coherent Frequency Shift Keying (NC-FSK)*, *Differentially Coherent Phase Shift Keying (DC-PSK)*, *Coherent Frequency Shift Keying (C-FSK)* and *Coherent Phase Shift Keying (C-PSK)* digital modulation schemes. Considerable improvement in system gain is observed with all modulation schemes in specific operational scenarios with negatively correlated signals or where such conditions can be enforced.





# Opsomming Afrikaans

Hierdie verhandeling handel oor die studie van intelligente antenna-konsepte vir Wyeband-Kode-Divise Multi-Toegang (WCDMA) stelsels. 'n Intelligente antenamodel met ruimtelike/temporale kanaal, gekorreleerde seinverswakking en maksimale verhoudingskominering ('maximum-ratio-combining') word voorgestel. 'n Analitiese benadering word gevolg om 'n robuuste en akurate model te ontwikkel. Die voorgestelde model verskaf 'n aansienlike verbetering in stelselwinst teen minimum addisionele hardewarekoste. Die stelsel ontgin inherente seininformatie, soos invalshoek, seinverswakking (deining) en korrelasie tussen multipadkomponente van die invalseine, om die stelselfunksionaliteit en werkverrigting noemenswaardig te verbeter. Die voorgestelde tegniek is gerealiseer deur die aanwending en kombinasie van drie submodelle, naamlik invalshoek, seinverswakking (deining) en diversiteitskominering. Die werkverrigting van die voorgestelde model word ge-evalueer deur gebruik te maak van maatstawwe soos bisfouttempometing en die bepaling van die waarskynlikheid dat die stelsel bokant 'n gespesifiseerde minimum bisfoutlimiet sal funksioneer ('probability of outage').

Die eerste submodel, naamlik die *ruimtelike of direksionele invalshoekmodel*, is gerealiseer deur die *verpreiding van seinobstruksies* en die *hoekdistribusie van mobiele selfooneenhede* in ag te neem. 'n *Klokvormige Gaussiese transmissie-obstruksiedistribusie* is aanvaar met die aanname dat die digtheid van distribusie hoogste is naby die mobiele selfoon en stelselmatig afneem namate verder weg van die middelpunt van die klok (dws die selfoon) beweeg word. Hoewel 'n *uniforme hoekverspreiding* van selfone aanvaar is, kan die selfoon-gebruikersdistribusiemodel sonder moeite gemodifiseer of aangepas word om enige situasie in die praktyk voor te stel.

Die tweede submodel is die *temporale seinverswakkingmodel*. Twee temporale verspreidingsmodelle, naamlik *eksponensiëel* en *Gaussies*, is gebruik om die kanaalparameter(s) van respektiewelik die *Siglyn-* (tipies stedelike omgewing) en *Nie-Siglyn-* (tipies swak stedelik omgewing) gevalle te bereken. Die kanaalparameters verteenwoordig die gekombineerde effek van die invalshoek en temporale seinverswakking (deining).



Die derde submodel is die *diversiteitstakke* *seinsterte* *temporale seinverswakking*, *konstante korrelasiemodel* en die *korrelasiekoëffisiënt*, wat 'n indikasie is van die ooreenkoms tussen multipadseine, in ag. 'n Belangrike bydrae word in hierdie verhandeling tot bestaande navorsing in die veld gedoen deur die berekening van die stelselaanwinst vir seine met negatiewe korrelasiekoëffisiënte.

Die algehele werkverrigting van die voorgestelde ruimtelike/temporale model word evalueer deur van twee evalueringskriteria, naamlik *bisfouttempo* en die *waarskynlikheid dat die stelsel bokant 'n gespesifiseerde minimum bisfoutlimiet sal funksioneer* ('*outage probability*') gebruik te maak. Die stelsel is evalueer vir Nie-Koherente Frekwensie-Skuif-Sleuteling (NK-FSK), Differentiële-Koherente Fase-skuif-Sleuteling (DK-PSK) en Koherente Fase-Skuif-Sleuteling (K-PSK) syfermodulasietegnieke. Resultate toon dat aansienlike stelselaanwinste verkry kan word deur die eksploitering van bepaalde temporaal-ruimtelike operasionele situasies waarin negatiewe seinkorrelasie voorkom of afgedwing kan word.



## Acknowledgements

Any deserving higher academic level successfully achieved is a direct result of hard work and sacrifices on the part of the recipient. However, from time to time, a work of this nature requires help and co-operation from a number of people - and external factors beyond the control of man.

I therefore should like to thank sincerely all those who contributed in so many different ways towards the success of this dissertation.

I thank God for giving me the strength, patience, and keeping me motivated during the period of my academic carrier.

I also thank my parents, brothers and sisters for their love, support and encouragement at all times.

I must thank my wife, Chandra, for all her support, encouragement, and for all the patience during the long period of my academic pursuits.

I should like to include in my thank my colleague and manager Wayne MacDermid for his help and understanding.

I should like to thank my supervisor, Prof. L. P. Linde for his time, helpful suggestions and the constant guidance, which he provided at all times.

Again, I thank all the members of my family, and my friends, for their contributions.

I wish to thank Alcatel South Africa for all the financial support, which they provided during the period of my studies.

Finally, I acknowledge with gratitude the authors of the books and journals made available to me.





# Content

Dissertation Summary .....	i
Opsomming Afrikaans .....	i
Acknowledgements .....	Error! Bookmark not defined.
Content .....	i
List of Figures .....	iv
List of Tables .....	vi
List of Abbreviations .....	vii
List of Symbols .....	ix
Chapter 1 .....	1
<b>INTRODUCTION</b> .....	1
1.1 Dissertation Overview .....	1
1.2 WCDMA and UMTS .....	2
1.2.1 WCDMA .....	3
1.2.2 UMTS .....	5
1.2.3 UMTS for Africa .....	6
1.2.4 The path to 4G .....	8
1.3 Smart Antenna Aspects .....	8
1.3.1 Antenna Arrays and Configurations .....	9
1.3.2 Factors influencing antenna performance .....	10
1.4 Problem Definition .....	10
1.4.1 Channel Model .....	11
1.4.2 Maximal Ratio Combiner .....	11
1.4.3 System Model Evaluation .....	11
1.5 Contributions .....	12
1.6 Structure of the dissertation .....	12
Chapter 2 .....	14
<b>LITERATURE SURVEY</b> .....	14
2.1 Overview .....	14
2.2 Beamforming .....	16
2.3 Antenna Diversity .....	19
2.3.1 Space Diversity .....	20
2.3.2 Diversity Combining .....	21
2.3.3 Maximal Ratio Combining .....	22
2.4 Survey of generic Channel Models .....	24
2.4.1 Temporal Parameters .....	24
2.4.2 Nakagami's $-m$ Distribution .....	28
2.4.3 Spatial Parameters .....	30
2.5 Bit Error Rate Performance .....	33
2.5.1 Direct Sequence Spread Spectrum .....	35
2.5.2 Direct Sequence Spread Spectrum for Multi-users .....	36
2.5.3 Performance of Digital Modulation in Fading Channels .....	37
2.5.4 Probability of Error for BPSK and QPSK (Quadrature Phase Shift Keying) ..	39
Chapter 3 .....	41
<b>SPATIAL CHANNEL MODEL</b> .....	41
3.1 Introduction .....	41
3.2 Direction of arrival (DOA) Techniques .....	41
3.2.1 The MUSIC Algorithm .....	42



3.2.2	The ESPRIT Algorithm .....	43
3.3	Spatial Model .....	43
3.3.1	User Distribution Model .....	44
3.3.2	Scatterer Distribution Model .....	47
3.3.3	DOA pdf for all user with local Scatterers.....	51
3.4	Conclusion.....	53
Chapter 4.....		<b>54</b>
	<b>SPATIAL/TEMPORAL CHANNEL MODEL.....</b>	<b>54</b>
4.1	Channel Model .....	54
4.2	Temporal Fading Model.....	54
4.3	Exponential Fading Distribution Model.....	55
4.4	Gaussian Fading Distribution Model .....	56
4.5	Spatial/Temporal Fading Model.....	57
4.6	Conclusion.....	61
Chapter 5.....		<b>62</b>
	<b>RAKE RECEIVER AND MRC .....</b>	<b>62</b>
5.1	Rake Receiver .....	62
5.2	Pdf of the signal power for M branch MRC .....	64
5.2.1	Signal at the Diversity Antenna .....	64
5.2.2	Correlation Model.....	66
5.2.2.1	Constant Correlation Model.....	66
5.2.2.2	Exponential Correlation Model .....	67
5.3	MRC reception .....	68
5.4	Extension of the MRC pdf in section 5.3 for negatively correlated signals.....	70
5.4.1	Condition for negative $\rho$ for M-branch Diversity with Gaussian Signal .....	70
5.4.2	Pdf of SNR for M-branch Diversity combining with negatively correlated Nakagami fading .....	73
5.5	Conclusion.....	79
Chapter 6.....		<b>80</b>
	<b>PROPOSED SYSTEM MODEL ANALYSIS AND SIMULATIONS .....</b>	<b>80</b>
6.1	Introduction .....	80
6.2	System Overview .....	81
6.2.1	Direction of Arrival Model .....	82
6.2.2	Temporal Fading Model .....	82
6.2.3	Diversity Combining.....	83
6.3	System Model Analysis.....	85
6.4	Conclusion.....	88
Chapter 7.....		<b>89</b>
	<b>SYSTEM PERFORMANCE EVALUATION.....</b>	<b>89</b>
7.1	Introduction .....	89
7.2	BER Performance.....	89
7.2.1	BER Performance for (NCFSK and DCPSK) .....	92
7.2.2	BER Performance for (CFSK and CPSK) .....	95
7.3	Probability of Outage .....	98
7.4	Results .....	105
7.5	Conclusion.....	106
Chapter 8.....		<b>108</b>
	<b>CONCLUSIONS.....</b>	<b>108</b>
8.1	Introduction .....	108
8.2	Overview .....	108
8.3	Main Contributions .....	110
8.4	Future research .....	110





---

8.5 Conclusion.....	111
<b>Bibliography.....</b>	<b>112</b>
<b>Appendix A.....</b>	<b>125</b>
Diversity and Combining Techniques.....	125
A-1 Diversity.....	125
A-1.1 Polarisation Diversity.....	125
A-1.2 Angle Diversity.....	125
A-1.3 Frequency Diversity.....	126
A-1.4 Path Diversity.....	126
A-1.5 Time Diversity.....	126
A-2 Combining Techniques.....	127
A-2.1 Selection Combining.....	127
A-2.2 Feedback diversity.....	128
A-2.3 Switched Combining.....	128
A-2.4 Equal Gain Combining.....	129
<b>Appendix B.....</b>	<b>131</b>
B-1 Small Scale Fading.....	131
B-2 Rayleigh Fading Distribution.....	134
B-3 Rician Fading Distribution.....	135
<b>Appendix C.....</b>	<b>137</b>
C-1 Q-function.....	137
C-2 The <i>erf</i> and <i>erfc</i> functions.....	137
<b>Appendix D.....</b>	<b>138</b>
D-1 Bit Error Rate of Frequency Hopping Spread Spectrum.....	138
<b>Appendix E.....</b>	<b>139</b>
E Mathematical Formulas [51].....	139
<b>Appendix F.....</b>	<b>141</b>
F Determinant for $k \times k$ matrix.....	141

# List of Figures

Figure 1.1: Coverage of wired and wireless technologies in different scenarios .....	2
Figure 1.2: (a) shows FDMA/TDMA concept and (b) CDMA concept.....	3
Figure 1.3: CDMA Transmitter.....	4
Figure 1.4: CDMA Receiver.....	4
Figure 1.5: UMTS coverage is universal [10]. .....	7
Figure 1.6: Some common array geometries.....	10
Figure 1.7: Dissertation summary.....	13
Figure 1.8: Summary of the proposed system model. ....	13
Figure 2.1: Classification of smart antenna techniques [26]. ....	15
Figure 2.2: A generic DBF antenna system.....	16
Figure 2.3: An analog beamformer reduces the signal dimensionality from $K$ to 1.....	17
Figure 2.4: Generalised block diagram for space diversity combining. ....	21
Figure 2.5: Maximum ratio combiner.....	22
Figure 2.6: Small-scale and large-scale fading.....	26
Figure 2.7: Fading Channel Manifestations.....	27
Figure 2.8: Geometry explaining the DOA $\phi_i$ from Tx to Rx for multipath echo. ....	32
Figure 2.9: Pdf of DOA for a GBSBEM, given by (2.6).....	33
Figure 2.10: Block diagram of a DS-SS system with binary phase modulation: (a) transmitter and (b) receiver. ....	35
Figure 2.11: Model of $K$ users in a CDMA spread Spectrum system.....	36
Figure 2.12: Probability of error for $K=1, 10, 100$ users.....	37
Figure 2.13: Probability of error for BPSK in one-sided Exponential, Rayleigh, Rician and Nakagami Fading .....	40
Figure 3.1: Modelling the location of users in a cellular system. ....	44
Figure 3.2: Qualitative description of the PDF of user distribution in a typical urban micro cellular scenario [68].....	46
Figure 3.3: Pdf of angular and uniform distribution of mobiles [68]. ....	46
Figure 3.4: Modelling of scattering elements as (a) a ring of scatterers or (b) a continuous disc of scatterers.....	47
Figure 3.5: Gaussian bell shape model of scattering elements.....	48
Figure 3.6: Pdf of AOA for Macro cell, LOS Micro cell, and NLOS Micro cell in local scattering environment [65]. ....	50
Figure 3.7: Pdf of AOA in scattering environment for LOS and NLOS micro cell.....	51
Figure 3.8: Pdf for DOA of signals at the base station with user location and local scatterer information in LOS and NLOS, macro cellular environments. ....	52
Figure 4.1: Fading parameter $\mu$ of multipath echoes at the base station using exponential model.....	57
Figure 4.2: Fading parameter $\mu$ of multipath echoes at the base station using Gaussian model.....	58
Figure 4.3: Comparison of Exponential and Gaussian Fading Models for $\mu$ values with multipath echoes.....	58
Figure 4.4: Channel fading parameter $\mu$ values with Exponential fading model for Typical Urban (LOS) and with Gaussian fading model for Bad Urban (N-LOS) scenarios. ....	59
Figure 4.5: Flow diagram for the realisation of spatial/temporal channel model [8]. ....	60
Figure 5.1: An $M$ -branch receiver.....	63
Figure 5.2: Basic Structure of a diversity combiner [26]. ....	74



Figure 5.3: Probability density function of MRC for $M = 3$ , channel fading parameter $\mu = 3.8$ , and $\rho = 0.9, 0.75, 0.4, \&-0.1$ .....	75
Figure 5.4: Probability density function of MRC for $M = 3$ , channel fading parameter $\mu = 0.6$ and $\rho = 0.9, 0.75, 0.4, \&-0.1$ .....	76
Figure 5.5: Probability density function of MRC for $M = 3$ , channel fading parameter $\mu = 0.6 \& 3.8$ and $\rho = 0.4 \& -0.1$ .....	76
Figure 5.6: Probability density function of MRC for $M = 5$ , channel fading parameter $\mu = 0.6 \& 3.8$ and $\rho = 0.4 \& -0.1$ .....	77
Figure 5.7: Probability density function of MRC for $M = 5 \& 3$ , channel fading parameter $\mu = 3.8$ and $\rho = 0.4 \& -0.1$ .....	77
Figure 6.1: Main features of the system model with smart antenna components.....	81
Figure 6.2: Summary of proposed system model. ....	84
Figure 6.3: Probability density function of received signals in LOS and NLOS for the proposed system model. ....	87
Figure 7.1: BER probability plot for NCFSK , for $M = 2, 3 \& 5$ . ....	90
Figure 7.2: BER probability plot for DCPSK, for $M = 2, 3 \& 5$ . ....	91
Figure 7.3: BER probability plot for CPSK, for $M = 2, 3 \& 5$ . ....	91
Figure 7.4: BER probability plot for CFSK, for $M = 2, 3 \& 5$ . ....	92
Figure 7.5: Probability of error for the proposed system model with negative $\rho$ , LOS & NLOS, and NCFSK modulation. ....	94
Figure 7.6: Probability of error for the proposed system model with negative $\rho$ , LOS & NLOS, and DCPSK modulation. ....	94
Figure 7.7: Probability of error for the proposed system model with negative $\rho$ , LOS & NLOS, and CFSK modulation. ....	96
Figure 7.8: Probability of error for the proposed system model with negative $\rho$ , LOS & NLOS, and CPSK modulation .....	97
Figure 7.9: Comparison of probability of error for NCFSK, DCPSK, CFSK & CPSK with $\rho = -0.4$ in LOS & NLOS.....	97
Figure 7.10: Probability of Outage plot for NCFSK with $M = 2, 3 \& 5$ .....	99
Figure 7.11: Probability of Outage plot for DCPSK with $M = 2, 3 \& 5$ .....	100
Figure 7.12: Probability of Outage plot for CFSK with $M = 2, 3 \& 5$ .....	101
Figure 7.13: Probability of Outage plot for CPSK with $M = 2, 3 \& 5$ .....	101
Figure 7.14: Probability of Outage for NCFSK with $P_e^* = 10^{-4}$ and $\rho = 0.1, -0.1, -0.4$ .....	102
Figure 7.15: Probability of Outage for DCPSK with $P_e^* = 10^{-4}$ and $\rho = 0.1, -0.1, -0.4$ .....	103
Figure 7.16: Probability of Outage for CFSK with $P_e^* = 10^{-4}$ and $\rho = 0.1, -0.1, -0.4$ .....	103
Figure 7.17: Probability of Outage for CPSK with $P_e^* = 10^{-4}$ and $\rho = 0.1, -0.1, -0.4$ .....	104
Figure 7.18: Comparison of Probability of Outage for NCFSK, DCPSK, CFSK & CPSK, with $M = 3, \rho = -0.4$ and $P_e^* = 10^{-4}$ .....	104
Figure A.1: Selection Combining. ....	127
Figure A.2: Feedback diversity.....	128
Figure A.3: Equal Gain Combiner. ....	129
Figure B.1: Matrix illustrating type of fading experienced by a signal as a function of ...	133





# List of Tables

Table 2.1: Summary of channel models for mobile cellular communication systems [8].	25
Table 3.1: Cell radii and standard deviation for macro and micro cells.	50
Table 3.2: Typical values of $2\alpha_b$ , $D$ , and $\sigma$ for the calculation of AOA.	50
Table 3.3: Comparison of angular spread of DOA at the base station calculated with the model presented here and the rule of thumb in [8].	52
Table 4.1: Summary of temporal fading model parameters	57
Table 4.2: Nakagami - $m$ values for LOS & NLOS with three multipath echoes	60
Table 6. 1: Summary of proposed system parameters.	85
Table 6. 2: Main system model parameter and values.	87
Table 7.1: Simulation Table of BER for NCFSK and DCPSK.	93
Table 7.2: Simulation Table of BER for CFSK and CPSK.	96
Table 7.3: Simulation Table of probability of outage for NCFSK and DCPSK.	102
Table 7.4: Simulation Table of probability of outage for CFSK and CPSK.	102



# List of Abbreviations

3G	Third Generation
4G	Fourth Generation
AOA	Angle Of Arrival
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CDTD	Code Division Transmit Diversity
CFSK	Coherent Frequency Shift Keying
CPFSK	Continuous Phase Frequency Shift Keying
CSC	Complex Symbol Combining
DBF	Digital Beam Forming
DCFSK	Differentially Coherent Frequency Shift Keying
DOA	Direction Of Arrival
DPSK	Differential Phase Shift Keying
DS-CDMA	Direct Sequence CDMA
DSP	Digital Signal Processing
DS-SS	Direct Sequence Spread Spectrum
EFD	Exponential Fading Distribution
ESPRIT	Estimation of Signal Parameters via Rotational Invariance Techniques
ETSI	European Telecommunication Standards Institute
FDMA	Frequency Division Multiple Access
FM	Frequency Modulation
FSC	Full Spectrum Combining
FSK	Frequency Shift Keying
GBSBEM	Geometrically Based Single Bounce Elliptical Model
GFD	Gaussian Fading Distribution
GPRS	General Packet Radio System
GSM	Global System for Mobile
I	Inphase



---

IMT-2000	International Mobile Telecommunication 2000
LOS	Line Of Sight
MBS	Mobile Broadband Systems
MDPSK	Minimum differential Phase Shift Keying
MMIC	Monolithic Microwave Integrated Circuit
MPSK	M-ary Phase Shift Keying
MR	Maximal Ratio
MRC	Maximal-Ratio Combining
MRRC	Maximal-Ratio Receiver Combining
MUSIC	<u>M</u> ultiple <u>S</u> ignal <u>I</u> dentification and <u>C</u> lassification
NCFSK	Non Coherent Frequency Shift Keying
NLOS	Non Line Of Sight
PDF	Probability Density Function
PLMN	Public Land Mobile Network
PN	Pseudo-Noise
PSK	Phase Shift Keying
Q	Quadrature phase
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
SC	Selection Combining
SDMA	Space Division Multiple Access
SER	Symbol Error Rate
SNR	Signal to Noise Ratio
TD-CDMA	Time-Division CDMA
TDMA	Time Division Multiple Access
TDTD	Time Division Transmit Diversity
TOA	Time of Arrival
UMTS	Universal Mobile Telecommunication System
VHE	Virtual Home Environment
WCDMA	Wideband Code Division Multiple Access
WLAN	Wireless Local Area Network
WLL	Wireless Local Loop



# List of Symbols

$\rho$	Correlation co-efficient
$\Phi$	Cumulative direction of arrival
$\kappa$	Rice factor
$\theta_0$	DOA due to user distribution, measured from some reference
$\phi_0$	DOA of the main received path
$\sigma^2$	Variance of a distribution
$\theta_b$	Angle of scattering point with reference to BS
$\phi_l$	DOA at the Rx after single bounce
$\theta_l$	DOA at the Tx after single bounce
$\varphi_K$	Phase shift
$\alpha_l$	Location of peak $l$ in user pdf
$\gamma_l$	Weight of peak $l$ in user pdf
$\delta_m$	$m$ -parameter decay rate
$\Omega_M$	Signal power received on branch $M$
$\sigma_m$	Standard deviation of fading parameter $m$
$\alpha_b$	$\frac{1}{2}$ antenna beam width
$A_{norm}$	Normalisation factor
$D$	Distance of scatterer from BS
$d_o$	T-R separation
$E_0/N_0$	Bit energy to-noise density
$f_c$	Carrier frequency
$\Gamma$	Gamma function
$G_M$	Antenna gain on branch $M$
$h_r$	Receiver height
$h_t$	Transmitter height
$i$	Symbol interval index
$K$	No of users
$m$	Nakagami's fading parameter
$M$	Number of diversity branches
$m_0$	Nakagami fading of the main received path



---

$m_k(t)$	Data sequence
$N$	No of chips
$P_e$	Probability of error
$PN_k(t)$	PN code sequence
$Q$	Q – Function
$R_c$	Cell radius
$r$	distance of mobile from base station
$R(t)$	Transmitted radio signal
$r_b$	Distance of mobile from BS
$S$	Fading signal power
$S(t)$	Modulated signal
$\theta$	Spatial DOA
$\mu$	Spatial/temporal channel fading parameter
$w_l$	Width of peak $l$ in user pdf
$w_M$	Weighting on branch $M$
$Z_M$	Correlator output
$L_M$	Number of multipath
$U(t)$	IF or base band CDMA signal with multipath
$Z$	Correlator
$\omega_c$	Carrier frequency
$\zeta$	A positive definite ( $2M \times 2M$ ) covariance matrix
$\wedge$	Is an $M \times M$ square Symmetric matrix
$\upsilon$	Twice variance ( $\sigma^2$ )
$\gamma$	Signal – to – Noise ratio
$S_k$	Instantaneous power in the $k$ th signal
$R$	Arbitrary correlation matrix
$\Psi_S$	Characteristic function of the pdf of MRC diversity system
$\alpha$	A constant that determines the modulation scheme when calculating Probability of BER
$\Omega$	Average signal power
$S_c$	Received signal strength in volts
$\alpha_F$	Amplitude of a fading channel
$\sigma$	Standard deviation

---



---

$r_K$	Signal received on a diversity branch
$X_{ck}$	Amplitude of the in phase component of the received signal on $k$ th branch of a diversity system
$X_{sk}$	Amplitude of the quadrature phase component of the received signal on $k$ th branch of a diversity system
$I$	A $2M \times 2M$ identity matrix
$\lambda$	A constant representing real numbers
$T$	A diagonal matrix
$t_k$	Symbol interval index